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Effects of technical and security factors on grid electricity reliability: evidence from Uganda national electricity grid network

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Abstract

Purpose – An unreliable supply of grid electricity has a strong negative impact on industrial and commercial profitability as well as on household activities and government services that rely on electricity supply. This unreliable grid electricity could be a result of technical and security factors affecting the grid network. Therefore, this study aims to investigate the effects of technical and security factors on the transmission and distribution of grid electricity in Uganda.

Design/methodology/approach – This study used the ordinary least squares (OLS) and autoregressive distributed lag (ARDL) models to examine the effects of technical and security factors on grid electricity reliability in Uganda. The study draws upon secondary time series monthly data sourced from the Uganda Electricity Transmission Company Limited (UETCL) government utility, which transmits electricity to both distributors and grid users. Additionally, data from Umeme Limited, the largest power distribution utility in Uganda, were incorporated into the analysis.

Findings – The findings revealed that technical faults, failed grid equipment, system overload and theft and vandalism affected grid electricity reliability in the transmission and distribution subsystems of the Ugandan power grid network. The effect was computed both in terms of frequency and duration of power outages. For instance, the number of power outages was 116 and 2,307 for transmission and distribution subsystems, respectively. In terms of duration, the power outages reported on average were 1,248 h and 5,826 h, respectively, for transmission and distribution subsystems.

Originality/value – This paper investigates the effects of technical and security factors on the transmission and distribution grid electricity reliability, specifically focusing on frequency and duration of power outages, in the Ugandan context. It combines both OLS and ARDL models for analysis and adopts the systems reliability theory in the area of grid electricity reliability research.

Keywords Power interruptions, Technical factors, Security factors, Grid electricity reliability

Paper type Research paper

1. Background

Access to reliable electricity services is crucial for poverty reduction and also promotes economic growth (World Bank, 2017; EnergyAfrica, 2018; Blimpo and Cosgrove-Davies,

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2019; IEA, 2019). However, globally, over 1 billion people lack access to a reliable electricity supply, of which approximately 62% reside in sub-Saharan Africa (EnergyAfrica, 2018; IEA, 2019). As a result, an unreliable electricity supply forces companies (industrial and commercial) to spend extra money to provide alternative sources of power, thus leading to reduced revenues (Cole *et al.*, 2018). Furthermore, new companies that depend solely on electricity to function are hindered from venturing into new markets especially in areas with unreliable electricity supply (Blimpo and Cosgrove-davies, 2019).

For households, unreliable electricity supply limits the use of electricity for both productive and non-productive uses (IEA, 2019), leading to an over-dependence on forest-based energy resources to meet their energy needs. At the community level, unreliable electricity constrains the provision and delivery of efficient healthcare services (WHO, 2023; Fashina *et al.*, 2018). In addition, from the perspective of electricity supply utility, an unreliable grid electricity supply could escalate illegal connections to the power grid, resulting in revenue losses for energy firms (Blimpo and Cosgrove-davies, 2019; IEA, 2019).

According to the World Bank (2017), a reliable electricity supply implies a lack of power outages, where power outages refer to the total (or partial) loss of electric power over a given period of time (Blimpo and Cosgrove-davies, 2019). These power outages have had a huge impact on the socioeconomic activities of countries and communities. For example, over 30 countries in Africa have lost between 1% and 5% of their GDP annually as a result of power outages (World Bank, 2017). Uganda is one of the countries that suffer from electricity shortages World bank (2017) and as a result, sectors such as residential, manufacturing, agriculture, transport as well as service sectors that depend to a large extent on grid electricity in particular to function continue to suffer (Fashina *et al.*, 2018).

Although several studies on electricity reliability have been conducted (Alhelou *et al.*, 2019; Veldhuis *et al.*, 2018; Vinogradov *et al.*, 2020), very few have investigated the effects of both technical and security factors on grid electricity reliability, especially in Uganda. For example, Mbabazi *et al.* (2013) in their study on Uganda's energy sector's points out vandalism of grid equipment and old transformers as a cause of unreliable power supply as a major challenge for the energy sector. However, this study used primary data and it does not show the extent to which these challenges affect both grid electricity reliability in terms of both frequency and duration of power outages. In addition, Patrick Kabanda (2018) and Johnpaul *et al.* (2014) in their studies point to vandalism as challenge for the grid at distribution and transmission subsystems, respectively. However, these studies only propose systems that can be used to reduce vandalism of distribution transformers and of transmission line equipment, respectively. They do not look at the technical related factors which too affect power grid reliability. Elsewhere, Ivanova *et al.* (2020) studied technical factors that influence grid electricity reliability in the transmission and distribution subsystems but used descriptive analysis and qualitative discussion methodology approach. Overholt (2001) looked at the technical factors that affect grid reliability but had a qualitative approach to the study. This study uses both the ordinary least squares (OLS) and autoregressive distributed lag (ARDL) models estimate the effect of technical and security factors on grid electricity reliability at transmission and distribution subsystems, in terms of both frequency and duration of power outages.

1.1 Purpose and contribution of the study

This study aimed to estimate the effects of technical and security factors on the reliability of both the transmission and distribution grid electricity in Uganda. The study makes a number of contributions; First, by employing a combination of the OLS and ARDL regression models, this study addresses a notable gap in the existing body of literature concerning grid electricity reliability within the transmission and distribution power networks. Furthermore, this study sheds light on the impact of technical and security considerations on grid electricity reliability, specifically focusing on both the frequency and the duration of power outages, with particular emphasis on the Ugandan context. Additionally, this study adopts a novel approach by incorporating systems reliability theory, a framework previously unexplored in the realm of grid electricity reliability research. This theoretical foundation enhances the understanding of the complex dynamics at play in ensuring the dependability of power supply within these grids.

2. Literature review and hypothesis testing

2.1 Theoretical review

This study is informed by the Systems Reliability Theory (Shewhart and Wilks, 2021). This theory defines reliability as the ability of an item or system to perform as expected of it for a stated period of Economic Consulting Associates Limited (2018) time (Shewhart and Wilks, 2021). This theory is attributed to the works of Robert Lusser 1899–1969, a German engineer and aircraft designer. This theory assumes that all systems are used in an environment that may influence the system. Sometimes, this environment can lead to system failure or system faults. A cause of system failure is defined as a set of circumstances that lead to failure, and this can be an event or condition of the item. On the other hand, system faults are caused by factors such as equipment failure and malicious damage. This theory defines technical factors as events that are expected to occur during the lifespan of the system, such as specific component failures and component faults that may result in the failure of the system, including the aging of system components (Shewhart and Wilks, 2021). Security factors are defined as deliberate hostile actions, physical attacks (e.g. arson, sabotage and theft), or cyberattacks on the system. Security of the system, as well as its technical attributes, is critical in ensuring its reliability (Shewhart and Wilks, 2021). The theory also states that overloads of software systems may be classified as secondary causes of system failures.

2.2 Empirical literature and hypothesis testing

The physical environment in which the power grid operates makes it susceptible to grid failures and faults, leading to power outages (Haes Alhelou *et al.*, 2018). Among other technical factors, antecedents, such as the tripping of transmission lines and generators have been identified as some of the technical faults that influences grid reliability (Alhelou *et al.*, 2019; Ekisheva *et al.*, 2020; Ivanova *et al.*, 2020; Lu *et al.*, 2008; Veldhuis *et al.*, 2018; Vinogradov *et al.*, 2020). Power grids, especially smart grids, are usually managed by computer software such as Supervisory Control and Data Acquisition (SCADA) systems and the failure of such computer software can also lead to power outages (Abdelghany and Tahar, 2021; Hatziargyriou *et al.*, 2005). Other technical faults that compromise grid reliability are unstable voltage levels (Bapin *et al.*, 2020; Okoye and Omolola, 2019; Papic *et al.*, 2018; Shaikh *et al.*, 2017) and reactive power levels (Hatziargyriou *et al.*, 2005; Veloza and Santamaria, 2016). The transmission and distribution grid are made of devices that are meant to protect it by addressing unacceptable problems and taking necessary corrective action; however, sometimes these devices fail and hence lead to grid unreliability. Some studies have documented these failures as influencing grid reliability, including (Okoye and Omolola, 2019; Pepyne, 2007; Vaiman *et al.*, 2012). Other scholars that have documented technical faults as influencers of grid reliability (Bapin *et al.*, 2020; Honang, 2015; Vaiman *et al.*, 2012; Zhu *et al.*, 2012). We therefore hypothesize that;

H1. Technical faults have a significant effect on the transmission and distribution grid electricity reliability in Uganda, in both the short and long run.

All electric power grid infrastructures depreciate over time and therefore, face challenges as they age which include failure. The aging of electric grid equipment could also lead to power outages because the functions of some grid components are compromised as they age and become absolute (Chakravorti, 2006; Hatziargyriou *et al.*, 2005; Okoye and Omolola, 2019; Vaiman *et al.*, 2012). Other technical factors that have been pointed out by scholars as influencers of grid reliability include the collapse of the grid components (Pepyne, 2007), component and line failures (Abdelghany and Tahar, 2021; Scherb *et al.*, 2019) and vulnerable and broken line segments (Ivanova *et al.*, 2020; Scherb *et al.*, 2019). We state the hypothesis that;

H2. Failed grid equipment has a significant effect on the transmission and distribution grid electricity reliability in Uganda.

In addition, load demand (consumption), if not equal to load supply (production), could lead to a drop in system frequency (excess load) or an increase in frequency (excess generation), which could impact grid reliability. Some studies such as these (Overholt; Faruqui *et al.*, 2010; Shaikh *et al.*, 2017; Veldhuis *et al.*, 2018; Veloza and Santamaria, 2016) have reported overload (excess load) as causes of power outages in the transmission and distribution grids. Thus, we hypothesize that;

H3. System overload has a significant effect on the transmission and distribution grid electricity reliability in Uganda.

Furthermore, security factors that influence grid electricity reliability have been reported in the literature. For instance (Ahuna *et al.*, 2020; Kithinji Kirunguru, 2017; Olugbenga *et al.*, 2013; Kabanda, 2018) reported that the vandalism of transmission infrastructure and distribution equipment is one of the causes of power outages on the grid. Hence, we hypothesize that;

H4. Theft and vandalism of grid equipment has a significant effect on the transmission and distribution grid electricity reliability in Uganda.

3. Research methodology

This study employs an explanatory research design which focuses on explaining the aspects of the phenomenon under study. Time series and quantitative study design was adopted because of the nature of the data being analyzed.

3.1 Data and data sources

This study utilized secondary time-series monthly power outage data (2012–2022) obtained from the electricity companies that transports and power on the national grid network. Time series data were used because they provide insights into how a variable changes over time, identify patterns and can be used to predict the future of grid electricity reliability. Power outage data (frequency and duration of power interruptions) were collected using the SCADA software system, which transmits it to a central computer for processing. We used this information to model the effect of technical factors on both the transmission and distribution grid electricity reliability. This study comprised of data from the Electricity Regulatory Authority, Ministry of Water and Environment, Uganda Electricity Transmission Company and Umeme Limited which contained the dependent and independent variables, such as the cost of repairs and replacements, the number of times the grid system experienced overload, the number of technical faults and failed equipment that occurred on the transmission and distribution grids.

3.2 Measurement and description of the study variables

Table 1 shows how the variables under study were measured, described and operationalized.

Variable label	Variable description	Variable proxy
Dependent variables		
Frequency of power outages	How often electricity disruptions occur and can be used as an indicator of the reliability of the grid	The number of outages recorded by UETCL and Umeme Limited per month
Duration of power outages	This is a measure of the length of time that a power outage lasts from the moment it begins until power is restored	The number of hours of power outages recorded by UETCL and Umeme Limited per month
Independent variables		
System overload	This occurs when the demand for electricity exceeds the supply capacity of the grid	Number of system overload events recorded by UETCL and Umeme Limited per month
Failed equipment	This refers to any malfunction, failed or damaged equipment within the grid infrastructure	Number of failed equipment recorded by UETCL and Umeme Limited 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	Number of technical faults recorded by UETCL and Umeme Limited per month
Theft and vandalism of electricity grid equipment	These actions refer to intentional damage, theft or tampering with the grid infrastructure	Number of times UETCL and Umeme Limited experienced theft and vandalism of grid equipment per month
Maintenance and repair costs	The amount of money power utilities spends on maintaining and repairing the power grid	Repair and maintenance costs incurred by UETCL and Umeme Limited per month
Rainfall	In this context, rainfall refers to the amount of precipitation in form of rain that is received throughout the country	Mill meters (mm) per month
Trees	Tree characteristics coming into contact with grid equipment	Number of times UETCL and Umeme Limited grid equipment came into contact with trees characteristics
System shutdowns	There are two types of system shutdowns. They include unplanned shutdowns caused by item failures, dig ins, paving way for other activities outside grid operations. Planned shutdowns are caused by grid planned operations	Number of times UETCL and Umeme Limited experienced system shutdowns per month

Source(s): Shewhart and Wilks (2021), Brown (2002), Ministry of water and environment (MWE); Electricity regulatory authority (ERA)

Table 1. Description of variables

3.3 Model estimation

According to the systems reliability theory (Shewhart and Wilks, 2021) grid electricity reliability is influenced by technical factors such as system overloads, failed equipment, technical faults as well as theft and vandalism of grid equipment. This paper adopts an ARDL and OLS models to estimate the effect of technical and security factors on grid electricity reliability in Uganda. This approach was also used by (Han *et al.*, 2009) to investigate and predict the spatial distribution of power outages that occurred due to hurricanes. Referring to (Tsimtsios and Safigianni, 2016) some of the basic parameters that define the reliability of the power grid are the number of failures and the length of time of the power outage. Basing on such a background, the study therefore formulated the time series function(s) as shown below.

$$FOU_t = \text{f}\,(SH_t, MR_t, RF_t, BE_t, TF_t, T_t, O_t, TVD_t) \quad (1)$$

$$DOU_t = \text{f}\,(SH_t, MR_t, RF_t, BE_t, TF_t, T_t, O_t, TVD_t) \quad (2)$$

The dependent variables are frequency of power interruptions FOU_t and duration of power interruptions DOU_t and the explanatory variables in the model include technical faults (TF_t), system overload (O_t), failed equipment (BE_t) and theft and vandalism of grid equipment (TVD_t). We controlled for system shutdowns (SH_t), maintenance and repair costs (MR_t), rainfall (RF_t) and trees (T_t), which have been documented to influence the grid electricity reliability. The following testing procedures were used:

The study first carried out pre-estimation tests on the data before deciding which time series model to use for estimation. To observe long-term movement in the data, this study used time series line plots. Time series line plots are graphical representations of time series data that help to visualize how a variable changes over time and allows the identification of trends, patterns and seasonal fluctuations. The time series line plots of the study variables are documented in Appendix section. It is important to perform tests for stationarity for all variables in the model before estimating the model. The intention is to avoid the problem of spurious results that originate from the estimation of non-stationary time series. Therefore, the study conducted unit root tests for stationarity using the Augmented Dickey–Fuller (ADF) (1979 and 1981) and Phillips and Perron (1988) tests to determine the order of integration of the variables in the model. This was done in levels and also in first difference for each of the variables. The ADF equation used in this study is as follows:

$$\Delta y_t = \beta_1 + \beta_2 + \rho y_{t-1} + \sum_{i=1}^{n} \beta_i \Delta y_{t-i}\, \beta_i \Delta y_{t-i} + u_t \quad (3)$$

where n is the most number of lags selected.

ADF tests the null hypothesis of $\rho = 0$. The null hypothesis implies that a unit root was detected and therefore, the series was non stationary. The alternative hypothesis is $\rho < 0$, which implies that there is no unit root and therefore, the series is stationary. Philips Perron test diminishes the assumptions of both serial correlation and heteroscedasticity and it is based on a first-order autoregressive (AR (1)) process.

$$\Delta y_t = \beta_1 + \beta_2 y_{t-1} + u_t \quad (4)$$

where: y_t is the variable of interest; β_1 is the constant; u_t is the error term which may be heteroscedastic. For both the ADF and PP tests, if the calculated statistic is greater than the critical value at a given level, then the time-series variable is stationary at that given order. The stationarity test revealed that all the variables of the study for the transmission subsystem were stationary, which led to the estimation of ordinary least squares (OLS) model, as shown in equations (5) and (6), respectively.

The study also carried out post estimation tests including Ramsey reset for model specification, Cameron and Trivedi's decomposition of IM test for heteroskedasticity and the multicollinearity test. These were done to check the robustness of the model.

$$FOU_t = \alpha + \beta_1 SH_t + \beta_2 MR_t + \beta_3 RF_t + \beta_4 TF_t + \beta_5 T_t + \beta_6 O_t + \beta_7 TVD_t + e_t \quad (5)$$

$$DOU_t = \alpha + \beta_1 SH_t + \beta_2 MR_t + \beta_3 RF_t + \beta_4 TF_t + \beta_5 T_t + \beta_6 O_t + \beta_7 TVD_t + u_t \quad (6)$$

For the distribution subsystem, the results showed that all the variables except, maintenance and repair costs, trees and technical faults were stationary in levels. Maintenance and repair costs, trees and technical faults became stationary after differencing them 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 both the variables in the distribution subsystem.

To ascertain if the independent variables in the distribution subsystems had a long run relationship with their dependent variables, the study carried out co-integration tests. The study used the ARDL bounds test for co-integration. The Autoregressive Distributed Lag (ARDL) co-integration approach was first introduced by Pesaran *et al.* (1997) and later modified by Pesaran *et al.* (2001). This co-integration technique is preferable when dealing with variables that are integrated of the same or different orders of integration that is I (0), I (1) or combination of the both. The technique provides for the lags of both the dependent and independent variables as regressors, (Pesaran, 2015). This test was preferred to Engle Granger which does not estimate more than one co-integrating vectors because it assumes that there is a unique co-integrating variable. On the other hand Johansen maximum likelihood approach cannot be used when there is a mixture of variables integrated of both order one and zero because it requires all variables to be integrated of order one. The results for the co-integration test(s) for the variables of the distribution subsystems are shown in Tables 2 and 3.

The computed F and t statistics were compared with the critical values of both F and t as provided by Pesaran *et al.* (2001) which report the critical values for the I (0) and I (1) bounds for all the variables. The results in the above tables shown that a long run relationship (co-integration) existed at 10%, 5 and 1% (significant levels) among the variables of the study for the distribution subsystem. Therefore, the study proceeded to estimate the ARDL model for estimation for the distribution subsystem.

For the distribution subsystem, the dependent variables were frequency of power outages ($\boldsymbol{FOU_t}$) and duration of power outages ($\boldsymbol{DOU_t}$) and their lagged values are expressed as $\boldsymbol{FOU_{t-1}}$ and $\boldsymbol{DOU_{t-1}}$ for frequency of power outages and duration of power outages, respectively. The explanatory variables in the model include; technical faults (TF), failed equipment (BE), technical faults (TF), system overload (O) and theft and vandalism system (TVD). Their lagged values are expressed as, TF_{t-1}, BE_{t-1}, O_{t-1} and TVD_{t-1}. This study controlled for maintenance and repair costs (MR), system shutdowns (SH), rainfall (RF_t) and trees (T_t). The lagged values of the control variables were expressed as; maintenance and repair costs (MR_{t-1}), system shutdowns (SH_{t-1}), rainfall (RF_{t-1}) and trees (T_{t-1}), which have been documented as influencers of grid electricity reliability.

Co-integration test results (frequency of outages)

Statistics		10% I(0)	10% I(1)	5% I(0)	5% I(1)	1% I(0)	1% I(1)	*p*-value I(0)	*p*-value I(1)
F	8.655	1.95	3.06	2.22	3.39	2.79	4.10	0.0000	0.0000
t	−6.547	−2.57	−4.40	−2.86	−4.72	−3.43	−5.37	0.0000	0.0000

Source(s): STATA software 17 output

Table 2. Pesaran *et al.* (2001) bounds test for co-integration

Co-integration test results (duration of outages)

Statistics		10% I(0)	10% I(1)	5% I(0)	5% I(1)	1% I(0)	1% I(1)	*p*-value I(0)	*p*-value I(1)
F	13.488	1.95	3.06	2.22	3.39	2.79	4.10	0.0000	0.0000
t	−9.563	−2.57	−4.40	−2.86	−4.72	−3.43	−5.37	0.0000	0.0000

Source(s): STATA software 17 output

Table 3. Pesaran *et al.* (2001) bounds test for co-integration

Equation (7) 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.

$$\begin{aligned} lnFOU_t = {} & \beta_0 + \beta_1 lnFOU_{t-1} + \beta_2 ln\, SH_{t-1} + \beta_3 ln\, \Delta MR_{t-1} + \beta_4 ln\, RF_{t-1} \\ & + \beta_5 \Delta T_{t-1} + + \beta_6 ln\, \Delta TF_{t-1} + \beta_7 ln\, BE_{t-1} + \beta_8 O_{t-1} + \beta_9 ln\, TVD_{t-1} \\ & + \sum\nolimits_{i=1}^{a} \beta_{10,i} lnFOU_{t-1} + \sum\nolimits_{i=1}^{b} \beta_{11,i}\, ln\, SH_{t-i} + \sum\nolimits_{i=1}^{c} \beta_{12,i}\, ln\, \Delta MR_{t-i} \\ & + \sum\nolimits_{i=1}^{d} \beta_{13,i}\, ln\, RF_{t-i} + \sum\nolimits_{i=1}^{e} \beta_{14,i} \Delta T_{t-i} + \sum\nolimits_{i=1}^{f} \beta_{15,i}\, ln\, \Delta TF_{t-i} \\ & + \sum\nolimits_{i=1}^{g} \beta_{16,i}\, ln\, BE_{t-i} + \sum\nolimits_{i=1}^{h} \beta_{17,i}\, O_{t-i} \\ & + \sum\nolimits_{i=1}^{k} \beta_{18,i}\, ln\, TVD_{t-i} \ldots\ldots\ldots\ldots\ldots + \theta_6 ECM_{t-1} + \mu_t \end{aligned} \tag{7}$$

Relatedly, for duration of power outages the same steps were followed and the ARDL model was established in equation (8).

$$\begin{aligned} lnDOU_t = {} & \beta_0 + \beta_1 lnDOU_{t-1} + \beta_2 ln\, SH_{t-1} + \beta_3 ln\, \Delta MR_{t-1} + \beta_4 ln\, RF_{t-1} \\ & + \beta_5 \Delta ln\, T_{t-1} + \beta_6 \Delta ln\, TF_{t-1} + \beta_7 ln\, BE_{t-1} + \beta_8 O_{t-1} + \beta_9\, ln\, TVD_{t-1} \\ & + \sum\nolimits_{i=1}^{a} \beta_{10,i} lnFOU_{t-i} + \sum\nolimits_{i=1}^{b} \beta_{11,i}\, ln\, SH_{t-i} + \sum\nolimits_{i=1}^{c} \beta_{12,i}\, ln\, \Delta MR_{t-i} \\ & + \sum\nolimits_{i=1}^{d} \beta_{13,i}\, ln\, RF_{t-i} + \sum\nolimits_{i=1}^{e} \beta_{14,i}\, ln\, \Delta T_{t-i} + \sum\nolimits_{i=1}^{f} \beta_{15,i}\, ln\, TF_{t-i} \\ & + \sum\nolimits_{i=1}^{g} \beta_{16,i}\, ln\, BE_{t-i} + \sum\nolimits_{i=1}^{h} \beta_{17,i}\, ln\, O_{t-i} \\ & + \sum\nolimits_{i=1}^{k} \beta_{18,i}\, ln\, TVD_{t-i} \ldots\ldots\ldots\ldots\ldots + \theta_6 ECM_{t-1} + \pi_t \end{aligned} \tag{8}$$

where Δ was the first order differential operator, $\mu_t\, and \pi_t$ represent the white noise. The maximum lag orders were determined by Hannan-Quinn Information Criteria (HQIC), Akaike information Criteria (AIC) and Bayesian Information Criteria (SCBI) and indicated in the results section. The subscript number in the variable stands for the lag period while t-1, stands for lag phase one.

4. Study results

4.1 Descriptive statistics

The data used in this study comprised 128 data points obtained from the transmission and distribution utility databases. These data points comprised both the frequency and duration of power interruptions (dependent variables of the study) on the transmission and distribution national grid system. This was monthly data as captured by the SCADA system from 2012 to 2022, hence 128 months were considered for the study because it was the data available for the study.

4.1.1 Descriptives of the study variables for the transmission subsystem. Table 4 summarizes the descriptive statistics of the variables (dependent and independent) for the transmission subsystem.

In the transmission subsystem, the average number of power interruptions was approximately 111 times per month. In contrast, the average duration of power interruption was 1,248 h per month. On average, technical faults occurred 42 times per month, whereas the components of the transmission grid fail on average three times per month. System overloads were experienced approximately twice per month and the average amount of rainfall received throughout the country was 11.65 mm per month. The transmission subsystem spends an average of 394 million (Uganda Shillings) to maintain and repair the grid. System shutdowns occurred approximately 30 times per month. Trees interrupting power at the transmission grid occur on average once a month. The transmission grid experiences theft and vandalism once per month.

4.1.2 Descriptive of statistics of the variables in the distribution subsystem. Table 5 shows a summary of the descriptive statistics of the variables (dependent and independent) for the distribution subsystem.

In the distribution subsystem, the average number of power interruptions was approximately 2,307 times per month. On the other hand, the average duration of power interruptions was 5,826.2 h per month. The distribution subsystem spends on average 1,586 million (Uganda Shillings) to maintain and repair the grid. system shutdowns averagely take place approximately 333 times in a month. On average technical faults occurred 955 times per month while the components of the distribution grid break on average 215 times per month.

Variable	Number of observations	Mean	Std. dev	Min	Max
Maintenance and repair costs	128	394.1287	70.12853	11	446
System shutdowns	128	30.35938	27.12808	2	199
Trees	128	0.2890625	11.754	0	5
Rainfall	128	111.65	52.59	3.29	247.71
Technical faults	128	42.00781	367.651	48	1897
Failed equipment	128	3.929688	43.749	73	382
System overload	128	1.570313	2.499397	0	18
Theft and vandalism	128	0.140625	0.5284709	0	4
Frequency of outages	128	116.4297	70.12853	11	446
Duration of outages	128	1248.829	1092.371	75.88	5976.38

Source(s): STATA software 17 output

Table 4. Descriptives of the variables for the transmission subsystem

Variable	Number of observations	Mean	Std. dev	Min	Max	Skewness	Kurtosis
Maintenance and repair costs	128	15860.3	17070.12	2830.6	50,366	1.180	2.62
Planned and unplanned shutdowns	128	333.25	289.29	0	2116	4.808	29.26
Trees	128	26.24	11.75	0	56	−0.013	2.93
Rainfall	128	111.65	52.59	3.29	247.71	0.03	2.25
Technical faults	128	954.96	367.65	48	1,897	−0.02	3.37
Failed equipment	128	215.20	43.74	73	382	0.56	4.53
System overload	128	4.5	4.36	0	26	1.76	7.53
Theft and vandalism	128	3.28	2.85	0	17	2.08	8.97
Frequency of outages	128	2307.85	492.97	1,027	3,862	0.44	3.74
Duration of outages	128	5826.15	1937.55	1359.4	16917.2	1.41	10.55

Source(s): STATA software 17 output

Table 5. Descriptives of the variables for the distribution subsystem

System overloads were experienced approximately four times in a month. The amount of rainfall on average, received throughout the country is 11.65 mm per month. Trees interrupting power at the distribution grid takes place on average 26 times in a month while theft and vandalism cases are 3 times per month.

4.2 Results for the unit root test

The study used both the Augmented Dickey–Fuller (ADF) and Phillips–Perrone tests to determine the stationarity of the variables in the study, as shown in appendix section of this document.

4.3 Estimation results OLS model for frequency and duration of power outages

Table 6 shows the estimation results (coefficients and probabilities) of the effect of technical factors on the frequency and duration of power interruptions in the transmission subsystem.

The study found that failed equipment in the transmission grid was negatively associated with grid electricity reliability. A percentage increase in the number of times the equipment in the transmission subsystem broke led to a 10% significant increase in the frequency of transmission grid power interruptions. On the other hand, a percentage increase in the number of times the equipment in the transmission subsystem broke led to a 13% (not significant) increase in the duration of transmission grid power outages. However, the effect was not statistically significant. The coefficients of failed grid equipment imply that frequently failed equipment have a negative effect on grid reliability in the transmission subsystem. Therefore, H2 was supported only in terms of frequency of power outages. Practically failed equipment implies an interruption of the power supply at the point of failure, and this can easily spill over to the entire grid system.

The findings further revealed that technical faults were negatively associated with grid electricity reliability. A percentage increase in technical faults in the transmission subsystem led to 46% significant increase in the frequency of grid power interruptions. On the other hand, a percentage increase in technical faults in the transmission subsystem led to 15% (not significant) increase in the duration of grid power interruptions. The coefficients of technical faults increased the probability of power outage duration in the transmission subsystem over time. H1 was supported only in terms of frequency of power outages. In daily practice, the grid electricity reliability decreases with the occurrence of technical fault events in the transmission subsystem. This could be due to poor quality or old age of the power grid equipment and therefore susceptible to faults.

Table 6.
Estimation results of OLS model (frequency and duration of power outages) for the transmission subsystem

Variable	Frequency of outages Coeff	Std	p-value	Duration of outages Coeff	Std	p-value
In system shutdowns	0.3565	0.0276	0.000***	0.3230	0.1161	0.007***
In maintenance and repair costs	0.1826	0.0685	0.009***	0.0942	0.2247	0.676***
In rainfall	−0.0123	0.0341	0.718	−0.0321	0.1752	0.855
In failed equipment	0.1008	0.0263	0.000***	0.1337	0.1124	0.237***
In technical faults	0.4600	0.0471	0.000***	0.1526	0.1659	0.360***
Trees	0.0279	0.0203	0.172	0.1101	0.1245	0.379
System overload	0.0008	0.0070	0.901	0.0295	0.0297	0.323
Theft and vandalism	0.1163	0.0360	0.002***	0.3147	0.0737	0.000***

Note(s): (1) * stands for level of significance. *, ** and *** stand for 10%, 5 and 1% level of significance, respectively. (2) $\overline{R}^2 = 0.845$ and) $\overline{R}^2 = 0.265$, respectively
Source(s): STATA software 17 output

The estimation results showed that overload events were negatively associated with the grid electricity reliability. A unit increase in the number of system overload events in the transmission subsystem led to a 0.08% (not significant) increase in the frequency of grid power outages in the transmission subsystem and a unit increase in the number of overload events led to approximately 3% (not significant) increase in the duration of transmission grid power outages. Therefore, H3 was not supported. In common practice, when the transmission subsystem is overloaded, this leads to power outages because the grid equipment cannot take on a load that it is not designed to carry.

The study found that stolen and vandalized equipment were negatively associated with the grid electricity reliability. A unit increase in stolen and vandalized equipment in the transmission subsystem led to 11% (significant) increase in the frequency of grid power outages while a unit increase in stolen and vandalized equipment in the transmission subsystem led to 31% (significant) increase in the duration of grid power outages. Both coefficients were significant. Therefore, H4 was supported. In daily practice, grid electricity reliability decreases with the occurrence of stolen and vandalized equipment events in the transmission subsystem.

4.4 Validity of the estimated models

The study carried out some post estimation tests including 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 model. The results of the tests presented in appendix show that the models ware robust.

4.5 Estimation results of the ARDL model for frequency and duration of power outages in the distribution subsystem

Table 7 shows the estimation results on the effect technical and security factors (coefficients and probabilities) on frequency and duration of power interruptions on the distribution subsystem.

The study found that failed equipment was negatively associated with grid electricity reliability. A percentage increase in the number of times equipment in the distribution subsystem failed led to 83% (not significant) increase in the frequency of distribution grid power outages in the long run. In the short run, a percentage increase in failed equipment in the distribution subsystem led to 35% increase in the frequency of distribution grid power outages. On other hand, a percentage increase in the number of times equipment in the distribution subsystem failed led to 11.1% increase in the duration of power outages in the long run. In the short run, a percentage increase in failed equipment in the distribution subsystem led to 20% increase in the duration of distribution grid power outages. However, these effects in both the short and long runs were not significant. H2, was not supported in this case in both the long and short runs. Practically failed equipment implies an interruption of power supply at the point of breakage, and this can spill over to the whole grid system.

In the short run, the results revealed that, overload events were negatively associated with grid electricity reliability. A unit increase in the overload events in the distribution subsystem led to 0.7% significant increase in the frequency of distribution grid power outages. This compromises grid electricity reliability. However, a unit increase in the overload events in the distribution subsystem led to 1.2% decrease in the duration of power outages. This improves grid electricity reliability. Practically when the distribution subsystem is overloaded, this leads to power outages because the grid equipment cannot take on a load for which it is not designed to carry. In the long run however, system overload related events do not have any significant affect in the distribution system. Therefore, H3 was supported in the short but not long run.

Models	Variable	Frequency of outages Coefficient	*p*-value	Duration of outages Coefficient	*p*-value
Long term model	In system shutdowns	0.6981	0.099	0.4138	0.000
	D. maintenance and repair costs	−0.0001	0.622	0.0000	0.270
	In rainfall	0.0922	0.717	0.0715	0.529
	In failed equipment	0.8273	0.203	0.1109	0.704
	D. technical faults	0.0023	0.234	0.0009	0.302
	Trees	−0.0039	0.829	−0.0142	0.104
	System overload	−0.0372	0.193	−0.0125	0.298
	In theft and vandalism	−0.0121	0.715	−0.0074	0.918
	Constant	−0.1222	0.845	3.9127	0.009
Short term model	In system shutdowns				
	D1				
	LD.	−0.1497	0.000	−0.0977	0.129
	L2D	−0.1200	0.000	−0.1100	0.112
	D. maintenance and repair costs				
	D1	−2.56e-06	0.315	−3.26e-06	0.606
	LD.				
	In rainfall				
	D1	−0.0111	0.701	0.0317	0.648
	LD	0.0001	0.994	0.0257	0.666
	L2D	−0.1857	0.384	0.0361	0.486
	In failed equipment	0.3485	0.000	0.2009	0.254
	D				
	D. technical faults				
	D1	0.0001	0.754	−0.0005	0.378
	LD.	0.0001	0.719	0.0001	0.697
	L2D	−9.98e-06	0.943	−0.0000	0.887
	L3D	−0.0001	0.421	−0.0000	0.637
	D. trees	0.0001	0.933	0.0047	0.171
	D1				
	System overload	0.0072	0.005	−0.0014	0.821
	D1				
	In theft and vandalism	0.0072	0.083	0.0343	0.405
	ECM	−0.1335	0.068	−0.7187	0.000
	For frequency of outages; $\overline{R}^2 = 70.7$			ARDL MODEL (1,2,1,3,1,4,1,1,1)	
	For duration of outages; $\overline{R}^2 = 60.9$			ARDL MODEL (1,2,1,3,1,4,1,1,1)	

Source(s): STATA software 17 output

Table 7.
The estimation results for the ARDL model for the distribution subsystem

The results show that technical faults were negatively associated with grid electricity reliability. A percentage increase in technical faults on the distribution grid led to 0.2% increase in the frequency of grid power outages in the long run. In the short run, a percentage increase in technical faults in the distribution subsystem leads to 0.0074% increase in the frequency of grid power outages. In terms of duration of power outages, a percentage increase in technical faults on the distribution grid led to approximately 0.01 and 0.018 (not significant) percent increase in the duration of grid power outages in the long run and short runs, respectively. Therefore, H1 was not supported in both the short and long runs. In daily practice, grid electricity reliability is compromised by technical faults. This is because the quality of the power grid equipment could be wanting or the grid equipment is old. In this context technical faults do not significantly increase duration of outages, implying that the distribution utility responds to technical related faults promptly.

The results of the study revealed that stolen and vandalized equipment were negatively associated with grid electricity reliability in the distribution part of the grid. A percentage increase in stolen and vandalized equipment in the distribution subsystem led to 8.3% increase in the frequency of grid power outages in the short run. On the other hand, a percentage increase in stolen and vandalized equipment in the distribution subsystem led to 3.4% (not significant) increase in the duration of grid power outages in the long run. The probability of the coefficient of stolen and vandalized equipment is not significant but increases the probability of power outages in the distribution subsystem, implying that the distribution utility responds to theft and vandalism related issues promptly. Theft and vandalism of grid equipment in the distribution subsystem are rampant and this could be due to the nature of the location of this equipment, which are highly accessible, making it easy for malicious damagers to access them. H4 was supported in the short run but not in the long run.

4.6 Validity of the estimated models

The study 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 appendix show that the models ware robust.

5. Discussion of results of the study

The study sought to investigate effect of technical and security factors on the transmission and distribution grid electricity reliability in Uganda. In the transmission subsystem the outcomes from the model estimation revealed that technical factors, such as failed equipment and technical faults, generally had a significant effect on the frequency but not the duration of power interruptions in the transmission grid. This implies that the transmission utility responds promptly to technical. On the other hand, theft and vandalism of grid equipment generally had a significant effect on both the frequency and duration of power interruptions in the transmission grid.

Failed grid equipment had a significant negative effect on the frequency of power interruptions in the transmission grid. This implies that other factors held constant, a percentage increase in failed equipment increased the frequency of power outages by approximately 10% in the opposite direction, thus compromising grid electricity reliability. However, failed equipment did not significantly affect the duration of power outages over time. In addition, failed equipment increased the duration of power by 11.1 and 20% in both the short and long runs, respectively. In the distribution subsystem, failed equipment did not significantly increase in both frequency and duration of power outages in the short and long run, respectively.

According to the systems reliability theory, failed equipment terminates the ability of the equipment to perform as required (Shewhart and Wilks, 2021). Failure may be understood as a shift from a working state to a failed state. In some situations, the early discovery of failures may avoid the actual shutdown of the system. This result agrees with the works of previous scholars, such as (Scherb *et al.*, 2019; Okoye and Omolola, 2019; Pepyne, 2007; Vaiman *et al.*, 2012), who document that component and line failures compromise grid reliability in the transmission system of the grid.

Technical faults had a negative significant (1% level of significance) effect on the frequency of power outages in the transmission subsystem. All factors constant, a percentage increase in technical faults brought about 46% increase in the frequency of power outages in the. In the distribution subsystem, a percentage increase in technical faults on the distribution grid led to 0.2% increase in the frequency of grid power outages in the long run. In the short run, a percentage increase in technical faults in the distribution subsystem also led to 0.0074% (not significant) increase in the frequency of grid power outages. Technical faults did not have a significant effect on the duration of grid electricity reliability in both the transmission and distribution subsystems. The findings of the study further agree with the findings of the other studies such as Kaipia *et al.* (2009) who found out that the fault rates of the converters are in electricity distribution. These technical faults have also been studied by other grid reliability scholars such (Ekisheva *et al.*, 2020; Hatziargyriou *et al.*, 2005; Vaiman *et al.*, 2012). This finding is in line with the theory of system reliability, which states that faults, influence reliability of systems. A fault is the state of an item where by the item is not able to perform as required. The theory further categorizes these faults into type 1 and type 2 faults.

System overload had no significant effect on both the frequency and duration of power interruptions in the transmission grid network. In the distribution subsystem, in the short run, unit increase in the overload events led to 0.7 significant percent increase in the frequency of distribution grid power outages. In the long run system overloads had no significant effect. These findings are supported by the systems reliability theory, which asserts that overloads of systems may also be classified as secondary causes of failure for systems (Shewhart and Wilks, 2021). In Uganda illegal connections to the grid system trigger system overloads. When a power system is experiences an overload, it is likely to experience sudden line tripping (Haes Alhelou *et al.*, 2018).

Theft and vandalism had a negative and significant (10% level of significance) effects on both the frequency and duration of power outages in the transmission subsystem. All factors remaining constant, a percentage increase in theft and vandalism of grid equipment led to 11% increase in the frequency of power outages and 31% increase on the duration of power outages. In the distribution subsystem, a percentage increase in stolen and vandalized equipment led 8.3% (significant) increase in the frequency power outages in the short run. The results of the study agrees with the findings of Olugbenga *et al.* (2013) document vandalization of the transmission and distribution equipment as influencers of cause grid electricity reliability. The systems reliability theory, also notes that a security failure is a type of failure resulting from a deliberate human action such as, arson, sabotage and theft.

6. Conclusion and policy implications

This study shows that technical and security factors influence the transmission and distribution grid electricity reliability in one way or another. Technical factors relate to the quality and age of the grid. If the components that make up the power grid are of low quality, this will compromise grid reliability to a great extent because low-quality grid equipment will easily break/fail. Likewise, as grid components age, they are more likely to fail compared to new ones. The poor quality of the power grid components, as well as the old age of grid components, makes them even more vulnerable to technical faults and failures.

This study noted that all the technical factor, apart from system overload, significantly affected the frequency but not the duration of power interruptions in the transmission grid. This could imply that the transmission utility quickly responds to technical faults as and when they occur on the grid. It also implies that the transmission utility responds to failed equipment as soon as they occur on the grid by either replacing or repairing them. The management in charge of the transmission grid does not allow technical faults or failed equipment to spill over into the following month. This implies that this utility is efficient when it comes to responding to technical grid issues. This study also noted that system overloads do not significantly affect the frequency and duration of power interruptions. This could imply that the system overloads are felt by the distribution and generation subsystems, and they hardly spill over into the transmission subsystem. This could also imply that the transmission grid has sufficient capacity that can contain an overload event.

In the distribution grid, the study noted that all the technical faults and failed equipment, did not significantly affect both the duration and frequency of power interruptions. This could imply that most of power outages in the distribution utility are not as a result of technical factors. However, system overloads affected the frequency of power outages but not duration implying that the distribution utility promptly addressed issues of system overload. In addition, theft and vandalism of power grid equipment remain prevalent on the Ugandan power grid and continue to compromise grid electricity reliability, as revealed by the results of the study in both the transmission and distribution subsystems. This study examined the effect of technical factors on grid electricity reliability using secondary time-series data and constantly found the following.

(1) Failed grid equipment negatively and significantly affect transmission grid electricity reliability over time but do not significantly affect distribution grid electricity reliability in both the short and long runs.

(2) Technical faults negatively and significantly affect transmission grid electricity reliability over time but do not significantly affect distribution grid electricity reliability in both the short and long runs.

(3) System overload does not significantly affect transmission grid reliability over time but significantly affects distribution grid electricity reliability in the short run.

(4) Theft and vandalism of grid equipment negatively and significantly affect grid electricity reliability in both the transmission and distribution subsystems.

Our findings contribute to literature in several ways. (a). analyzing the effect of technical and security factors on the transmission and distribution grid electricity reliability in the Ugandan context; (b). System reliability theory was used to analyze the effect of technical factors on grid electricity reliability (c). Both OLS and ARDL models were used to estimate the relationship between technical and security factors and transmission and distribution grid electricity reliability (in terms of both the frequency and duration of power interruptions).

Our findings imply that the government of Uganda should devise policies to improve grid electricity reliability. We suggest in order to reduce power outages on the transmission and distribution power grid, government should invest in quality grid infrastructure with the aim of making the power grid robust enough to withstand technical challenges. This will reduce both the frequency and duration of power outages on the grid. We propose an inclusive engagement in the management and protection of electricity equipment. The government should decentralize ownership of transmission and distribution grid equipment to the community. By allowing the community to own and protect electricity equipment, they are more likely to protect the grid and report failed grid equipment within their reach. Replacing all wooden poles with steel poles could help reduce the problem of failed grid equipment on the grid. Steel poles are less likely to break in the case of accidents and sever weather than wooden poles.

In addition, the results of this study indicate that the transmission subsystem is experiencing technical issues and, therefore, increases the financial budget in terms of repairing and replacing failed and faulty grid equipment. Investing in a strong and quality grid could reduce the expenses of the utility that go into repairing the grid in order to keep it up and running as well expenses in compensating users who could have experienced a power outage as a result of failed equipment or technical faults. Power companies should plan more underground cables in the future because underground power cables are less susceptible to theft, vandalism and sever weather which is a climate change reality today. In addition Uganda is currently up grading its transmission and distribution grid systems, from largely manual to largely an automated system and therefore cyberattacks have not been a challenge to grid electricity reliability. However, it is important to note that the threat is real and could be disastrous. Policy makers should implement strict policies that prevent the community from stealing and vandalizing grid equipment.

7. Limitations and areas of future research

Accessing data on human errors, floods, thunderstorm and lightning which do influence grid reliability according to the systems reliability theory and also other studies (Haes Alhelou *et al.*, 2018; Hatziargyriou *et al.*, 2005; Ward, 2013) was rather difficult in this study. This could have compromised our model estimation. The electricity grid is made up of three subsystems namely generation, transmission and distribution. We propose that future studies include the generation subsystem as well since the grid operates as a system of subsystems. Studying the grid system in parts is solving the problem of grid electricity reliability partially. In addition future studies need to investigate as to whether the size of the electric grid, as well as its location have an influence/catalyse security and technical related factors that in turn influence grid electricity reliability especially in the Ugandan context.

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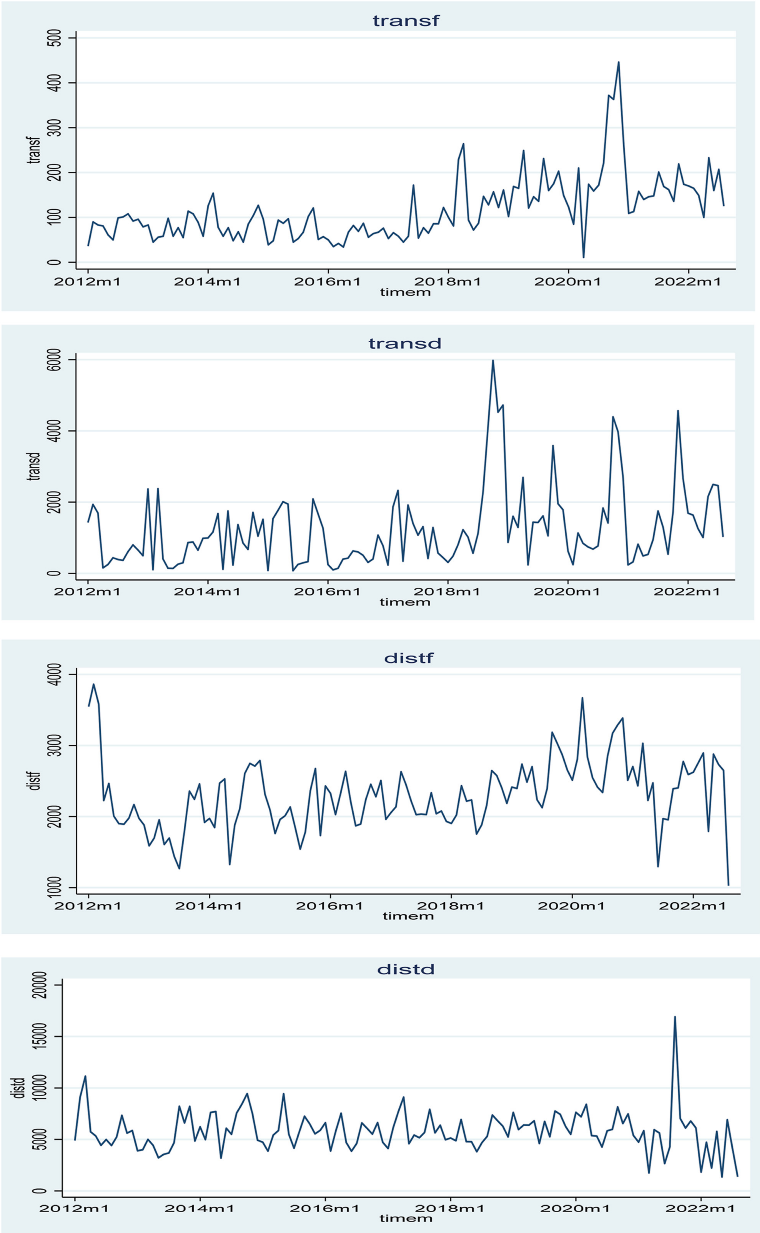
Appendix
Time series line plots for the study variables



Source(s): STATA software 17 output

Figure A1.
Dependent variables

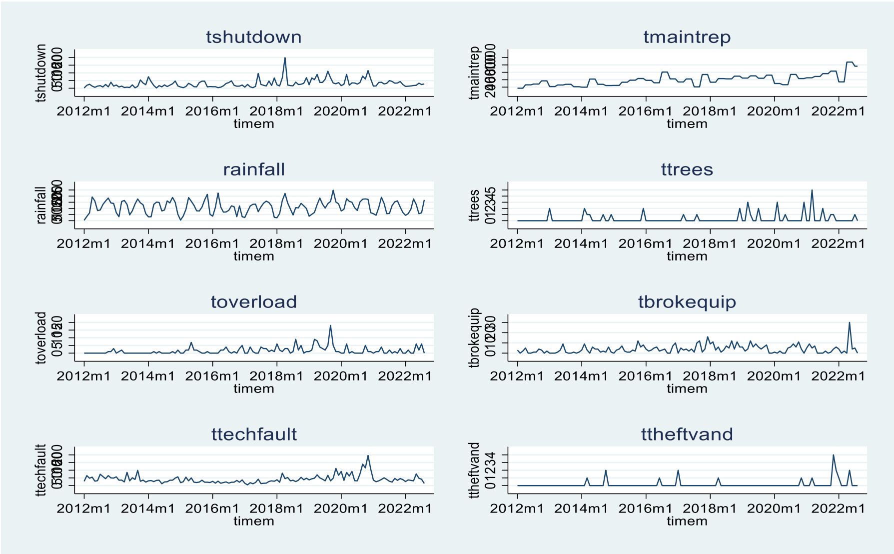


Figure A2.
Independent variables (Transmission subsystem)

Source(s): STATA software 17 output

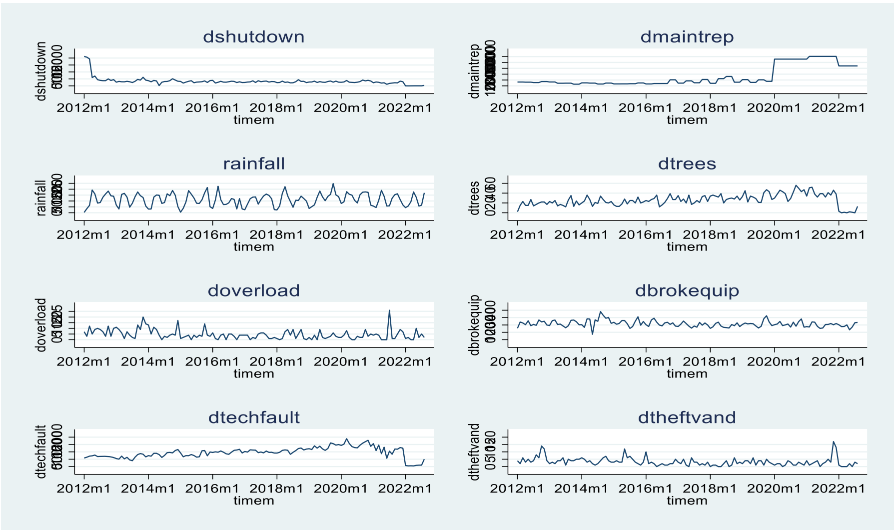


Figure A3.
Independent variables (Distribution subsystem)

Source(s): STATA software 17 output

Variable	Test statistic	1% Critical value	5% Critical value	10% Critical value	*p*-value
Frequency of outages					
Dickey–Fuller	−3.691	−3.502	−2.888	−2.578	0.0001
Phillips–Perron	−5.062	−3.501	−2.888	−2.578	0.0001
Duration of outages					
Dickey–Fuller	−5.389	−3.502	−2.888	−2.578	0.0005
Phillips–Perron	−5.062	−3.501	−2.888	−2.578	0.0000
System shutdowns					
Dickey–Fuller	−5.325	−3.502	−2.888	−2.578	0.0006
Phillips–Perron	−8.173	−3.501	−2.888	−2.578	0.0000
Maintenance and repair costs					
Dickey–Fuller	−3.977	−3.502	−2.888	−2.578	0.0001
Phillips–Perron	−3.134	−3.501	−2.888	−2.578	0.4592
Rainfall					
Dickey–Fuller	−9.819	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−6.687	−3.501	−2.888	−2.578	0.0000
Trees					
Dickey–Fuller	−5.499	−4.032	−3.447	−3.147	0.3765
Phillips–Perron	−11.739	−3.501	−2.888	−2.578	0.0000
Technical faults					
Dickey–Fuller	−4.523	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−6.502	−3.502	−2.888	−2.578	0.0000
Failed equipment					
Dickey–Fuller	−5.982	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−9.409	−3.501	−2.888	−2.578	0.0000
System overload					
Dickey–Fuller	−5.377	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−8.291	−3.501	−2.888	−2.578	0.0000
Theft and Vandalism					
Dickey–Fuller	−6.391	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−8.987	−3.501	−2.888	−2.578	0.0000

Source(s): STATA software 17 output

Table A1. Results of the unit root test for the variables for the transmission subsystem

Distribution subsystem

Variable	Test statistic	1% Critical value	5% Critical value	10% Critical value	*p*-value
Frequency of outages					
Dickey–Fuller	−5.546	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−5.402	−3.501	−2.888	−2.578	0.0000
Duration of outages					
Dickey–Fuller	−6.405	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−9.088	−3.501	−2.888	−2.578	0.0000
Planned and un planned shutdowns					
Dickey–Fuller	−14.037	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−8.511	−3.501	−2.888	−2.578	0.0000
Maintenance and repair costs					
Dickey–Fuller	−2.339	−4.032	−3.447	−3.147	0.4126
Phillips–Perron	−2.255	−4.031	−3.446	−3.146	0.4592
Rainfall					
Dickey–Fuller	−9.819	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−6.687	−3.501	−2.888	−2.578	0.0000
Theft and vandalism					
Dickey–Fuller	−5.081	−3.502	−2.888	−2.578	0.000
Phillips–Perron	−7.389	−3.501	−2.888	−2.578	0.000
Technical faults					
Dickey–Fuller	−2.644	−4.032	−3.447	−3.147	0.2600
Phillips–Perron	−3.099	−4.031	−3.446	−3.146	0.1065
Failed equipment					
Dickey–Fuller	−6.480	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−8.417	−4.031	−3.446	−3.146	0.0000
Trees					
Dickey–Fuller	−5.149	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−5.210	−4.031	−3.446	−3.146	0.0001
Overload					
Dickey–Fuller	−5.328	−3.502	−2.888	−2.578	0.0000
Phillips–Perron	−9.618	−3.501	−2.888	−2.578	0.0000

Source(s): STATA software 17 output

Table A2.
Results for the unit root test for the variables for distribution subsystem

Validity of the model for the transmission subsystem (frequency of power outages)
Model specification test

Test statistic	Degrees of freedom	p-value	Result
0.70	3	0.5544	

Source(s): STATA software 17 output

Table A3. Ramsey reset test for model specification

Heteroscedasticity test

Source	chi	Degrees of freedom	p-value
Heteroscedasticity	45.49	44	0.3979
Skewness	10.72	8	0.2183
Kurtosis	1.64	1	0.1998
Total	58.15	53	0.2916

Source(s): STATA software 17 output

Table A4. Cameron and Trivedi's decomposition of IM test

Multicollinearity test

Variable	VIF	1/VIF
In system shutdowns	1.40	0.715
In maintenance and repair costs	1.30	0.769
In failed equipment	1.22	0.820
In technical faults	1.20	0.836
System overload	1.16	0.863
In rainfall	1.15	0.869
Theft and vandalism	1.07	0.933
Trees	1.06	0.939
Mean VIF	1.19	

Source(s): STATA software 17 output

Table A5. VIF test for multicollinearity

Validity of the model for the transmission subsystem (duration of power outages)
Model specification test

Test statistic	Degrees of freedom	p-value	Result
1.74	3	0.1650	

Source(s): STATA software 17 output

Table A6.
Ramsey reset test for model specification

Heteroscedasticity test

Source	Chi	Degrees of freedom	p-value
Heteroscedasticity	31.51	44	0.9208
Skewness	5.11	8	0.7452
Kurtosis	3.36	1	0.0668
Total	39.98	53	0.9065

Source(s): STATA software 17 output

Table A7.
Cameron and Trivedi's decomposition of IM test

Multicollinearity test

Variable	VIF	1/VIF
In system shutdowns	1.40	0.715
In maintenance and repair costs	1.30	0.769
In failed equipment	1.22	0.820
In technical faults	1.20	0.836
System overload	1.16	0.863
In rainfall	1.15	0.869
Theft and vandalism	1.07	0.933
Trees	1.06	0.939
Mean VIF	1.19	

Source(s): STATA software 17 output

Table A8.
VIF test for multicollinearity

Validity of the model for the distribution subsystem (frequency of power outages)
Serial correlation test

Table A9. Breusch–Godfrey test for serial correlation

Lags(p)	Chi2	Degrees of freedom	Prob > chi2
1	3.785	1	0.0517

Source(s): STATA software 17 output

Model specification test

Table A10. Ramsey reset test for model specification

Test statistic	Degrees of freedom	*p*-value
3.33	3	0.0229

Source(s): STATA software 17 output

Heteroscedasticity test

Table A11. Cameron and Trivedi's decomposition of IM test

Source	Chi	Degrees of freedom	*p*-value
Heteroscedasticity	118.00	117	0.4567
Skewness	35.07	23	0.0511
Kurtosis	2.39	1	0.1220
Total	155.47	141	0.1913

Source(s): STATA software 17 output

Multicollinearity test

Variable	VIF	1/VIF
In system shutdowns	4.79	0.20
L1		
In frequency of power outages	3.50	0.28
L1		
In system shutdowns	3.26	0.30
L2	3.21	0.31
D. technical faults	3.03	0.33
L1	2.68	0.37
In failed equipment	2.64	0.37
L1		
D. trees	2.54	0.39
D. technical faults		
L3	2.53	0.39
L2	2.50	0.39
D. trees	2.49	0.40
L1		
In rainfall		
L1	2.35	0.42
L2	2.29	0.43
D. technical faults	2.24	0.44
L4		
In rainfall	2.00	0.49
L3	1.76	0.56
In theft and vandalism	1.56	0.63
L1		
In failed equipment	1.44	0.69
Theft and vandalism	1.42	0.70
System overload	1.33	0.75
L1	1.32	0.75
In maintenance and repairs costs	1.27	0.78
L1	1.08	0.92
Mean VIF	2.31	

Source(s): STATA software 17 output

Table A12. VIF test for multicollinearity

Validity of the model for the distribution subsystem (duration of power outages)
Serial correlation test

Lags(p)	Chi2	Degrees of freedom	Prob > chi2
4	11.313	4	0.0233

Source(s): STATA software 17 output

Table A13. Breusch- Godfrey test for serial correlation

Model specification test

Test statistic	Degrees of freedom	*p*-value
0.42	3	0.7371

Source(s): STATA software 17 output

Table A14. Ramsey reset test for model specification

Heteroscedasticity test

Source	Chi	Degrees of freedom	p-value
Heteroskedasticity	118.00	117	0.4567
Skewness	32.08	23	0.0986
Kurtosis	2.16	1	0.1413
Total	87.99	141	0.2445

Source(s): STATA software 17 output

Table A15. Cameron and Trivedi's decomposition of IM test

Multicollinearity test

Variable	VIF	1/VIF
In system shutdowns	4.58	0.21
L1	3.35	0.29
L2	3.30	0.30
D. technical faults	3.19	0.31
L1	3.01	0.33
L2	2.76	0.36
L3	2.51	0.39
In rainfall		
L1	2.38	0.42
L2	2.29	0.43
D. technical faults	2.20	0.45
L4		
In failed equipment	2.03	0.49
L1		
In rainfall	2.00	0.49
In duration of outages	1.97	0.50
L1		
D. trees	1.95	0.51
In rainfall	1.75	0.57
L3		
D. trees	1.68	0.59
L1		
D. theft and vandalism	1.54	0.65
L1		
In failed equipment	1.46	0.68
D. theft and vandalism	1.40	0.71
System overload	1.34	0.74
L1	1.29	0.77
D. maintenance and repair costs	1.26	0.79
L1	1.10	0.90
Mean VIF	2.19	

Source(s): STATA software 17 output

Table A16. VIF test for multicollinearity