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Keywords: *grid electricity reliability, power outage frequency, power outage duration, hydrology levels, ARDL model.*

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Environmental Influences on Electricity Reliability in Uganda's Grid System

Adella Migisha Grace ^α, Joseph Ntayi ^σ, Faisal Buyinza ^ρ, Muyiwa S Adaramola ^ω, Livingstone Senyonga [¥] & Joyce Abaliwano [§]

Abstract- This study investigated the environmental factors that influence the reliability of grid electricity at the generation subsystem, in Uganda. The systems reliability theory and the auto regressive distributed lag (ARDL) model were used to estimate the effects of hydrology levels of Lake Victoria and rainfall on both the frequency and duration of power outages on the Ugandan power grid network. Both the short and long run effects were estimated and the findings revealed that hydrology levels of Lake Victoria significantly affected grid electricity reliability in the generation subsystem of the Ugandan power grid network in both the short and long runs. On the other hand, rainfall significantly affected the generation grid electricity reliability in only the short run, implying that rainfall effects on grid electricity reliability on the generation subsystem, do not spill over onto the long run. The study recommends proper management of lake Victoria and other water resources so that reliability of grid electricity at the generation subsystem is not disrupted by the environmental factors under study.

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I. INTRODUCTION

Electricity is a vital resource in modern society and its reliability is essential for economic development, public safety, and general well-being (Alhelou et al., 2019; Worldbank, 2018). Therefore, the lack of reliable electricity (especially grid electricity) is a constraint on economic development (Worldbank 2017). According to the World Bank, sub-Saharan Africa is facing significant challenges in terms of grid reliability. An example of such a challenge is the cumulative time of power outages in the region, which amounts to approximately three months of production time lost per year (Karekezi et al., 2012; World Bank, 2017).

Approximately 15 years ago, Uganda had electricity challenges of electricity demand exceeding supply by a 2-to-1 ratio and this was because low water levels in Lake Victoria (Wabukala et al., 2021). Although environmental factors have been reported to cause

power outages, empirical studies on their effect of Uganda's case especially in terms of their effect on the frequency and duration of power interruptions are scarce.

Furthermore, despite the fact that environmental factors have been documented to influence grid electricity reliability (Alhelou et al., 2019; Cadini et al., 2017; Rentschler et al., 2019; Veloza & Santamaria, 2016; Wabukala et al., 2021), studies that have used the systems reliability theory are rare. In addition, some of the studies like (Alhelou et al., 2019; Veloza & Santamaria, 2016; Ward, 2013) used a qualitative approach to review, discuss and report environmental related challenges of grid electricity reliability. The studies that have used a quantitative approach such as Kabir et al., (2019) and Sahai & Pahwa (2006) used probability analysis to assess the reliability of the grid components whereas, Andersson et al., 2005; Davidson et al., 2003; Ivanova et al., 2020; Mitchell, 2013; Vinogradov et al., 2020) used descriptive analysis to investigate environmental factors that influence grid systems reliability performance. The studies that have used ARDL to investigate the environmental factors that influence grid electricity reliability are scarce. The econometric ARDL model separates the long run from the short run effects. This helps policy makers to plan accordingly for both the short run shocks as the long run approaches.

This study uses the autoregressive distributed lag (ARDL) model and systems reliability theory to estimate the effect of environmental factors in particular hydrology levels of Lake Victoria, as well as rainfall, on generation grid electricity reliability, in terms of both frequency and duration of power outages.

The generation subsystem of the Ugandan power grid is largely dependent on hydropower sources (Katutsi et al., 2021; Wabukala et al., 2021), whose water levels are easily vulnerable to changes in the environment, weather patterns, and other natural disasters. In addition, natural disasters, such as floods, are serious and recurring events that can result in, among others, the destruction of power grids, leading to power outages (Kumar & Biswanath, 2020). Disasters such as floods could be triggered by heavy rains. To avoid such electricity supply interruptions, it is necessary to investigate whether environmental factors such as hydrology levels of water resources and rainfall

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could be responsible for unreliable electricity power generation in Uganda.

a) *Main Objective*

This study aims to investigate the effect of environmental factors on the reliability of grid electricity in the generation subsystem in Uganda.

b) *Specific Objectives*

1. To examine the effect of hydrology levels of lake Victoria on the generation grid electricity reliability in Uganda.
2. To examine the effect of rainfall on the generation grid electricity reliability in Uganda.

c) *Motivation of the study*

This study gets its motivation from the United Nations Sustainable Developmental Goal Seven (SDG 7) which is "ensuring access to affordable, reliable, sustainable and modern energy for all by 2030" United Nations (2017). However, Uganda like other developing countries, continues to suffer from unreliable grid electricity supply. Uganda was ranked 108 out of 137 countries, by the World Economic Forum (WEF) in 2019, with an electricity reliability score of 3.4 out of 7. This was a decline for Uganda, from 103 in 2016 to 108 in 2019(WEF, 2019). In addition, grid reliability in Uganda is currently at 73.3% with customers experiencing power outage durations and power outage frequency averagely at 189.6 hours and 84 times per month (ERA, 2020b). This supply of unreliable grid electricity continues to compromise the functions sectors ranging from residential, manufacturing, agriculture, transport as well as service sectors that depend to a large extent on electricity in particular to function (Fashina *et al.*, 2018). However, grid electricity is subject to a range of factors that influence it reliability and some could be environmental in nature. It is therefore important to examine these factors and address the grid electricity related challenges, so that the electricity dependent functions of these sectors are not compromised.

II. LITERATURE REVIEW AND HYPOTHESIS TESTING

a) *Theoretical Review*

In this study, we use systems reliability theory (Shewhart & Wilks, 2021) to argue that reliability is the ability of a system to perform as required in a stated operating context and for a given time. This theory further states that a system is made up of interrelated elements that are organized to achieve one or more stated purposes. These interrelated elements are usually classified as subsystems (Shewhart & Wilks, 2021) such that a failure on one subsystem leads to failure on the other subsystems and hence failure of the whole system. A failed system is not able to deliver as expected and therefore becomes unreliable. The

systems reliability theory, assumes that all systems are used in some sort of environment that may influence the system and could make them susceptible to faults and failures (Shewhart & Wilks, 2021). These system failures and faults lead to system unreliability. System failures and faults are defined as a set of circumstances that lead to system failure and these can be an environmental event, including but not limited to; rainfall and hydrology levels of water resources (Ward, 2013).

Relatedly, grid electricity system, reliability has been defined as the ability of power grid elements to supply electricity to all consumers connected to it (Borecki *et al.*, 2020). The power grid is an electrical system network which is comprised of subsystems that include; generation, transmission and distribution subsystems. These subsystems are connected and interrelated together in such a way that a failure on one subsystem of the grid leads to failure on the entire grid system, thus compromising the reliability of the power grid system. The generation subsystem is essential on the power grid in such a way that, failure or fault on this part of the power grid compromises grid electricity reliability on the entire power grid system since it's the genesis of the power grid system. The power grid system too resides in an environment that makes it susceptible to system failures and system faults and these comprise the reliability of the power grid system. These system failures and system faults could be caused by rainfall and hydrology levels of water resources.

b) *Empirical Review And Hypothesis Testing*

The effect of weather and other changes in the environment on the reliability of grid electricity have been studied (Alhelou *et al.*, 2019; Wang & Billinton, 2002; Ward, 2013). For example, (Davidson *et al.*, 2003) looked at the effect of different cover types on grid electricity reliability but focused on only the distribution subsystem. In addition, (Carreras *et al.*, 2019; Ivanova *et al.*, 2020; Vinogradov *et al.*, 2020) studied the effect of different tree characteristics on grid electricity reliability (Carreras *et al.*, 2019; Ivanova *et al.*, 2020; Vinogradov *et al.*, 2020) but these studies concentrated on the transmission and distribution subsystems. Other studies that also looked at environmental factors considered antecedents such flooding (Koks *et al.*, 2019; Kwasinski *et al.*, 2009) but had a qualitative approach and also were done in the distribution subsystem. A few studies that have looked at the generation grid electricity reliability, have looked at the effect of hurricanes and mainly had a qualitative approach and have been done in developed countries (Alhelou *et al.*, 2019; Liu & Singh, 2011). However, the above studies seem to be silent on the effect of hydrology levels of water resources on grid electricity reliability specifically in the generation subsystem on the Uganda.

Furthermore, Ward (2013) reviewed the effects of weather on the reliability of power grid systems and found out that in North America, some of the grid faults were caused by rainfall. However this study was done in the distribution subsystem, and had a qualitative approach. Davidson *et al.*, (2003) also examined the relationships between power grid disruptions caused by rainfall and found out that rainfall led to power grid outages while Kabir *et al.*, (2019) in their study on predicting power outages point out rainfall as one of the influences of grid electricity reliability. These studies were also done in the distribution subsystem. In addition most of these studies have been done in the developed countries and a few in developing countries and besides, there is no empirical evidence in literature on the effect of both hydrology levels of Lake Victoria and rainfall, especially in terms of frequency and duration of power outages in Uganda. Therefore this study hypothesizes that;

H1: Hydrology levels of lake Victoria have a significant effect on generation grid electricity reliability in Uganda in both the short and long run.

H2: Rainfall has a significant effect on the generation grid electricity reliability in Uganda in both the short and long run.

III. RESEARCH METHODOLOGY

a) Data and Data Sources

To attain the objective of this study took on an explanatory research design which focuses on explaining the aspects of the effect of hydrology levels of Lake Victoria and rainfall on the generation grid electricity reliability. The study used monthly time series data covering a period from 2012–2022. Time series data was used because it provides insights into how a given variable changes over time, identifies patterns in the data and can be used to predict the future behaviour of a variable. Data containing the dependent variables of the study was obtained from Uganda Electricity Generation Company Limited (UEGCL). This was power outage data from four large hydropower generation plants in Uganda and also connected to the power grid. (Kiira hydropower plant, Owen falls hydropower plant, Bujagali hydropower plant, and Isimba hydropower plant), collected and recorded using the SCADA software system. Power outage data was measured using both the frequency of power outages and duration of power outage.

The study also obtained monthly data for the independent variables which included hydrology levels of lake Victoria and rainfall from the Ministry of Water and Environment and Uganda National Metrological Authority databases. These organisations collect and record data on weather, environmental features and power utility parameters. In this context, hydrology levels of lake Victoria refers to the amount of water available in

Lake Victoria and used for electricity generation. It was measured in meters from a reference point of 1122.892m to Mombasa from Jinja. On the other hand, rainfall refers to the amount of precipitation in form of rain that is received throughout the country and measured in millimeters (mm) per month.

b) Variables of the Study

The variables of the study were defined in line with the systems reliability theory, previous literature and also according to ERA and Ministry of Water and Environment (ERA, 2020a; Haes Alhelou *et al.*, 2018; Shewhart & Wilks, 2021; Tsimsios & Safigianni, 2016). The dependent variables were frequency and duration of powers which are used to measure grid electricity reliability.

i. Dependent Variable

Frequency of Power Outages:

This is defined as how often electricity disruptions occur on the grid subsystems. It was measured by the No. of power interruptions experienced by the large hydropower plants per month.

Duration of Power Interruptions:

This is a measure of the length of time that a power outage lasts from the moment it begins until power is restored and it was measured by the No. of hours of power interruption experienced by the large hydropower plants per month.

ii. Independent Variables

Rainfall:

In this context, rainfall refers to the amount of precipitation in form of rain that is received throughout the country in millimeters (mm) per month.

Hydrology levels:

This refers to the amount of water available in Lake Victoria and used for electricity generation. It was measured in meters from reference point of 1122.892m.

System overload:

This occurs when the demand for electricity exceeds the supply capacity of the grid. It was measured using the number of system overload events experienced by the large experienced by the large hydropower plants per month.

Failed Equipment:

This refers to any malfunction or damaged equipment within the grid infrastructure such as transformers, power lines or circuit breakers. It was measured using the number of failed equipment recorded by the large hydropower plants per month.

Technical Faults:

They refer to any technical issue that occurs within the grid infrastructure such as faults in control systems, communication systems or protection

systems. It was measured using the number of technical faults recorded by the large hydropower plants

Repair and maintenance costs:

The amount of money power utilities spend on maintaining and repairing the power grid and was measured using repair and maintenance costs incurred by the large hydropower plants per month.

System shutdowns:

These include unplanned shutdowns caused external or internal operations and planned shutdowns caused by planned operations. It was measured using

the number of times the large hydropower plants experienced system shutdowns per month.

c) *Estimation Model Procedure*

One of the basic parameters that define the reliability of the power grid is the number of and length of time of power grid system failures (Tsimtsios & Safigianni, 2016). This paper sought to determine the effect of environmental factors on the reliability of generation grid electricity. Theoretically and empirically, grid reliability can be influenced by environmental factors (Alhelou *et al.*, 2019; Shewhart & Wilks 2021).

$$Reliability\ of\ Grid\ Electricity_t = \alpha + \beta_1 environmental\ factors_t + e_t \dots\dots \quad Equation\ 1$$

The study first carried out pre estimation tests on the data before deciding on which time series model to use for estimation. In order to observe the long term movement in the data this study used time series line plots. The time series line plots of the study variables are documented in the appendix section this paper. It is paramount to do unit root tests of all the variables in the model before estimating the model in order to avoid the problem of spurious results which emanate from estimation of non-stationary time series. Therefore the study carried unit root tests for stationarity using Augmented Dickey Fuller (ADF) (1979 and 1981) and (Phillips and Perron, 1986) tests to determine the order of integration of the variables in the model both in levels and in first difference. The results of the unit root test as shown in the appendix section, show that all the variables except hydrology levels, were stationary in levels. Hydrology levels became stationary after differencing it once. Therefore, since the variables had a mixture of both I (0) and I (1) orders of integration, it was possible to estimate the ARDL model for the generation subsystem.

To ascertain if the independent variables had a long run relationship with their dependent variables, the study carried out co-integration tests. The results for the cointegration test(s) for the are shown in the appendix section.

For the generation subsystem, the dependent variables are frequency of power outages (FOU_t) and duration of power outages (DOU_t) and their lagged values were expressed as FOU_{t-1} and DOU_{t-1} for frequency of power outages and duration of power

outages respectively. The explanatory variables in the model include; hydrology levels of lake Victoria (HL) and rainfall (RF). Their lagged values are expressed as HL_{t-1} and RF_{t-1} . This study controlled for system shutdowns (SH_t), maintenance and repair costs (MR_t), technical faults (TF_t), failed equipment (BE_t) and system overload (O_t). The lagged values of the control variables were expressed as; shutdowns (SH_{t-1}), maintenance and repair costs (MR_{t-1}), technical faults (TF_{t-1}), failed equipment (BE_{t-1}) and system overload (O_{t-1}), which have been documented as influencers of grid electricity reliability.

d) *Econometric model Estimation for the study*

According to the systems reliability theory Shewhart and Wilks (2021) and Ward (2013) grid electricity reliability is influenced by environmental factors such as hydrology levels and rainfall. Basing on such a background, the study therefore formulated the ARDL regression model (s) shown equations 2 and 3 for both frequency and duration of power outages;

$$FOU_t = f(SH_t, MR_t, RF_t, HL_t, BE_t, TF_t, O_t) \dots\dots Equation\ 2$$

$$DOU_t = f(SH_t, MR_t, RF_t, HL_t, BE_t, TF_t, O_t) \dots\dots Equation\ 3$$

Equation 4 is the ARDL estimation model, which was used to analyze the long term and short term relationship between the variables of the study plus the error correction term for the frequency of power outages.

$$\begin{aligned} \ln FOU_t = & \beta_0 + \beta_1 \ln FOU_{t-1} + \beta_2 \ln SH_{t-1} + \beta_3 \ln MR_{t-1} + \beta_4 \ln RF_{t-1} + \beta_5 \Delta \ln HL_{t-1} + \beta_6 \ln TF_{t-1} + \\ & \beta_7 \ln BE_{t-1} + \beta_8 \ln O_{t-1} + \sum_{i=1}^a \beta_{9,i} \ln FOU_{t-i} + \sum_{i=1}^b \beta_{10,i} \ln SH_{t-i} + \sum_{i=1}^c \beta_{11,i} \ln MR_{t-i} + \sum_{i=1}^d \beta_{9,i} \ln RF_{t-i} + \\ & + \sum_{i=0}^e \beta_{10,i} \Delta \ln HL_{t-0} + \sum_{i=0}^f \beta_{10,i} \ln FT_{t-0} + \sum_{i=0}^g \beta_{10,i} \ln BE_{t-0} + \sum_{i=0}^h \beta_{10,i} \ln O_{t-0} + \\ & \dots \dots \dots + \theta_6 ECM_{t-1} + e_t \dots\dots\dots \end{aligned} \quad Equation\ 4$$

Relatedly, for duration of power outages the same steps were followed and the ARDL model was established as below in equation 5;

$$\begin{aligned}
 \ln DOU_t = & \beta_0 + \beta_1 \ln DOU_{t-1} + \beta_2 \ln SH_{t-1} + \beta_3 \ln MR_{t-1} + \beta_4 \ln RF_{t-1} + \beta_5 \Delta \ln HL_{t-1} + \beta_6 \ln TF_{t-1} + \\
 & \beta_7 \ln BE_{t-1} + \beta_8 \ln O_{t-1} + \sum_{i=1}^a \beta_{9,i} \ln FOU_{t-1} + \sum_{i=1}^b \beta_{10,i} \ln SH_{t-i} + \sum_{i=1}^c \beta_{11,i} \ln MR_{t-i} + \sum_{i=1}^d \beta_{9,i} \ln RF_{t-i} + \\
 & + \sum_{i=0}^e \beta_{10,i} \Delta \ln HL_{t-0} + \sum_{i=0}^f \beta_{10,i} \ln TF_{t-0} + \sum_{i=0}^g \beta_{10,i} \ln BE_{t-0} + \sum_{i=0}^h \beta_{10,i} \ln O_{t-0} + \\
 & \dots \dots \dots + \theta_6 ECM_{t-1} + \lambda_t \dots \dots \dots
 \end{aligned}$$

Equation 5

Where Δ was the first order differential operator, λ_t and e_t represent the white noise.

IV. RESULTS OF THE STUDY

a) *Descriptive Statistics*

Table 1 presents the descriptive statistics of the study variables (dependent and independent) for the generation subsystem.

Table 1: Descriptive Statistics of Variables of the Study (N= 128)

Variable	Mean	Std. dev.	Min	Max	Skewness	Kurtosis
Maintenance and repair costs	408.01	651.29	54	3860	3.99	20.24
System shutdowns	21.86	18.18	1	118	2.08	9.46
Hydrology levels	12.174	0.47	11.31	13.4	-0.49	8.41
Rainfall	111.65	52.59	32.90	247.71	0.03	2.25
Technical Faults	53.57	39.48	6	248	1.85	7.58
Failed Equipment	2.81	3.42	0	21	2.39	10.67
Frequency of Outages	230.08	74.36	92	643	2.52	13.45
Duration of Outages	4757.02	1351.44	17.38	5976.38	0.57	7.42

Source: STATA Software 17 outputs.

All the large hydropower plants combined experienced an average of 230 power interruptions per month. The average duration of power interruption was 4757 h per month. On average, the water levels were 12.17 m above 1122.892 m in reference to Mombasa from Jinja. On average, technical faults occurred 54 times per month, whereas grid components failed on average three times per month. The average amount of rainfall received throughout the country is 11.65 mm per month. The generation grid spends an average of 408 million (Uganda Shillings) on maintaining and repairing the grid. On average, system shutdowns took place 21 times per month.

V. RESULTS OF THE STUDY

a) *Estimation results of the short term and long term ARDL model for the frequency and duration of power outages*

Table 2 shows the estimation results on the effect of the effect of hydrology levels of lake Victoria and rainfall on both the frequency and duration of power outages on the generation subsystem in both the short and long run. The optimal lag order of each variable in the models was identified using HQIC, AIC and SBIC. Therefore, the ARDL (1, 4, 3, 1, 3, 2, 2, 2) was identified to be the most appropriate. The coefficients together with their respective probabilities are displayed below.

Table 2: The Estimation Results of the Long Term and Short Term Model of ARDL for the Frequency and Duration of Power Outages.

Models	Variable	Frequency of power outages		Duration of power outages	
		Coefficient	P-value	Coefficient	P-value
Long term model	In system shutdowns	0.1720	0.010	0.1201	0.273
	In maintenance and repair costs	-0.0348	0.330	-0.7555	0.011
	In rainfall	0.1949	0.009	0.1125	0.326
	D. Hydrology levels	-0.9151	0.043	-0.4486	0.518
	In technical faults	0.2080	0.002	-0.0141	0.907
	In failed equipment	-0.0125	0.833	0.2102	0.066
	System overload	0.0442	0.077	-0.1001	0.809
	C	3.004	0.000	4.8252	0.001
	Short term model	In system shutdowns			
D1.		0.0077	0.895	-0.0003	0.996
LD.		-0.0309	0.526	-0.0060	0.920
L2D.		-0.5952	0.140	-0.0362	0.448
L3D.		-0.0901	0.004	-0.0430	0.209
In maintenance and repair costs					
D1.		-0.0424	0.347	0.0572	0.266
LD.		-0.0046	0.906	0.0104	0.822
L2D.		-0.0248	0.523	0.0608	0.160
In rainfall					
D1.		-0.0951	0.065	-0.0194	0.724
D. Hydrology levels					
D1.		0.7626	0.019	0.3039	0.405
LD.		0.1913	0.276	0.3649	0.070
L2D.		0.0448	0.707	0.0074	0.958
In failed equipment					
D1.		-0.0207	0.642	-0.1125	0.044
LD.		0.1018	0.162	0.0527	0.149
In technical faults					
D1.		-0.0231	0.754	0.0863	0.228
LD.		0.1018	0.108	0.1376	0.844
System overload					
D1.	-0.0020	0.911	0.0306	0.128	
LD.	-0.0025	0.839	0.0070	0.617	
ECM	-0.8679	0.000	-0.5672	0.002	

Source: STATA Software 17 outputs

In table 2, the study found that a unit increase in meters in the hydrology levels of Lake Victoria led to 91.5 percent (significant) decrease in the frequency of generation grid power interruptions hence increasing grid electricity reliability. The coefficient of hydrology levels in the long run implies that high hydrology levels improve grid reliability to large extent. In the short run however, hydrology levels of lake Victoria were negatively associated with grid electricity reliability in the long run because a unit increase in meters in the hydrology levels of Lake Victoria led to 76 percent (significant) increase in the frequency of generation grid

power interruptions hence compromising grid electricity reliability. This implies that the increases in the water levels of lake Victoria were not sufficient enough for power generation purposes.

In terms of duration of power outages, a unit increase in meters in the hydrology levels of Lake Victoria in the long run, led to 44 percent (not significant) decrease in the duration of power outages, hence improving grid electricity reliability. In the short run, however, a unit increase in meters in the hydrology levels of Lake Victoria led to 36 percent (significant) increase in the duration of power outages. This implies

that the increases in the water levels of lake Victoria were not sufficient enough for power generation purposes.

Therefore the H1 was supported in both in terms of frequency of power outages in both the long and short runs. In terms of duration of power outages, H1 was supported only in the short run.

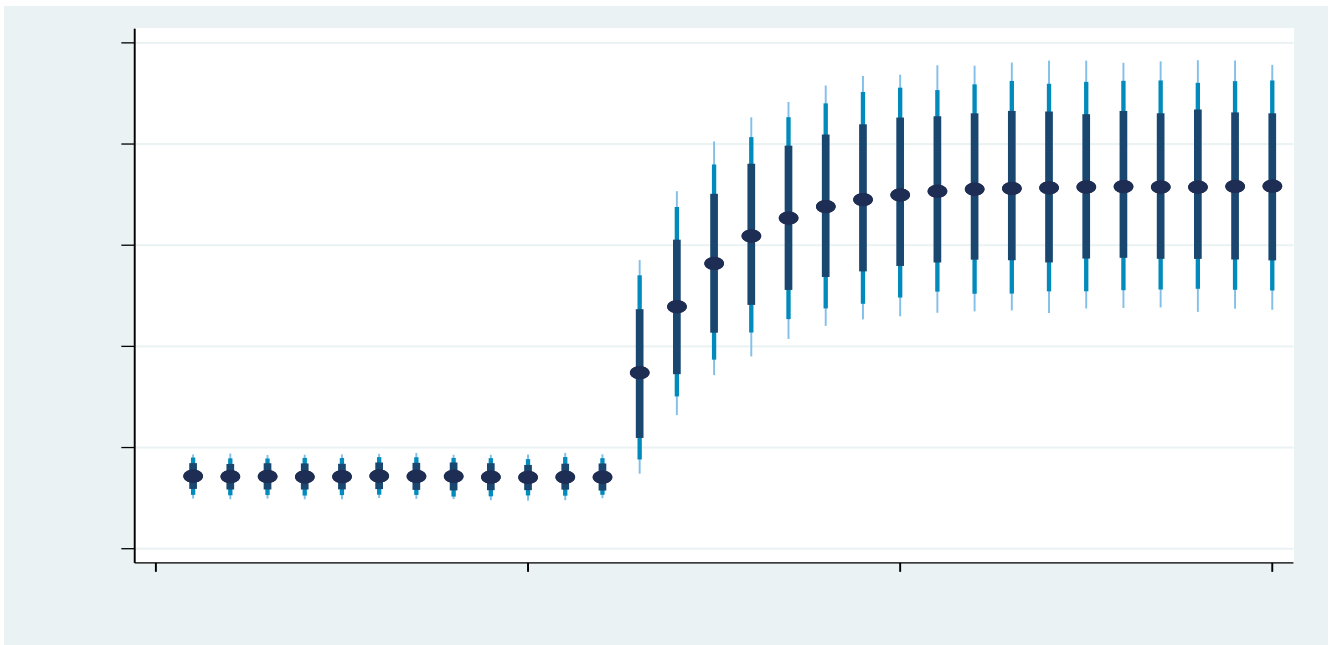
In normal practice, in Uganda, the River Nile Basin management, with the permission of the Directorate Water Resources under the Ministry of water and Environment, regulates the amount of water that each generator can draw from Lake Victoria for power generation purposes. This is referred to as the flow rate usage. In the event that the flow rate usage is $Q = 1000\text{cc/ per second}$, this implies that a generator can only supply 4173.6 MWh an equivalent of 17 MWh. This could sometimes be below the capacity of the generator. This poses a big challenge in the face of growing demand for energy amidst climate change shocks especially in the future. Bujagali, Owen falls and Kiira dams all experienced low hydrology levels between 2012 and 2022.

In terms of frequency of power outages, a unit increase in the percentage of rainfall in the generation subsystem led to 19.5 percent (significant) increase in the frequency of generation grid power interruptions hence reducing grid electricity reliability in the long run. In the short run, rainfall significantly reduced power interruptions by 9 percent. This implies that rainfall did not disrupt the power generation activities at the hydro power plants in the short run.

In terms of duration of power outages, the study found out that a unit increase in the percentage of rainfall in the generation subsystem led to 11.3 percent (not significant) increase in the duration of generation grid power interruptions, hence reducing grid electricity reliability in the long run. In the short run, a unit increase in the percentage of rainfall in the generation subsystem led to 1.9 percent (not significant) decrease in the duration of generation grid power interruptions, hence improving grid electricity reliability. The coefficients of rainfall in both the long and short runs imply that rainfall, did not significantly affect the duration of power interruptions in the generation of hydropower. Therefore the H2 was supported in terms of frequency of power outages both the long and short runs. In terms of duration of power outages H2 was not supported.

b) *Dynamic ARDL Simulations for the Frequency of Power Outages Due to Changes in Environmental Variables.*

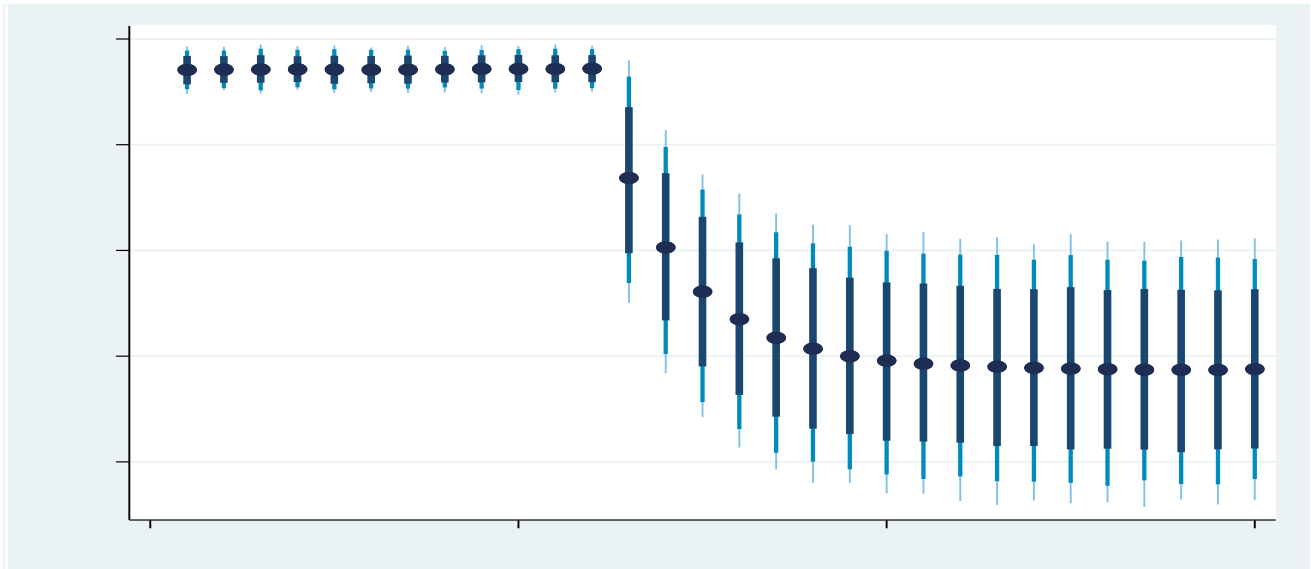
This study also carried out dynamic ARDL simulations to capture future shocks in the frequency of power outage due to changes in both hydrology levels of lake Victoria of in the generation subsystem. The dynamic ARDL simulations revealed that a 10 percent shock in predicted decrease in hydrology levels of lake Victoria may increase the frequency of power outages in the short only at 75 percent, 90 percent and 95 percent confidence levels as shown in figure 1.



Source: STATA Software 17 outputs

Figure 1: Dynamic ARDL Simulations for Frequency of Power Outages in the Generation Subsystem Due to -10% Shock in Hydrology Levels

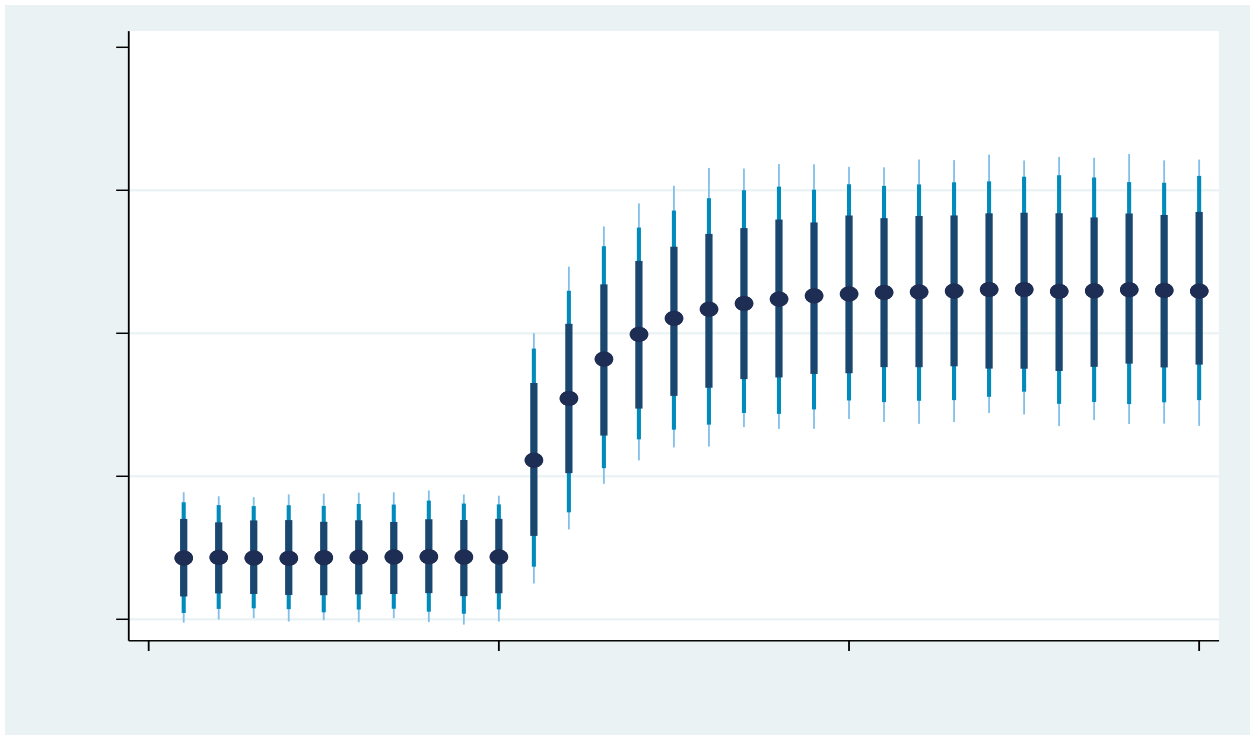
On the other hand, the dynamic ARDL simulations revealed that a 10 percent shock in predicted increase in hydrology levels of lake Victoria may reduce in the frequency of power outages in only the short run only at 75 percent, 90 percent and 95 percent confidence levels as shown in figure 2.



Source: STATA Software 17 outputs

Figure 2: Dynamic ARDL Simulations for Frequency of Power Outages in the Generation Subsystem Due to 10% Shock in Hydrology Levels

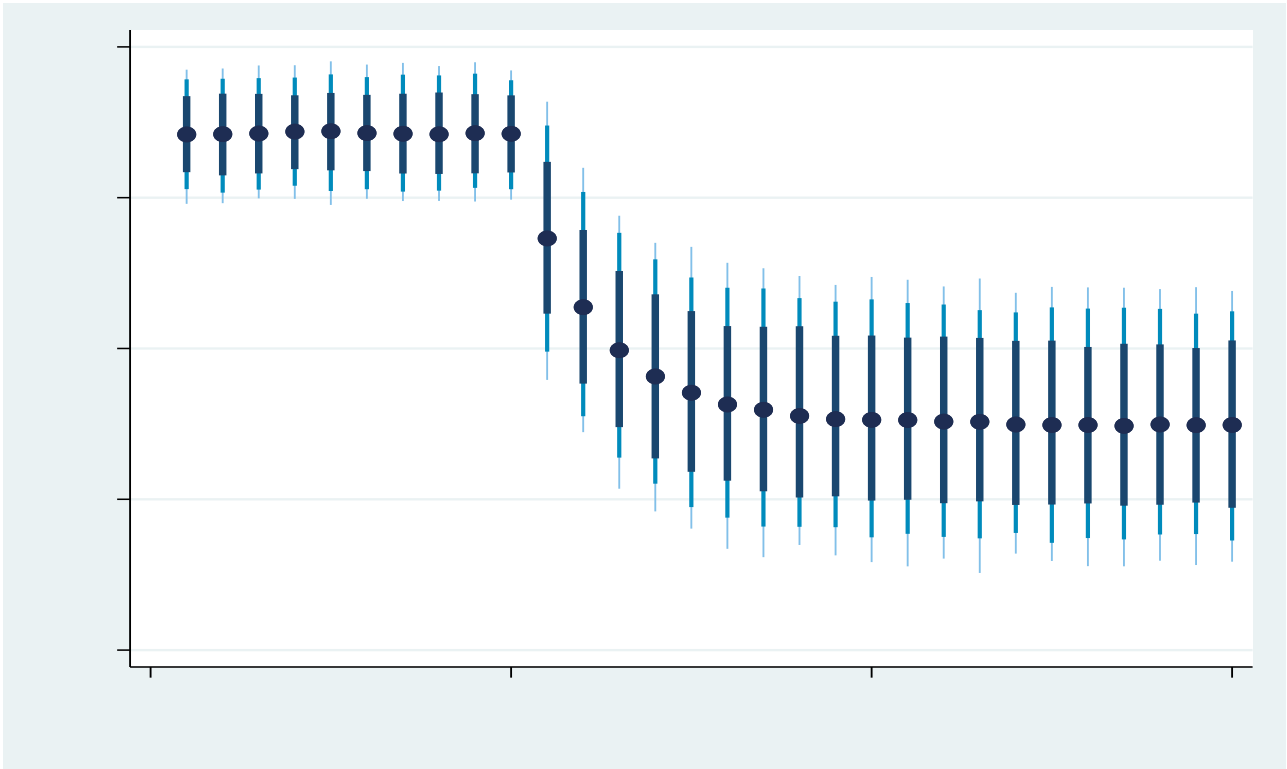
The dynamic ARDL simulations revealed that a 10 percent shock in predicted increase in rainfall may increase the frequency of power outages in the short only at 75 percent, 90 percent and 95 percent confidence levels as shown in figure3.



Source: STATA Software 17 outputs

Figure 3: Dynamic ARDL Simulations for Frequency of Power Outages in the Generation Subsystem Due to 10 Percent Shock in Rainfall

The dynamic ARDL simulations revealed that a 10 percent shock in predicted decrease in rainfall may reduce the frequency of power outages in the short only at 75 percent, 90 percent and 95 percent confidence levels as shown in figure 4.

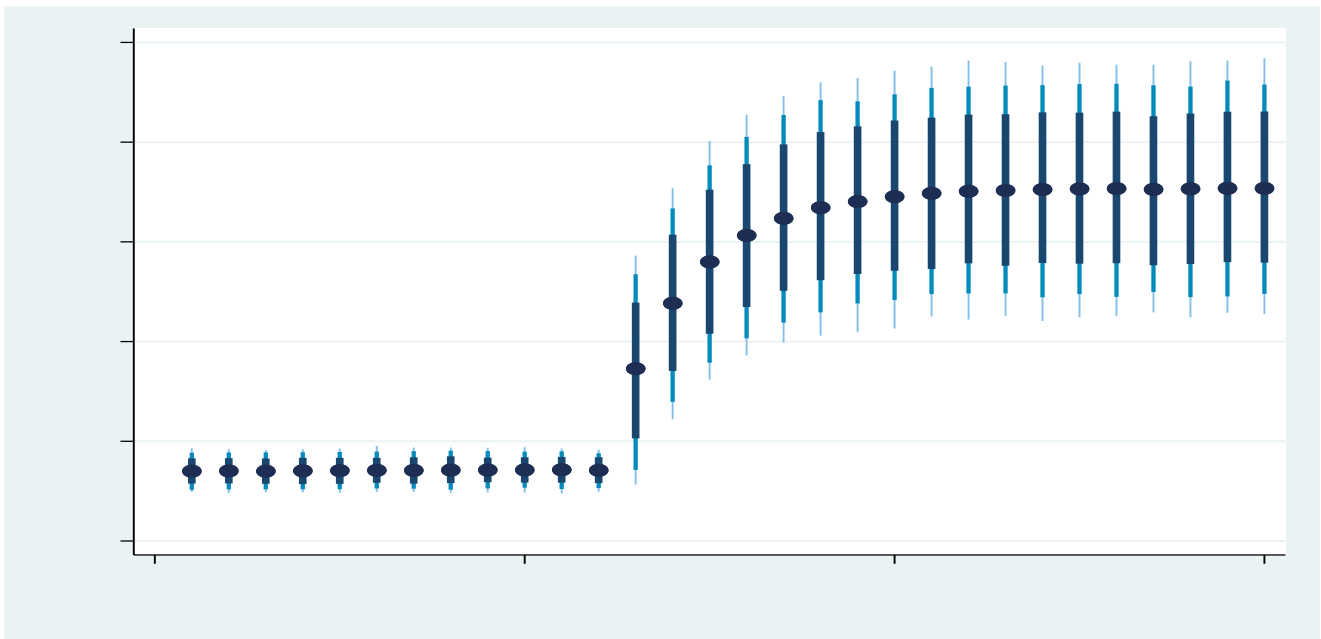


Source: STATA Software 17 outputs

Figure 4: Dynamic ARDL Simulations for Frequency of Power Outages in the Generation Subsystem Due to 10 Percent Shock in Rainfall

c) *Dynamic ARDL Simulations for the Frequency of Power Outages Due to Changes in Environmental Variables*

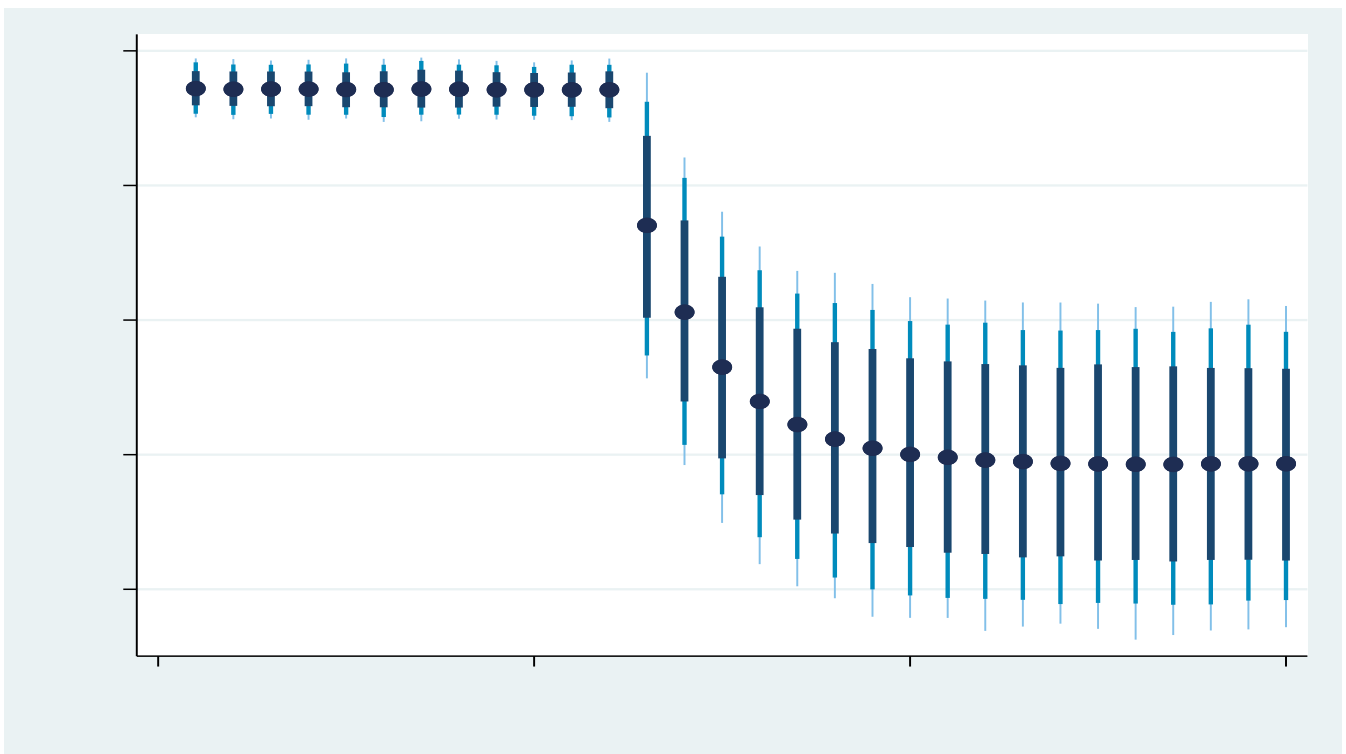
This study also carried out dynamic ARDL simulations to capture future shocks in the duration of power outage due to future changes in both hydrology levels of lake Victoria and rainfall in the generation subsystem. The dynamic ARDL simulations revealed that a 10 percent shock in predicted decrease in hydrology levels will reduce the duration of power outages in the short only at 75 percent, 90 percent and 95 percent confidence levels in figure 5.



Source: STATA Software 17 outputs

Figure 5: Dynamic ARDL Simulations for Duration of Power Outages in the Generation Subsystem Due to -10% Shock in Hydrology Levels

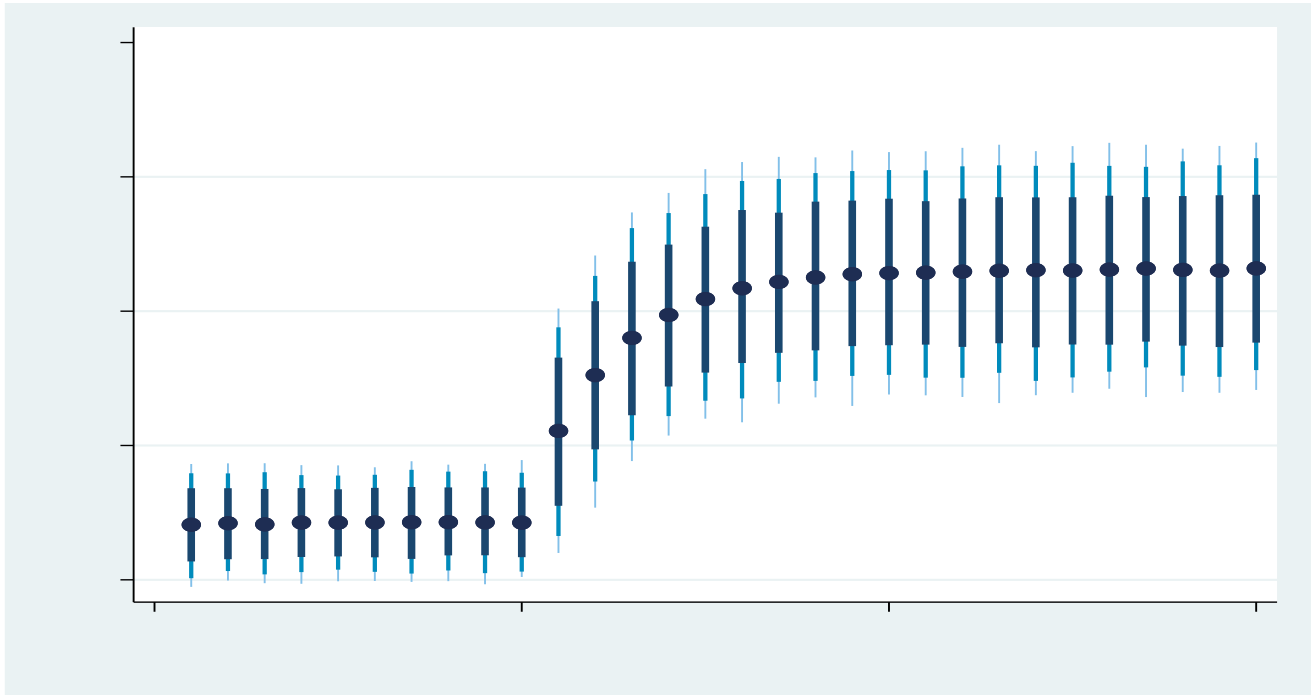
Similarly, the dynamic ARDL simulations revealed that a 10 percent shock in predicted increase in hydrology levels of lake Victoria may decrease the duration of power outages in the short run only 75 percent, 90 percent and 95 percent confidence levels as shown in figure 6.



Source: STATA Software 17 outputs

Figure 6: Dynamic ARDL Simulations for Duration of Power Outages in the Generation Subsystem Due to 10% Shock in Hydrology Levels

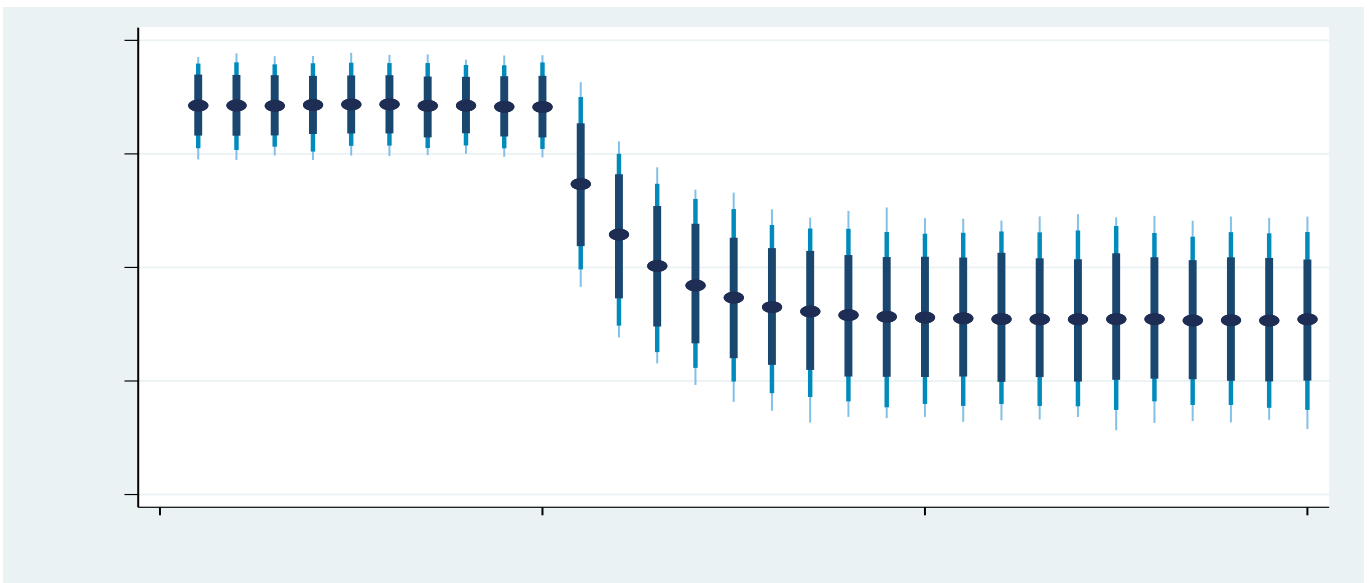
The dynamic ARDL simulations further revealed that a 10 percent shock in predicted increase in rainfall may increase the duration of power outages in the short run only 75 percent, 90 percent and 95 percent confidence levels as shown in figure 7.



Source: STATA Software 17 outputs

Figure 7: Dynamic ARDL simulations for duration of power outages in the generation subsystem due to 10 percent shock in rainfall

On the other hand, the dynamic ARDL simulations further revealed that a 10 percent shock in predicted decrease in rainfall may reduce the duration of power outages in the short run only 75 percent, 90 percent and 95 percent confidence levels as shown in figure 8.



Source: STATA Software 17 outputs

Figure 8: Dynamic ARDL Simulations for Duration of Power Outages in the Generation Subsystem Due to 10% Shock in Rainfall

d) 4.2 Validity of the Estimated Models

The study first carried out pre estimation tests on the data before deciding on which time series model to use for estimation. The time series line plots of the study variables to observe the long term movement in the data were carried out by the study. Unit root and co integration tests of all the variables in the model were also carried out. The study also carried out some post estimation tests including Breusch- Godfrey serial correlation test, Ramsey reset model specification test, Cameron and Trivedi's decomposition of IM test for heteroskedasticity test and the multicollinearity test, to ensure the validity of the estimated models. The results of the tests presented in the appendix show that the models were robust.

VI. DISCUSSION OF RESULTS

The outcomes from the model estimation reveal that in the long run, both rainfall and hydrology levels of Lake Victoria, have statistically significant effect on both the frequency and duration of power outages. Hydrology levels of Lake Victoria had a positive and statistically significant effect on the frequency of power outages in the generation subsystem in the long run. This implies that high hydrology levels of Lake Victoria will improve grid electricity in the generation subsystem in the long run through reduced frequency of power outages. However, hydrology levels of lake Victoria in the short run, had a negative effect on the frequency of grid electricity reliability in the generation subsystem. This implies that, despite the increase of hydrology levels of lake Victoria, power outages will still take place in the short run. This could be because this increase in hydrology levels will not be sufficient for the power generation purposes as earlier pointed out.

In terms of duration of power interruptions, hydrology levels of lake Victoria significantly affected the duration of power outages in only the short run. This implies that the hydrology levels of Lake Victoria have not been sufficient enough for power generation activities in the recent time periods and therefore this led to long hours of power outages. This study notes that this challenge did not spill over to the later time periods because the duration of this duration of the power outages was insignificant in the long run. The study notes that the effect of hydrology levels of Lake Victoria on the generation grid reliability in terms of both frequency and duration of power outages have not been discussed before in empirical literature.

This finding is in line with the theory of system reliability which states that environmental factors influence the reliability of a system in one or the other, by leading to either system failures or system faults (Shewhart & Wilks, 2021). Other studies also agree with the findings of this study, which point out that Uganda's power sector is sensitive to water fluctuations from

climatic change effects and this has caused unreliable power supply on the grid network (ERA, 2019; Wabukala et al., 2021) although these studies do not explain this fluctuation in terms of both frequency and duration of power outages.

Rainfall had a statistically significant (at 1 percent level of significance) positive effect on the frequency of power interruptions in the long run. This implies that rainfall will interrupt negatively the future power generating activities for the hydropower plants because by increasing the frequency of power outages. In the short run, rainfall has a negative effect on the frequency of power interruptions (at 10 percent level of significance). This implies that rainfall will not significantly interrupt power generating activities for the hydropower plants, despite an increase in the rainfall intensity.

In terms of duration of power interruptions, rainfall did not significantly affect the duration of power outages in both short and long run. This implies that rainfall leads to power outages on the generation grid but not for a long duration. The power generation activities quickly resume after rainfall events.

This result is consistent with the works of (Ward, 2013) who points out that the effects of weather on power grid systems and revealed that rainfall has an effect on grid systems, hence influencing grid electricity reliability. Additionally, (Ward, 2013) adds that heavy rain is normally associated with strong winds or lightning and concludes that faults brought about by normal weather usually have no significant effect on the supply of electricity to the customers. However (Ward, 2013) studied the distribution subsystem while this study looked at the generation subsystem. In addition, Davidson *et al.*, (2003) also found out that rainfall led to power grid outages while Kabir *et al.*, (2019) in their study also document rainfall as one of the influences of grid electricity reliability. However, these studies were also done in the distribution subsystem.

This results of this study are supported by the systems reliability theory which states that environmental factors can influence the reliability of a system hence resulting in either system interruptions (Shewhart & Wilks, 2021). In the past, rainfall has also been associated with floods (Ward, 2013) and floating vegetation (UEGCL, 2020) which are common features of Lake Victoria usually and have in the past disrupted electricity generation activities hence leading to power outages.

a) Conclusion and Policy Recommendation

This study investigated the environmental factors that influence grid reliability in the generation subsystem. The study focused on the large hydropower plants that are connected to the national grid network that is Kiira, Owenfall, Bujagali and Isimba hydropower plants. The study estimated an ARDL to model

secondary time series data from 2012 to 2022 and found out that;

1. Rainfall increased frequency of power interruptions in the generation subsystem in both the short and long runs.
2. Rainfall did not increase duration of power interruptions in the generation subsystem in both the short and long runs.
3. Hydrology levels of Lake Victoria reduced frequency of power interruptions in the generation subsystem in the long run, but increased frequency of power interruptions in the generation subsystem in the short.
4. Hydrology levels of Lake Victoria significantly increased the duration of power interruptions in the generation subsystem in only the short run.

Our findings contribute to literature in the following ways. a). Analysing the effect of hydrology levels of Lake Victoria and rainfall on the generation grid electricity reliability in the Ugandan context b). The use of the systems reliability theory to analyse the effect of environmental factors on grid electricity reliability c). Using the ARDL model to estimate the short and long run effect of hydrology levels of Lake Victoria rainfall on both the frequency and duration of power outages .

Our findings imply that government should devise policies that increase grid electricity reliability in Uganda at the generation subsystem. We therefore suggest in order to reduce power interruptions in the generation subsystem, the government should invest in also strengthen policy in line with climate related action. This will help reduce the effect of environmental factors on grid electricity reliability. Hydropower generating firms are stakeholders of water resources and should participate in protecting them the environment if we are to have sustainable water resources for future use. Government needs to sensitize both the water users as well as the water source stakeholders of the need to appreciate the risks of poorly managed or neglected water sources that result in the compromised quality and quantity of water supply. This will increase the necessity to protect and preserve water sources in order to solve the ever-increasing challenges of sustaining acceptable supply of clean water required for among others the generation of grid power.

Government should also mobilise the various hydropower generating firms to contribute in all spheres towards the management of water sources. This will create a sense of ownership and of the water resource by its users and this could increase the protection of the water resources. We suggest stringent punishments for organisations and individuals who misuse the water resources. This will go an extra mile in the protection of water resources thus ensuring quality and quantity for hydropower production and also other uses.

In addition, we also suggest investing in robust power generating infrastructure as an alternative way of adapting to the changing environmental conditions as well as considering having alternative energy sources such as solar and wind onto the grid to diversify the energy mix and reduce dependence on hydropower.

b) *Areas for Further Research*

This study focused rainfall and hydrology levels of Lake Victoria as factors that influence generation grid electricity reliability. However, there could be more environmental factors that influence grid electricity reliability. Future research in Uganda should investigate further the effect of floods and floating vegetation that influence grid electricity reliability. In addition further research needs to investigate the effect of the environmental factors on each of the hydro power plants for better future policy direction

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Appendix

For the Frequency of power outages
Validity of the estimated model

The study carried out some post estimation tests to ensure the validity of the model.

a) Serial Correlation Test

The study tested for serial correlation at 5 lags as shown in table A1 and concluded that the errors were not serially correlated.

Table A1: Breusch-Godfrey Test for Serial Correlation

Lags(p)	Chi2	Degrees of Freedom	Prob> chi2
5	14.374	5	0.0134

The results show that the p value (0.0134) is greater than 0.01 implying that we fail to reject the null hypothesis and conclude that there is no serial correlation at 1 percent level of significance.

b) Model Specification Test

The results in table A2 show that the p value (0.0752) is greater than 0.05 implying that we fail to reject the null hypothesis and conclude that the model is correctly specified.

Table A2: Ramsey Reset Test for Model Specification

Test statistic	Degrees of Freedom	P-Value	Result
2.58	3	0.0752	

c) Heteroskedasticity Test

The results in table A3 show that the p value (0.4365) is greater than 0.05 implying that we fail to

reject the null hypothesis and conclude that homoscedasticity is present.

Table A3. Cameron and Trivedi's Decomposition of IM test

Source	Chi	Degrees of Freedom	P-value
Heteroskedasticity	55.00	54	0.4365
Skewness	32.99	25	0.1313
Kurtosis	0.00	1	0.9766
Total	87.99		0.2533

d) Multicollinearity Test

The results in table A4 show that the mean VIF value (3.26) is less than 5 implying that the variables do not have multicollinearity. The study concludes that there is a moderate level of correlation among the independent variables of the study.

Table A4: VIF test for multicollinearity

Variable	VIF	1/VIF
In maintenance and repair cost L1.	8.59	0.11
In frequency of power outages L1.	8.28	0.12
In maintenance and repair cost L2.	6.94	0.14
In Technical faults L1.	5.39	0.18
In maintenance and repair cost L3.	4.36	0.22
In system shutdowns L1.	3.72	0.26
In Technical faults L2.	3.09	0.32
In Rainfall L1.	2.52	0.39
In system shutdowns L3.	2.29	0.43
In Technical faults	2.25	0.44
Hydrology levels L3.	2.21	0.45
In system shutdowns L2.	2.17	0.46
In Rainfall	2.08	0.48
System overload	2.07	0.48
Hydrology levels	1.99	0.50
In Failed equipment	1.95	0.51
Hydrology levels L1.	1.94	0.51
In System overload L1.	1.90	0.52
Hydrology levels L2.	1.78	0.56
In Failed equipment L2.	1.75	0.57

In system shutdowns L4.	1.65	0.60
In Failed equipment L1.	1.64	0.60
System overload L2.	1.48	0.67
Mean VIF	3.26	

For the Duration of Power Outages Validity of the Estimated Model

The study carried out some post estimation tests to ensure the validity of the model.

a) *Serial correlation test*

The study tested for serial correlation at 4 lags as shown in table A5 and concluded that the errors were not serially correlated.

Table A6: Breusch- Godfrey Test for Serial Correlation

Lags(p)	Chi2	Df	prob> chi2
4	7.810	4	0.0988

The results show that the p value (0.0988) is greater than 0.05 implying that we fail to reject the null hypothesis and conclude that there is no serial correlation at five percent level of significance.

b) *Model Specification Test*

The results in table A6 show that the p value (0.0054) is less than 0.05 implying that we reject the null hypothesis and conclude that model could be having some missing variables.

Table A6: Ramsey Reset Test for Model Specification

Test statistic	Degrees of Freedom	P -Value	Result
5.33	3	0.0054	

c) *Heteroscedasticity Test*

The results in table A7 show that the p value (0.4365) is greater than 0.05 implying that we fail to reject the null hypothesis and conclude that homoscedasticity is present.

Table A7: Cameron and Trivedi's Decomposition of IM Test

Source	Chi	Degrees of Freedom	P-value
Heteroscedasticity	55.00	54	0.4365
Skewness	25.06	25	0.4592
Kurtosis	0.30	1	0.5859
Total	80.35	80	0.4678

d) *Multicollinearity Test*

The results in table A8 show that the mean VIF value (2.98) is less than 5 implying that the variables do not have multicollinearity. The study concludes that

Time Series Plots for the Independent Variables

there is a moderate level of correlation among the independent variables of the study.

Table A8: VIF Test for Multicollinearity

Variable	VIF	1/VIF
In maintenance and repair cost L1.	8.75	0.11
L2.	6.82	0.14
L3.	6.11	0.16
In Technical faults L1.	4.25	0.23
In maintenance and repair cost L3.	4.13	0.24
In Duration of outages L1.	3.65	0.27
In system shutdowns	3.10	0.32
In Technical faults L2.	3.08	0.32
In system shutdowns L1.	2.44	0.40
D. Hydrology levels L3.	2.40	0.41
In In Rainfall L1.	2.39	0.41
In system shutdowns L3.	2.34	0.41
In Technical faults	2.22	0.44
In system shutdowns L2.	2.19	0.45
System overload	2.14	0.46
D. Hydrology levels L1.	2.07	0.48
In Rainfall	2.05	0.48
In Failed equipment L2.	1.92	0.48
D. Hydrology levels	1.87	0.52
System overload L1.	1.85	0.56
In system shutdowns L4.	1.75	0.57
In Failed equipment L1.	1.75	0.60
D. Hydrology levels L2.	1.48	0.60
System overload L2.	1.40	0.67
Mean VIF	2.98	



Source: STATA Software 17 outputs

Figure 9: Time Series Line Plots Independent Variables (Generation Subsystem)

Table 5: Results for the Unit Root Test for the Study Variables

Variable	Test statistic	1% critical value	5% critical value	10% Critical value	P-value
Frequency of outages	-4.643	-3.502	-2.888	-2.578	0.0001
Dickey fuller	-4.635	-3.501	-2.888	-2.578	0.0001
Phillips Perrone					
Duration of outages	-4.280	-3.502	-2.888	-2.578	0.0005
Dickey fuller	-5.253	-3.501	-2.888	-2.578	0.0000
Phillips Perrone					
System shutdowns	-4.231	-3.502	-2.888	-2.578	0.0006
Dickey fuller	-6.393	-3.501	-2.888	-2.578	0.0000
Phillips Perrone					
Maintenance and repair costs	-4.759	-3.502	-2.888	-2.578	0.0001
Dickey fuller	-3.952	-3.501	-2.888	-2.578	0.4592
Phillips Perrone					
Rainfall	-9.819	-3.502	-2.888	-2.578	0.0000
Dickey fuller	-6.687	-3.501	-2.888	-2.578	0.0000
Phillips Perrone					
Hydrology levels	-2.406	-4.032	-3.447	-3.147	0.3765
Dickey fuller	-2.955	-3.501	-2.888	-2.578	0.000
Phillips Perrone					
Technical faults	-5.301	-3.502	-2.888	-2.578	0.000
Dickey fuller	-5.732	-3.502	-2.888	-2.578	0.0000
Phillips Perrone					
Failed equipment	-4.823	-3.502	-2.888	-2.578	0.0000
Dickey fuller	-9.011	-3.501	-2.888	-2.578	0.0000
Phillips Perrone					
System overload	-5.610	-3.502	-2.888	-2.578	0.0000
Dickey fuller	-9.520	-3.501	-2.888	-2.578	0.0000
Phillips Perrone					

Source: STATA Software 17 outputs

Co-integration test results (Frequency of outages)

Table 2: Pesaran, Shin, and Smith (2001) Bounds Test for Cointegration

Statistics		10%		5%		1%		P-value	
		I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
F	5.183	2.03	3.13	2.32	3.50	2.96	4.26	0.0000	0.0000
t	-4.878	-2.57	-4.23	-2.86	-4.57	-3.45	-5.19	0.0000	0.0000

Co-integration test results (Duration of outages)

Table 3: Pesaran, Shin, and Smith (2001) Bounds Test for Cointegration

Statistics		10%		5%		1%		P-value	
		I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
F	2.899	2.03	3.13	2.32	3.50	2.96	4.26	0.0000	0.0000
t	-3.394	-2.57	-4.23	-2.86	-4.57	-3.45	-5.19	0.0000	0.0000

