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Review

Review of Concepts and Determinants of Grid Electricity Reliability

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Abstract: The reliability of the electricity supply is important since any interruption to the supply has direct and indirect consequences for its users. A reliable electricity supply requires a reliable electrical grid system to transmit and distribute the power from the generating plants to the consumers. This study reviewed the literature to find out how the reliability concept has been understood with a special focus on grid electricity reliability, what factors influence grid electricity reliability, what measures have been used to measure grid electricity reliability, which theories and methodologies have been applied to study grid electricity reliability and what are the likely research gaps that require future address. This review found that the literature documents four categories of factors that influence grid electricity reliability, and these are environmental, security, organizational and technical. The biggest influencers of grid electricity reliability were the technical-related factors followed by the environmental-related factors. In addition, we found that sixty studies focused on one subsystem, eleven on two subsystems while seven studies considered three subsystems. Most studies were found to address the distribution of subsystem reliability. As per the methodology adopted, this review found that eleven studies used a qualitative approach, forty-five studies used a quantitative approach, while eleven studies used a case study approach to study the concept of grid electricity reliability. In addition, we found that thirty-seven studies used the duration and frequency of power outages to measure grid electricity reliability.

Keywords: grid availability; grid electricity reliability measures; power outages; reliability index

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1. Introduction

1.1. Background

A reliable and stable supply of grid electricity is key for the economic growth, poverty reduction and social and cultural transformation of any country [1–3]. Sectors of the economy, ranging from residential, manufacturing, agriculture and transport as well as services sectors, depend to a large extent on electricity in particular to function [4] and therefore any interruption in supply implies an interruption in those economic activities. In households, a reliable grid electricity supply is associated with benefits including increased income generation for businesses supported by electricity, more time for women to engage in income-generating activities rather than fuel wood collection, improved health due to controlled household air pollution from solid fuels and improved quality of education outcomes since children are able to study during nighttime while at home [5,6].

Grid electricity reliability has been defined as the ability of power grid elements to supply electricity to all consumers connected to it [7]. According to the North American Electricity Reliability Corporation, grid electricity reliability is defined as the degree to

which the performances of the elements of the electric systems result in power being delivered to the customers within the acceptable standards and the amounts desired [8]. Ref. [9] on the other hand defined grid electricity reliability as "the ability of the power system components to deliver electricity to all points of consumption, in quantity and the quality demanded by the consumer". Whereas ref. [10] notes that a reliable electricity supply requires a reliable electrical grid system to transmit and distribute the power from the generating plants to the consumers, while ref. [1] emphasizes that the reliability of the electricity supply implies the lack of power outages.

The electric grid system consists of a series of interconnected networks of generation, transmission and distribution systems and could be several hundreds of meters in length with voltage levels. Due to these complexities, the grid usually experiences frequent disruptions, leading to power outages which could be at different temporal and spatial scales. These disruptions can be due to many reasons, ranging from substandard and malfunctioning equipment, poor management, lack of investment, as well as natural stresses and disasters [11]. In addition, aging equipment, underfunding, poor maintenance, and unplanned and rapid expansion of the electrical grids can also result in an unreliable electricity grid performance [11].

Studies have revealed that about 56% of electricity grid unreliability is attributed to weather challenges [10,12,13]. Some major outages in Europe and Asia have been attributed to natural disasters or technical faults [14,15]. Several power outages in the Philippines (1992–1994) were as a result of the lack of enough generating capacity and this resulted in an average outage duration of 12 h per day [16]. Furthermore, heatwaves in Australia in January 2019 led to loadshedding events [17], while in the UK, severe storms and floods resulted in power outages for tens of thousands of customers per year in 2016. In addition, floods also led to power interruptions that lasted up to 56 h in northwest England. The major cause of power outages in African countries, for example, Tanzania [11] and Uganda [18,19], is frequent urban flooding and sensitivity to water fluctuations from climatic change effects, respectively.

The literature such as [10,13,20,21] points to weather and technical challenges as the major causes of electricity unreliability. Apparently, there are more than just these two factors contributing to limited grid electricity reliability in most of the regions. For instance, in sub-Saharan Africa, the unreliability of grid electricity is more of a limited capacity issue [19]. In addition, previous reviews on factors influencing grid electricity reliability such as [8,22] focused on only the transmission and distribution subsystems of the power grid but ignored the generation subsystem of the power grid. Ref. [21] looked at the generation and transmission subsystems of the power grid and ignored the distribution subsystem of the grid. In addition, ref. [10] focused on only weather factors that affect the reliability of the grid electricity but ignored other factors including organizational, security and technical factors that can also influence grid reliability. The author of [21] seemed to have looked at most of the factors that influence grid reliability but in only two and not three subsystems of the power grid. These studies did not go further to discuss the factors influencing grid reliability in totality.

1.2. Innovations and Contribution of the Study

The aforementioned studies have not attempted to document the effect of environmental, technical, security and organizational factors on grid reliability in all the three subsectors in a single study. An electricity network is a combination of three main subsystems, which are generation, transmission and distribution systems, and problems with any of these subsystems could influence the reliability of the entire electricity network and have a negative impact on the users.

Given the wide-ranging nature of the linkages in the grid system, a full understanding of the causes and effects of grid failures is difficult to ascertain if studied in isolation. Understanding how these subsystems are affected by factors such as environmental, technical, security and organization is critical to manage the electricity network efficiently and help to

narrow down management activities to a specific subsystem. To fill these gaps, this study comprehensively reviews the articles that reported factors that influence grid electricity reliability in the generation, transmission, and distribution subsystems of the power grid. This study reveals which subsystem has been studied the most and which part of the grid system has not been given so much attention in terms of the empirical literature. In addition, this study highlights the subsystem of the power grid that is most affected by different factors. Furthermore, this study presents a review of updated (up to 2022) and relevant studies in the area of grid network reliability as well as highlighting potential future research areas that need further attention.

The rest of this paper is structured as follows: Section 2 explains the methodology and the procedures this study has adopted, and Section 3 presents the detailed descriptive analysis, results, and discusses the findings of this study. Section 4 provides the conclusion and areas for further research.

2. Materials and Methods

A systematic literature review has been used as a core methodology for defining answerable research questions, to search the literature for available evidence and for evaluating and collecting aggregating data for answering the set questions [23]. A systematic literature review methodology was adopted because it employs a transparent and rigorous approach to identify and synthesize the available research findings concerning the already specified research questions [24]. In this study, more than one database was used to counter the biases associated with systematic literature review methodology. Methodological procedures proposed by [25,26] include question formulation, locating studies, study selection and evaluation, reporting and using the results. The following steps in this review paper are briefly described in the following subsections.

2.1. Step 1: Question Formulation

To be able to gain understanding and knowledge of grid reliability, the following questions were formed to guide the study.

1. How is the reliability concept understood with special focus on grid electricity reliability?
2. What precursor factors influence grid electricity reliability?
3. What are the measures or computational tools of grid electricity reliability?
4. Which theories and methodologies are applied to study grid electricity reliability?
5. What are the likely research gaps that need to be addressed in the future?

2.2. Step 2: Locating Studies

To explore the state of knowledge in grid electricity reliability, this study searched different credible databases and journals. This study considered the literature published between 1964 and 2022 to have a vast source of data to help carry out a comprehensive study. To achieve the objective of this study, the process of identifying the content and or materials for this review was performed using the processes described below.

2.2.1. Database Selection

As shown in Figure 1, this study search focused on online published materials (such as research articles and book chapters). The databases used in this study include Emerald, Science Direct and Google Scholar publishers. Most of the previous reviews used these databases [10,22], which is an indication that these could be trusted databases.

2.2.2. Journal Selection

While selecting journals, emphasis was put on major leading journals identified using the Clarivate (2021) journal ranking together with the impact and citation factors. Journals ranked A, B and C were considered and used for content selection. Whereas the interest of the researchers was bent toward high-ranking journals, few high-quality articles and conference papers published from low-ranking journals were also considered. Furthermore,

where the Clarivate Analytics classification was not applicable, journal impact and cite factors were used to identify credible journals from which the articles and records were extracted. For the case of gray literature, reputable and credible organizations like World Bank and the IEEE standards were also consulted during the review.

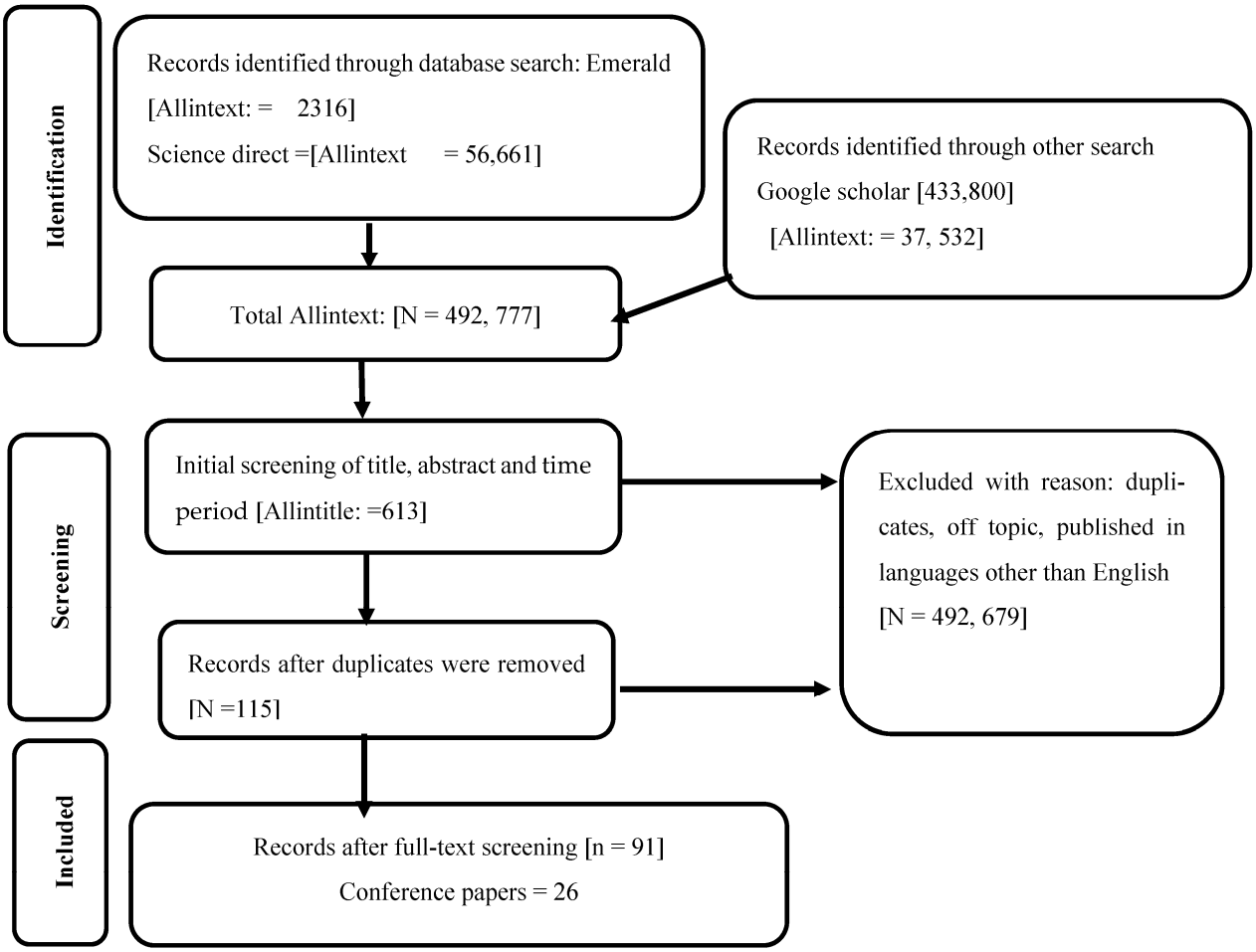


Figure 1. Flow chart for material search and collection process.

2.3. Step 3: Selection and Evaluation of Studies (Content Collection)

2.3.1. Search Terms (Boolean Words)

The systematic literature review process of selecting articles starts with defining the key search (Boolean) expressions. For this study, the keywords and scientific terms of interest were "power blackouts", "power outages", "grid electricity reliability" and "reliability indices".

2.3.2. The Criteria for Exclusion and Inclusion

(i) Inclusion criteria

All articles published between 1964 and 2022 were considered and included for synthesis in this study because this study wanted to have a comprehensive review from a wide coverage of the literature. Articles and papers still under press but accepted for publishing were accepted for this study. Articles written in English were specifically considered since the researcher is more familiar with the English language. The records from reputable organizations (gray literature) including World Bank and the IEEE standards were considered. Also, book chapters, reports and conference papers were included in this review.

(ii) Exclusion criteria

All material published earlier than 1964 did not qualify and was therefore excluded in this study. All material published in other languages other than English was not considered since the researchers were not conversant with other languages.

2.4. Step 4: Synthesis (Content Categorisation/Grouping)

Synthesis involves summarizing the papers/documents based on the content, type of study and the field of research. The full-text articles were analyzed in several steps. Ref. [27] recommends that analytic categories should be derived before analyzing the material, thus using a deductive approach. Following the procedure of Siva et al. [28], we first established the categories: year, publication, theories, nature of the study and analysis techniques [26]. The thematic analysis included the conceptualization and antecedents of the grid electricity reliability.

3. Analysis and Synthesis

This section provides the analysis of the set of the reviewed papers along various dimensions. A total of 91 documents were reviewed. The results are summarized and presented in tables and figures under different categories for better understanding and interpretation.

3.1. Descriptive Statistics of Reviewed Articles

3.1.1. Distribution of Articles According to the Year of Publication

Figure 2 shows the annual numerical distribution for the set of 91 documents reviewed in this study. The study findings show that most of the documents (29 papers) were published between 2018 and 2020. A significant number of papers (eight) and (nine) were published in 2016 and 2018, respectively. Whereas there is a noticeable rise in publication from 2006, we also note that publication in this area started as early as the 1960s with one article recorded in 1964. The results show that research has been growing in this area of grid reliability as the global demand for reliable energy also grows.

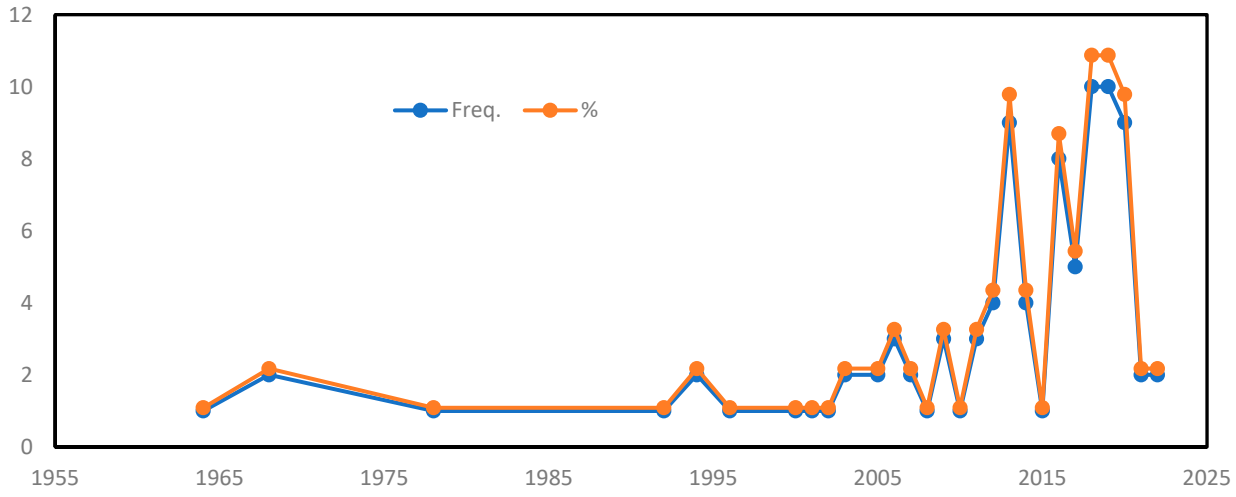


Figure 2. Publication by year.

3.1.2. Distribution of the Studies by Region

Figure 3 and Table 1 show the analysis of the articles by region (continent and country). The results show that most of the papers were published in North America (35.2%) followed by Europe and Asia with 14 (15.4%) documents each. A significant number of papers came from Africa (8.8%) while the lowest number were published in Australia (2.2%). About 12.1% of the articles published did not indicate the region where they were published while 7.7% of the papers cut across different continents.

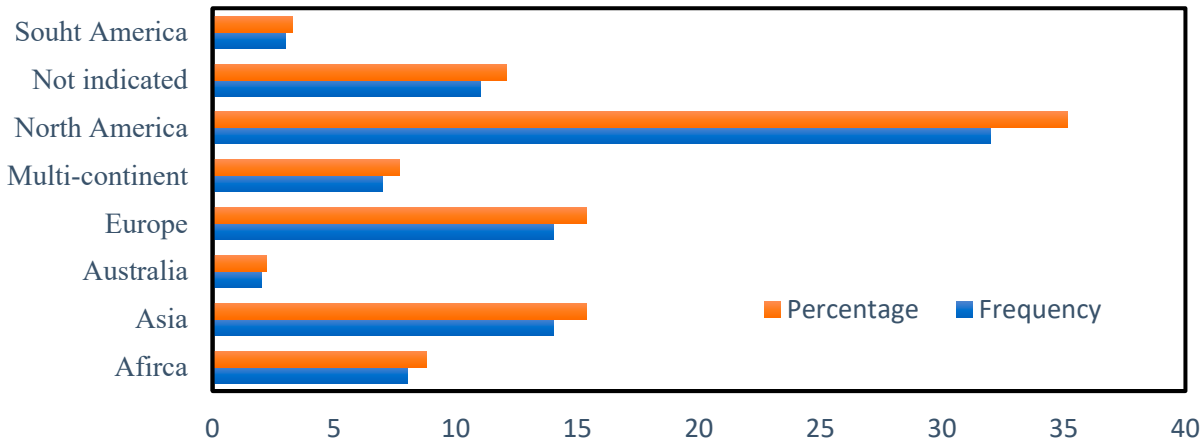


Figure 3. Analysis by continent where the study was conducted.

Table 1. Analysis by country where the study was conducted.

Country	Freq.	Country	Freq.	Country	Freq.
Brazil	3	Libya	1	USA	25
Canada	3	Multicountry	13	Sweden	1
China	7	Nigeria	3	Ukraine	1
Tajikistan	1	Not indicated	12	Kenya	2
Finland	1	Poland	2	Uganda	2
Germany	2	Bulgaria	1	Iran	2
Great Britain	1	Russia	1	Thailand	2
Greece	1	Switzerland	1	Indonesia	1
India	2	South Australia	1		

In terms of countries, most of the papers included in the dataset were published in the USA (25 papers) while 12 of the papers did not indicate the country in which they were published. Furthermore, 13 studies were conducted in more than one country. The rest of the countries, as shown in Table 1, had at least one paper published in the area of grid electricity reliability. The results seem to be pointing out an important observation that the countries where more research in the area of grid reliability has been carried out could be having more reliable grid electricity compared to countries with less research in the same area.

3.1.3. Publication by Research Design/Approach

This study grouped the articles into qualitative, quantitative, mixed methods and reviews. Figure 4 shows the distribution of the various research designs used by various studies. The findings show that 45 studies were quantitative in nature while case study and qualitative approaches comprised 18 papers.

Mixed methods had seven papers, and this was followed closely by the literature review approach which had six documents. The experiment and systems model approach had two documents each while historical meteorology records and images—qualitative data approaches—registered one document each.

3.1.4. Theories/Frameworks/Models

This study also pointed out the theories that have been used in the literature that was reviewed (see Table 2).

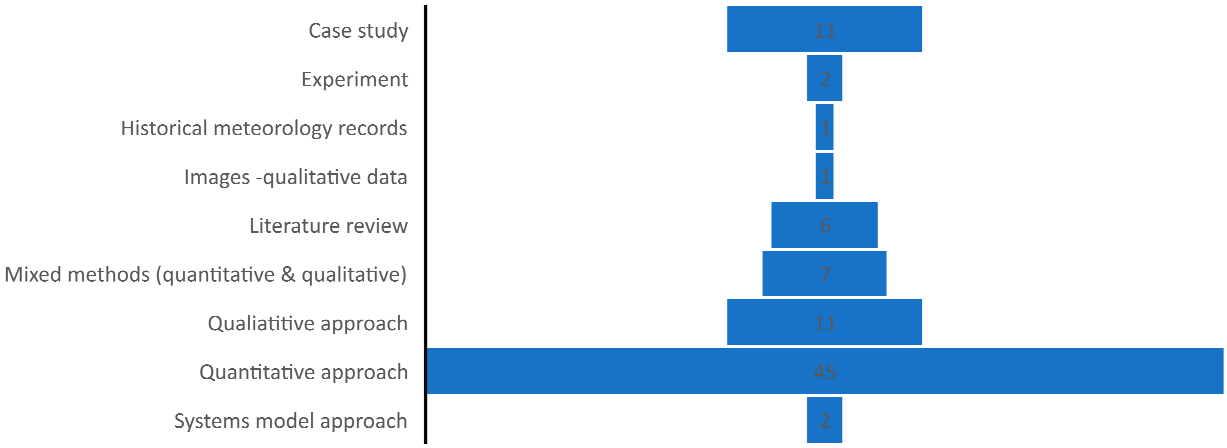


Figure 4. Data collection methods/approaches.

Table 2. Theories/models/frameworks used in the study of grid reliability.

Models/Frameworks/Theories	Freq.	Models/Frameworks/Theories	Freq.
Kolmogorov–Smirnov theory	1	Load model	3
Predictive modeling	1	Localized intensity indices	1
Weighted kernel density Eestimation method	1	Sensitive outage prediction framework	1
OPA cascading blackout model	2	Markov modeling	8
Abstract cascading failure model	1	Theory of HVDC protection and control system	1
Aggregated restoration model	1	MILP model	1
Automatic generator model	1	Motter–Lai model	1
Bayesian model	1	Multiregional supply–use model (MRIA model)	1
Bayesian networks DC-flow model	1	Negative binomial regression models	1
Three stages blackout predictor decision tree	1	Noisy OR-gate model	1
Calibrated hurricane wind speed model	1	Not indicated	34
Cascading line outage model	1	Operational reliability theory	1
Complex network theory	2	Optimization model	1
Component fragility model	2	Physical damage model	1
Composite risk index (CRI) assessment model	1	Climate models (ECHAM4-OPYC3 & HadAM3-H)	1
Optimal power flow (OPF) model	1	Power-flow model	2
Bathtub curve	2	Power network model	1
Consequence path and consequence box	1	Power system blackout model	2
Cost–benefit model	1	Power system simulation theory	1
Google Inception deep convolutional object detection model	1	Predictive models	1
Customer interruption cost model	1	Generalized linear model	1
DC load-flow model	1	Reliability and cost model	1
Deterministic model	1	Reliability assessment model	3
Distribution feeder model	1	Renewable generation model	1
Distribution network model & formulas	1	Sandpile model	1
Drawing theory	1	Self-organized critical theory	1
Two-stage mixture models (QRF, RF, BT or SVM, SVDD-QRF)	1	Infrastructure hardening and condition-based maintenance scheduling model	1
Entropy-based metric model	1	State space model	1
Spatial random field model	1	Synergetic predictive model	1
Generation capacity and system model	3	The dynamic model	1
Graph theory	3	Two-state Markov model	1
Hazard model	1	Two-state model	1
Hidden failure model	1	Two-state weather model	1
Investment–benefit model	1	Under-frequency load	1
AIRS & ANN Model	1	Weather stochastic model	1
Graph model	1	Three-state model	3

Interestingly, quite a few documents (34) were not anchored on any theory/model/framework. The findings, however, reveal some theories that were frequently used. For example, the Markov model was the most used followed by graph theory, the generation capacity and system model, three-state models, load model and reliability assessment model with each of them being reflected in three papers. The rest of the theories and models, as shown in Table 2, were used in at least one or two papers.

3.1.5. Publication by Journal/Publisher

Tables 3 and 4 show the journals and conference proceedings from which the papers on grid electricity reliability were published. Most of the documents analyzed were published by IEEE journal (19 documents) followed by Applied Energy, Reliability Engineering and System Safety and IJERT (International Journal of Engineering Research and Technology) with 3 articles each. The rest of the journals, as shown in Table 3, published between one and two articles on grid electricity reliability. We note that there are quite a number of journals publishing work on grid electricity reliability. This could imply that there is now increased interest in the area of grid reliability from scholars.

Table 3. Journals that have published grid reliability studies.

Journals	FREQ.	Journals	FREQ.
Power Africa	1	IEEE on Transactions on power Apparatus and systems	3
African Journal of Engineering Research	1	The Electricity Journal	2
Applied Energy	3	IEEE Systems Journal	1
Bulletin of Electrical Engineering And Informatics	1	IEEE Transactions on Power delivery	1
Bulletin of The Polish Academy of Sciences Technical Sciences	1	IEEE Transactions on Power Systems	6
CSEE Journal of Power And Energy Systems	2	Electrical Power and Energy Systems	1
Electric Power Systems Research	1	Applied Sciences	1
Electrical & Electronic Engineering	1	IEEE Transactions on Reliability	2
Energies	1	IEEE Transactions on a smart grid	1
Energy Policy	1	International Journal of Engineering Research and Technology	1
Engineering Failure Analysis	1	Int J Disaster Risk Sci	1
Forecasting	1	International Journal of Sensors and Sensor Networks	1
Green Energy and Smart Grids	1	International Journal of System Assurance Engineering and Management.	1
IEEE Access	1	International Journey of Engineering and Science	1
IEEE Milan Power Tech	1	Journal of Electrical Technology UMY	1
IEEE Power & Energy Society Section	1	Natural Hazards Review	1
IEEE Systems Journal	1	PES T&D 2012	1
Reliability Engineering and System Safety	3	The International Journal of Engineering and Science	1
Renewable and Sustainable Energy Reviews	1	Life Science Journal	2
		Climatic Change	1

Among the documents reviewed were books, conference papers and conference proceedings. In total, there were 23 conference papers and proceedings and 5 book chapters, as shown in Table 4. Most conference papers (five) were published in the International Conference on Probabilistic Methods Applied to Power. This was followed by the IEEE Power & Energy Society General Meeting, International conference on Electric Utility Deregulation and Restructuring and Power Technologies and Proceedings of the IEEE with three papers each. The rest of the conference publications had only one paper each. This study reveals the publishers that are increasingly publishing the concept of electricity grid reliability. Future researchers and policy makers may find these publishers' articles as a guide for their future research work in both publishing their work and in following the growing body of knowledge in the area of power grid reliability.

Table 4. Conferences that have published grid reliability studies.

Conferences and Meetings	Freq.	Conferences and Meetings	Freq.
China International Conference on Electricity Distribution	1	International Conference on Lightning Protection	1
Proceedings of the IEEE	2	Smart grid conference	1
Electrical and Computer Engineering Conference Papers, Posters and Presentations.	1	International Conference on Probalistic Methods Applied to Power	5
Electrical Engineering Faculty Conference	1	International conference on Signals and Electronic Systems	1
IEEE Power & Energy Society General Meeting	2	International Conference on System and Science	1
International conference on Advances in human-oriented and Personalized Mechanism	1	International Society Conference on Electric Power Engineering	1
IEEE Power Engineering Society Winter Meeting	1	Conference for Engineering Sciences and Technology	1
International Conference on Cogeneration, Small Power Plants and District Energy	1	International Conference on Environment and Electrical Engineering	1
International conference on Electric Utility Deregulation and Restructuring and Power Technologies	2	International Conference and Exhibition on Electric Distribution.	1
International Power and Energy Conference	1	International Conference on Electricity Distribution.	1
E3S Web of Conferences.	1		

3.1.6. Data Analytic Tools

A data analytical tool is usually a technique for examining, changing and representing data with an aim of finding meaning in the data, recommending conclusions and coming up with decisions at different stages. Data analysis is made up of various features and methodologies, including different techniques with different labels. Table 5 shows the analysis tools employed by different scholars while studying grid electricity reliability. The study findings on analytical tools show that descriptive analysis (22 papers) was the most employed analysis technique followed by qualitative discussion (18 papers) and a Monte Carlo-based simulation approach (14 papers). Other analysis tools frequently used include Weibull distribution (seven papers), sensitivity analysis (seven papers), normal distribution (five papers), Markov decision processes (four papers), reliability analysis (five papers), statistical analysis (four papers), log normal distribution (three papers), conditional probability analysis (three papers) and probability simulations (five papers). The rest of the tools, as shown in Table 5, were employed in at least one or two papers. Some papers employed more than one analytical tool.

3.1.7. Subsystem of the Grid

The electric grid is made up of three subsystems: generation, transmission and distribution. There are numerous studies that have been conducted on either generation, transmission, distribution, or any two of them or even all three of them. Regarding the subsystems of the grid, the study findings indicated in Figure 5 revealed as follows: most of the studies (28) studied only distribution, 24 studies looked at only transmission while only 88 studies looked at the generation subsystem. Transmission and distribution, distribution and generation and generation and transmission attracted four, two and five studies, respectively. A significant number of studies (seven) studied all the three subsystems of the grid while (nine) studies did not hinge their investigation on any subsystem. This study highlights that the generation subsystem of the grid has been researched the least and yet problems still prevail in the generation part of the grid. This calls for further research in the generation subsystem of the grid.

Table 5. Analytic tools.

Analysis Tools	Freq.	Analysis Tools	Freq.
Poisson distribution	2	Not indicated	4
Root cause analysis	1	Observation analysis	2
Bayesian networks	2	OPENCV a python computer vision library	1
Beta distributions	1	Periodic reviews	1
Binomial distribution	1	Crash indices	1
Cause–consequence analysis	1	Power-flow analysis	1
Chi square distribution	1	Principal components analysis (PCA)	2
Comparative analysis	1	Probability simulations	5
Cost–benefit analysis	2	Conditional probability analysis	3
DC-flow analysis	1	Geometric analysis	1
Descriptive analysis	22	Qualitative discussion	18
Localised intensity indices	1	Slow and fast dynamic simulations	1
Event tree analysis	1	RAM analysis	1
Exploratory analysis	1	Reactive power resources	1
Exponential distribution	3	Rectangular distribution	1
Failure probabilities	2	Regression analysis	1
Failures of overhead lines	1	Reliability analysis	5
Fuzzy inference systems	2	Sensitivity analysis	7
Gamma distribution	3	State probabilities	1
Gumbel distribution	1	Statistical analysis	4
Loading analysis	1	Step analysis	1
Log normal distribution	3	Stochastic processes	1
Markov decision processes	4	System brittleness indices	1
Monte Carlo-based simulation approach	14	The method of moments	1
Negative binomial regression analysis	2	Theoretical reliability analysis	1
Network reliability analysis (RDA and MSR)	1	Uniform distribution	1
Normal distribution	5	Weibull distribution	7

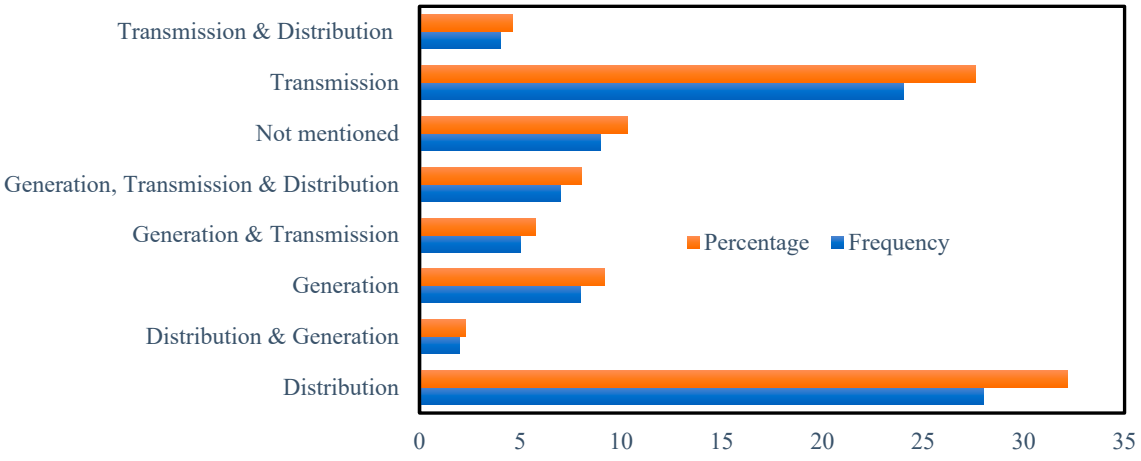


Figure 5. Grid subsystem.

3.2. Conceptualizing Grid Electricity Reliability

The word reliability comes from the old French word "reliable", which means "trustworthy or dependable". The reliability concept has not been applied for more than 60 years [27]. In terms of grid electricity, several authors have studied and conceptualized grid electricity reliability differently, as shown in Table 6. Whereas different authors view grid reliability differently, what is common is the ability of the grid to provide an uninterrupted supply of electricity to the customers connected to the grid.

Table 6. Conceptualization and definition of grid electricity reliability.

Description	Source
1. Reliability is about an uninterrupted supply of electricity.	Scott et al. [29]
2. Reliability of the electricity supply implies lack of power outages.	World Bank (2017) [1]
3. "The ability of the electric grid to deliver electricity to customers without degradation or failure."	[7,9,30,31]
4. "The degree to which the performances of the elements of the electric system result in power being delivered to consumers within accepted standards and in the amount desired."	Hirst & Kirby (2000) [8]
5. "The reliability of electricity supply is very often defined in terms of the number and duration of interruptions in a customer's voltage supply."	Kornatka [32]
6. "The probability that a system will perform its intended functions without failure, within design parameters, under specific operating conditions, and for a specific period of time"	IEEE (2012) [33]
7. "The reliability of electricity supply is very often defined in terms of the number and duration of interruptions in a customer's voltage supply."	Hossain et al. (2021) [34]
8. The interruption of electricity or as a sequence of successive observations reporting at least one grid user without service at a definite point location.	Eto et al. (2017) [35]

This study also explored some grid reliability constructs in the literature over time. Constructs such as grid system failures and faults, common causes of grid system failure, reliability metrics, mitigating grid system failures and faults using smart grids, aging of grid infrastructure, maintenance and costs of grid reliability are some of the areas that have received a lot attention.

3.3. Parameters Used in the Measures of Grid Electricity Reliability

Table 7 shows the most frequently used parameters for measuring grid electricity reliability. The duration of outages appeared in 20 articles followed by the frequency of outages which appeared in 17 documents. This was followed by failure rates which was in eight documents, mean time to repair rates in seven documents and mean time to repair in six documents. Other parameters used to compute grid reliability, as identified in the literature, include availability (three), mean duration of reserve states (one), mean time to failure (three), load level (two), unavailability (five), power network system (one), load duration curve (one), forced outage rate (six), capacity credit (one), size of blackout (two), redundancy/reserve the margin (three), failure characteristics (one), failure criticalness (one) and probability that a customer will be off service (one).

Table 7. Parameters used for measuring grid reliability.

Parameter	Freq.	Parameter	Freq.
Duration of outages	20	Frequency of outages	17
Failure rates	8	Mean time to repair rates	7
Availability	3	Mean duration of reserve states	1
Mean time to failure	3	Load level	2
Unavailability	5	Power network system	1
Load duration curve	1	Forced outage rate	6
Capacity credit	1	Size of blackout	2
Redundancy/reserve margin	3	Failure characteristics	1
Failure criticalness	1	Probability that a customer will be off service	1

3.4. Measures/Computational Tools of Grid Electricity Reliability

The findings in Table 8 show the measures and computational tools for evaluating grid reliability. Some of the generation reliability indices are loss of load probability (LOLP) [36,37], loss of load expectation (LOLE) [21,38] and energy not supplied (ENS) [39]. Some of the transmission reliability indices include SAIDI, SAIFI, SARI and DPUI [39,40]. Some of the distribution reliability indices are SAIFI, CELID, MAIFI, CAIDI and SAIDI [9,14,41,42].

Table 8. Measures of grid reliability.

Measures of Grid Reliability	Freq	Measures of Grid Reliability	Freq
Average service availability index (ASAI)	4	Monetary average interruption frequency index (MAIFI)	3
Average system interruption duration index (ASIDI)	1	Peak load carrying capability (PLCC)	1
Average system interruption frequency index (ASIFI)	1	Energy index of reliability (EIR)	1
Average service unavailability index (ASUI)	2	Equivalent forced outage rate (EFOR)	2
Customer total average interruption duration index (CTAIDI)	1	Expected interruption cost (EIC)	1
Delivery point unreliability index (DPUI)	1	Average duration of load curtailments (ADLCs)	1
Expected cost of unserved energy (ECOST)	1	Customer average interruption duration index (CAIDI)	4
Expected demand not supplied (EDNS)	3	Customer average interruption frequency index (CAIFI)	6
Loss of load duration (LOLD)	3	Customer experiencing long duration interruptions (CELIDs)	1
Loss of load expectation (LOLE)	4	Customers experiencing multiple interruptions (CEMIs)	1
Loss of load frequency (LOLF)	1	Value of lost load	1
Loss of load probability (LOLP)	6	Expected energy not supplied (EENS)	2
Index of reliability (IOR)	1	Frequency & duration (F & D)	2
Energy not supplied (ENS)	2	Loss of energy expectation (LOEE)	3
Forced outage rate (FOR)	1	Systems average interruption duration index (SAIDI)	16
Interrupted energy assessment rate (IEAR)	1	Systems average interruption frequency index (SAIFI)	13
System average RAM frequency index (SARFI)	1	System instantaneous average RAM frequency index (SIAFRI)	1
System monetary average RMS variation frequency index (SMARFI)	1	Customers experiencing multiple sustained interruptions (CEMSIs)	1
Loss of load occurrence (LLO)	1	Probability of load curtailments (PLCs)	1
Expected frequency of load curtailments (EFLCs)	1	Energy index of unreliability (EIU)	1
NH_2	1	Component reliability (COMREL)	1
Reliability evaluation complex systems (RECSs)	1	Coordinated outage restoration algorithm (CORAL)	1
Transmission reliability evaluation of large-scale systems (TRELSSs)	1	Coordinated planning for multienergy power systems (CPMEPS)	1
Cognitive reliability and error analysis method (CREAM)	1	DIGSILENT	1
Outage scheduling and reliability analysis of electric power system (OSCAR)	1	Operational scheduling decision support platform based on reliability assessment (OSDSP-RA)	1
System reliability risk model (SRRM)	1	Short-term assessment of risk and flexibility index (STARFI)	1
Bulk electricity system reliability evaluation–tsinghua (BESRE_TH)	1	Transmission contingency analysis and reliability evaluation (TransCARE)	1
Probabilistic composite system evaluation program (PROCOSE)	1	GATOR	1

3.5. Precursor Factors Influencing Grid Electricity Reliability

The precursor factors (antecedents) were categorized into several broad categories, i.e., environmental/weather factors, technical factors, organizational factors, security factors and other external factors. As shown in Table 9, technical factors were reported in most of the papers (117), followed by environmental/weather factors (77), organizational factors (56), security factors (24) and other factors (12).

Table 9. Antecedents for grid reliability.

Environment/Weather Factors (77)	Technology Factors (117)
Damage from falling trees and tree contacts and other tree characteristics (10)	Insulation (1)
Lightning (6)	Tripping lines circuits and generators, network failure/technological breaks (7)
Heat storms (5)	System topology (6)
Thunderstorms (3)	Fuel and gas (SF 6) supply disruptions (4)
Thermal conductivity of soil, soil moisture and other soil characteristics (3)	Arcing (1)
High wind and gust wind speed (9)	Grid equipment contact (1)
Ice and snow storms (2)	Load level (11)
Rainfall (4)	Interchange levels (1)
Floods (2)	Reactive power levels (5)
Landslides (1)	Meshed and radial grid (2)
Hurricanes (10)	Flow time (1)
Land cover type for example crops (1)	System inertia (1)
Animal (large and small) contact, for example (5)	Synchronous reserve (1)
El Nino/La Nina (1)	Voltage levels (11)
Earthquake (3)	Stability levels (2)
Duration of stormy weather (2)	Oscillatory transients (1)
Weather season (1)	Protection systems (7)
Time of the day (1)	Equipment failure (10)
Catastrophic days and major event days (1)	Frequency levels (2)
Dust storms (1)	Tie lines (2)
Others (6)	System condition (4)
	Contingencies (1)
	System faults (3)
	Phases affected (1)
	Switch closing (1)
	Current transducers (1)
	Line capacity (2)
	Line segments (2)
	Power system variables (number of transformers, poles, switches, overhead and underground lines, length of lines) (6)
	System collapse behavior and disturbances (1)
	Computer software failures (3)
	Energy storage (1)
	Overlapping component outages (1)
	Reserve capacity usage (1)
	Design of power system (1)
	Capacity credit (2)
	Independent failures (1).
	Transient and technical faults for example bus faults (3)
	Aging of equipment (5)
	Operating conditions (1)
Organizational factors (56)	**Security factors (malicious damage/attacks)—(24)**
System operations (6)	Collision with objects (for example, vehicle accidents) (4)
Measuring reliability metrics (1)	Other security issues (2)
Reporting reliability metrics (1)	Vandalism (9)
Inconsistencies (1)	Cyberattacks (2)
Vegetation management (5)	Theft of power grid equipment (5)
Outage management system (1)	Fire (2)
Controlling operation parameters (2)	**Other factors (12)**
Modern smart metering (1)	Load curtailment policies (1)
Planned maintenance (5)	Loadshedding policies (2)
Human errors (3)	Foreign IEEE standards (1)
Maintenance levels (9)	Renewable energy penetration (1)
Frequency of inspection/monitoring of equipment (3)	Over demand (1)
Periodic/technical reviews (3)	Requests for dig ins for parties outside the utility firm(s) (1)
Use of technical staff/adequate understanding of the system and support from the system coordinator (2)	Geographical/spatial variability (1)
Reduction in cost of spare parts (1)	Hidden failures (5)
Level of operation (2)	
Planned outages and unplanned (2)	
Level of situation awareness (1)	
Islanding (1)	
Outage data management (1)	
Improper relay coordination (1)	
Planning of repair and replacement activities (4)	

4. Discussion

This review finds that the studies on the concept of grid electricity reliability start as early as the 1960s and keep growing, with most work being published between 2018 and 2020. Most of the studies were conducted in developed countries, especially those found in North America and Europe. Few studies were conducted in countries found in Asia, Africa, and Australia. This could imply why countries in developed continents have a high grid electricity reliability level as compared to countries in the developing world. In addition, this review finds that 45 studies have been conducted quantitatively, especially using the Markov modeling approach, while 11 studies were conducted qualitatively. This should call for more qualitative studies to deeper interrogate the grid electricity reliability concept and constructs.

Furthermore, the findings reveal that the distribution subsystem has been studied the most, with 28 studies, and the generation subsystem the least, with only 8 studies. In total, 60 studies have looked at 1 subsystem while only 7 studies have been conducted on the entire power grid, thus making policy recommendations biased toward either 1 or 2 subsystems of the power grid. The entire grid system has not been given so much attention in terms of the empirical literature. This study appreciates that the electric grid functions as a system of subsystems, and therefore the grid subsystems should not be studied singularly, but where possible, all three subsystems should be given consideration in a study. Studying the three subsystems of the grid system leads to an unbiased approach in dealing with power grid reliability challenges. The interlinkage nature of the power grid subsystems implies that a problem on a subsystem could cascade to another subsystem, thus compromising the reliability of the whole power grid system. A few studies that have attempted to have a three-subsystem approach, for example [41], qualitatively and focused on a few challenges and opportunities of smart grids. Ref. [42] only focused on key issues pertaining to aging, maintenance and how they influence the reliability of electricity while [43] also addresses issues pertaining to maintenance. Refs. [30,43,44] looked at the measures for the three subsystems. The findings of this review reveal a diverse set of factors that influence grid electricity reliability. These factors seem to play a dual role [45], as discussed in the following subsections.

4.1. Environmental/Weather Factors

Environmental/weather factors are widely understood as the operating conditions under which the system is (or is expected to be) operating. According to this review, and as anticipated from theory, environmental/weather factors seem to be affecting grid reliability in one way or the other and are also on the rise, starting from 2011 to date. These factors were the second-biggest influencers of grid electricity reliability, according to this review, with hurricanes and tree characteristics topping the list. Hurricanes caused simultaneous failures on both grid components and the grid itself [46–54] and are affecting power grid systems in the western part of the world. Other environmental factors that influence grid reliability include rainfall [47,55,56], the land cover type [47,57], different tree characteristics [47,58–62], flooding [50,63], storms, for example, heat storms [15,64–67], lightning [60,66,68–70], El Nino/La Niña [46], ice and snow storms [71,72], atmospheric surges [73], fires [63], gust wind and wind speed [48,49,52], birds [61,74], thunderstorms [75,76], earthquakes [72], dust storms [56,69] and thermal conductivity of soil and other soil characteristics [58]. The above studies on the failure of power systems due to weather-related causes seem to be pointing to the fact that the power systems are facing external challenges that are beyond their control. These factors mainly affected the transmission and distribution subsystems.

4.2. Technical Factors

These are normal events (events that are expected to occur during the life span of the system), specific component failures and faults that may result in the system failure [77]. If the quality of the grid is wanting, its reliability will be compromised, other factors withstanding. This study affirms that most of the findings from the literature seem to be pointing

to technical factors, especially equipment failure and voltage-related issues, as the biggest contributor to grid unreliability. Technical factors such as tripping of transmission lines and generators [21,60,78,79], equipment failure [7,15,55,56,80,81], insulation level [60], the load level on the grid system [13,20,79,82,83], voltage levels [20,83–87], reactive power levels [13,88], computer software failures [56,88,89], protecting devices such as relays [88], system collapse behavior and disturbances [53,90], aging of grid components [20,44,88,91], transient and technical faults [74,92–94], vulnerable line segments [15], specific line capacities [15,53], overlapping component outages [80], length of power line [20,32,56,93], arcing [59], operating conditions of the grid system [94] and fuel and gas supply disruptions [20,50,74,94] were also documented as grid reliability influencers.

Power grids, especially smart grids, are usually managed by computer software such as supervisory control and data acquisition (SCADA) systems and the failures of such computer software were also reported as influencers of grid electricity reliability by [56,87,92]. The power grid is made of devices that are meant to protect it by addressing unacceptable problems and taking necessary corrective action. Protecting devices such as relays [87] were also documented as grid electricity reliability influencers and these protective devices are intended to improve grid electricity reliability. Recent works (see, for example, refs. [95–97]) also propose energy storage systems as influencers of grid electricity reliability and contribute to grid reliability enhancement. All electric power grid infrastructures depreciate over time and, therefore, face challenges as they age; for instance, [20,44,88,91] reported the aging of grid components as influencers of grid electricity reliability. Similarly, studies conducted on the generation subsystem frequently reported aging as an influencer of grid electricity reliability. Technical-related factors were reported the most in the transmission subsystem.

4.3. Organizational Factors

These are management actions during the life cycle of the grid system intended to retain the system or restore it to a state in which it can perform as required [77]. According to the review findings, ref. [20] found that forced outages are the main cause of blackouts on the transmission system. Other organizational factors that influence grid electricity reliability include scheduled and unscheduled maintenance activities [13,21,44,60], human errors [13,21,56,72], vegetation management [80,88,88,98], frequency of system inspections [7], technical reviews [7], monitoring of electrical equipment [7], period for periodic reviews [7], use of technical staff [7,88], reduction in the cost of spare parts and a high level of operational reliability [7], planned and unplanned outages [20,72], repair and replacement activities [77,93], inadequate understanding of the system [88], inadequate support from the reliability coordinator [88] and improper relay coordination [20]. Although human errors were reported the most in the generation subsystem, overall, organization-related factors appeared the most in the distribution subsystem.

4.4. Security Factors (System Threats)

System security threats imply deliberate hostile action on the grid system, and these can be physical attacks on the system (e.g., arson, sabotage, and theft) or cyberattacks [77]. A system security failure is a type of failure caused by deliberate human action. Many grid systems are exposed to several threats that could be physical or cyber in nature. The findings from this review reveal that the concept has been studied with an approach of grid components being stolen or vandalized or both [20,99–101]. These vices have heavily compromised grid reliability and strategies to curb the vice have been suggested [102,103]. Recent studies such as [95,104,105] also propose various solutions to the cybersecurity problem. Other factors under this category include vehicle accidents [47,56,72] and cyberattacks [21,56]. Security-related factors were reported in the distribution and transmission subsystem, especially in countries on the African continent. Security-related factors were the least grid influencers according to this review's findings with cyberattacks on the grid being documented, starting from 2017 onward.

4.5. Other External Factors

This review further found that there are other exogenous factors influencing grid electricity reliability such as load curtailment policies, for example, loadshedding policies [40,90,106,107], foreign IEEE standards [39], renewable energy penetration [79], over demand [21], geographical/spatial variability [14], requests for dig ins from parties [72] and other hidden failures [78,81].

4.6. Measurements of Grid Reliability

According to system reliability theory, measuring grid reliability is vital in power system reliability calculation. Reliability indices are used to calculate the grid reliability performance of the power system against some expected minimum requirements or reliability standards, compare different designs, recognize weak spots, and identify ways for improvement to be unified with both expenses and performance reflections for decision-making [108]. The findings of this review reveal that the reliability indices were studied at the generation subsystem [37], transmission subsystem [40], distribution subsystem [14] and in other perspectives [35,39]. According to the literature reviewed, some of the parameters that were used to compute the indices were availability [109,110], frequency of occurrence [14,34,40,42,43], duration of occurrence [56,87], mean time between failure [110], fault duration [107], mean duration of reserve states [14,34,40,42,43,109], failure rate [105,109], repair rate [37,80,109], mean time to failure [109], mean time to repair [36,41,43,109,110], forced outage rate [36,39,80,105,108], load level on index [105], unavailability [93,108], load duration curve [36], capacity credit [36], average restoration time [77,80], average total interruption time [77,80] and maximum expected restoration time [80].

5. Conclusions

5.1. Summary of Results

The aim of this study was to find out how grid electricity reliability has been conceptualized, the factors that influence grid reliability as well as to discover the measures of grid reliability as portrayed in the literature. This review identified that there seems to be a consensus in the way grid reliability has been defined and conceptualized over time. However, this study notes that conceptualizing grid reliability would be incomplete without critically examining the factors (such as environmental/weather conditions, organizational factors, security and technical factors) that influence its reliability, as well as the duration and frequency of these factors. Furthermore, accurate information on the number of power outages, frequency and duration of these power outages are key required data for correctly computing power grid reliability indices. This study notes that few studies on grid electricity reliability are being conducted on the entire grid system and yet the power grid operates as a system of subsystems, such as the generation, transmission, and distribution networks. Understanding the causes of power failures and faults under each subsystem could help policy makers to make targeted regulations to address each subsystem appropriately and improve their level of reliability in supplying electricity to the users.

5.2. Directions for Further Research

The reviewed studies on security failures point out that grid equipment is either vandalized or stolen or both. Despite the suggested solutions to the vice, the problem still prevails. This study therefore proposes further studies to investigate the underlying socio-cultural behavior and vandalization of power grid networks by individuals and/or communities, especially in developing countries.

In addition, this study proposes quantitative studies to investigate the degree of contribution of each identified technical and environmental factors that are impacting grid network reliability using econometric analysis techniques. Findings from these kinds of studies could assist in ranking these factors in order of severity on the grid network performance. Furthermore, in developing countries, medium- to short-term forecasting studies

on the impact of weather and environmental conditions (such as ambient temperature, destructive storm and heavy rainfall that could lead to flooding) are needed to help the system operators plan and manage the impact of events appropriately.

The studies that looked at environmental-related factors as grid electricity influencers seem to also be silent on some causes of failure due to floating islands/vegetation, rivers bursting their banks and restrictions of river usage from authorities that control the river in some countries. Therefore, this study calls for further research to fill this gap.

The studies on the concept of aging infrastructure ignore the effect of the environmental conditions in which the aging power infrastructure operates. These conditions could be a contributing factor to this aging. If the weather is harsh to the grid, then the components on the grid are likely to have a shorter life. Therefore, there is a need to investigate the length of life of equipment in areas which experience harsh weather/environmental conditions vis a vis the length of life of equipment in areas that experience not so harsh weather/environmental conditions. There is a need to find out the length of the different equipment in the various geographical areas that experience different weather/environmental conditions.

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