

Reliability Assessment of Medium Voltage Underground Cable Network—Saudi Arabia Jeddah Case Study

Meshari Alwagdani¹, Mousa Marzband^{2,3}, Sultan Alghamdi^{2,3}

¹Department of Electrical and Computer Engineering, Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

²Center of Research Excellence in Renewable Energy and Power Systems, Department of Electrical and Computer Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

³Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

Email: abdulqaderalghamdi@gmail.com, majour@kau.edu.sa

How to cite this paper: Alwagdani, M., Marzband, M. and Alghamdi, S. (2026) Reliability Assessment of Medium Voltage Underground Cable Network—Saudi Arabia Jeddah Case Study. *Energy and Power Engineering*, 18, 374-396.
<https://doi.org/10.4236/epe.2026.186018>

Received: May 17, 2026

Accepted: June 23, 2026

Published: June 26, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

The reliability of medium voltage (MV) underground cable networks is critical for uninterrupted electricity supply in urban environments, particularly in regions with harsh climatic conditions. This study presents a comprehensive reliability assessment of the MV underground cable network in Jeddah, Saudi Arabia, operated by the Saudi Electricity Company (SEC). A six-year dataset (2019-2024) comprising 435 validated fault records, cable infrastructure data, environmental parameters, and restoration times was analyzed using statistical modeling techniques. The methodology integrates descriptive statistics, Pearson correlation analysis, and probabilistic distribution modeling, including Gamma, Weibull, and Log-Logistic distributions. Goodness-of-fit was evaluated using the Kolmogorov-Smirnov test. Reliability indices (SAIFI, SAIDI, CAIDI) were calculated according to IEEE Std 1366-2012 and benchmarked against NRS 047-1 standards. The results reveal that equipment failures account for 60% of all incidents, with insulation failure (51%), cable joint faults (20%), and termination faults (17%) being the predominant mechanisms. Joint and termination defects collectively constitute 37% of equipment failures. The mean restoration time was 5.56 hours, approximately 79% higher than the SEC national average of 3.1 hours, and failed to meet NRS 047-1 targets for 30%, 60%, and 90% restoration milestones. Temperature exhibited a strong positive correlation with failures ($r = 0.954$), while load demand also showed strong correlation ($r = 0.942$). The worst-performing feeder (Hera-Feeder-01) recorded 5 failures in 2023 with a mean restoration time of 17.17 hours. The failure rate increased by 25% from 2019 to 2024, indicating progressive infrastructure deterioration. This study provides actionable recommendations for predictive maintenance, climate-adaptive strategies, and database integration to enhance

network reliability. The findings offer practical guidance for utilities operating in environmentally demanding regions.

Keywords

Reliability Assessment, Medium Voltage Underground, Cable Network, Saudi Arabia, Jeddah Case

1. Introduction

The development of a robust, intelligent and flexible power distribution network is a high priority [1] [2]. This transformation is particularly reliant on medium voltage underground cable networks, especially in urban cities like Jeddah, where there is a need to have underground distribution systems due to issues of visual appearance, safety and land use [1] [3]. These networks however have their reliability questioned by the extreme environmental conditions present in Jeddah, including high temperatures for long periods, high humidity, rainfall at certain times of the year and soil that is saline. This results in a combination of increased deterioration of cables and increased risks when the networks are operational [2] [4].

Research carried out before now has indicated that environmental factors can accelerate insulation aging, increase cable failure rates, joints and terminations and increase the likelihood of water entering and thermal damage occurring [4] [5]. Utility operators face increased thermal and mechanical stresses as well as more complicated fault detection and longer restoration times when dealing with high feeder usage and the rapid growth of urban areas. In spite of the significant investments that the Saudi Electricity Company has made in the automation of its systems, asset management and network digitization, recurrent MV cable failures continue to impose operational constraints on Jeddah's underground network.

The operational reliability of a distribution system is also influenced by the geographical locations of its facilities, namely substations and maintenance depots. Research has shown that how close a depot is, how readily available spare parts are and how effectively faults are dealt with are key factors in deciding the length of power cuts and how quickly power is restored [6] [7]. The network in Jeddah is divided into 5 separate operational zones—North, East, South, West and the airport itself. Each of these areas has a central storage facility for maintenance. This fundamental basis is laid by accurately mapping the geographical distribution of substations and support facilities, in MV underground cable networks, and this is essential for the reliability assessment, for predictive failure analysis and for optimized maintenance techniques [6] [8].

Utilities can use this kind of information to enhance the operational efficiency of their systems, reduce outages that are not planned and prioritise their interventions accordingly.

In Jeddah, the medium voltage underground cabling suffers from frequent faults. The joints and ends are the components most susceptible to failure because of me-

chanical stress, moisture and temperature fluctuations. Most faults are brought about by faulty construction, installer mistake or low-grade components. Under conditions of rapid restoration and operational pressure, the quality of maintenance can be compromised, leading to network reliability issues [9] [10]. The harsh Jeddah environment, which features extremely high temperatures and high humidity, adds to the degradation of the materials used in insulation and the deterioration of joints. Saline soil is another issue found in the area. In urban Jeddah, **Figure 1** shows the classification of MV cable failure causes into three categories: Human, Environmental and Operational factors. The diagram shows how mistakes, in practices, bad environmental conditions and operational issues all cause MV cable failures [11].

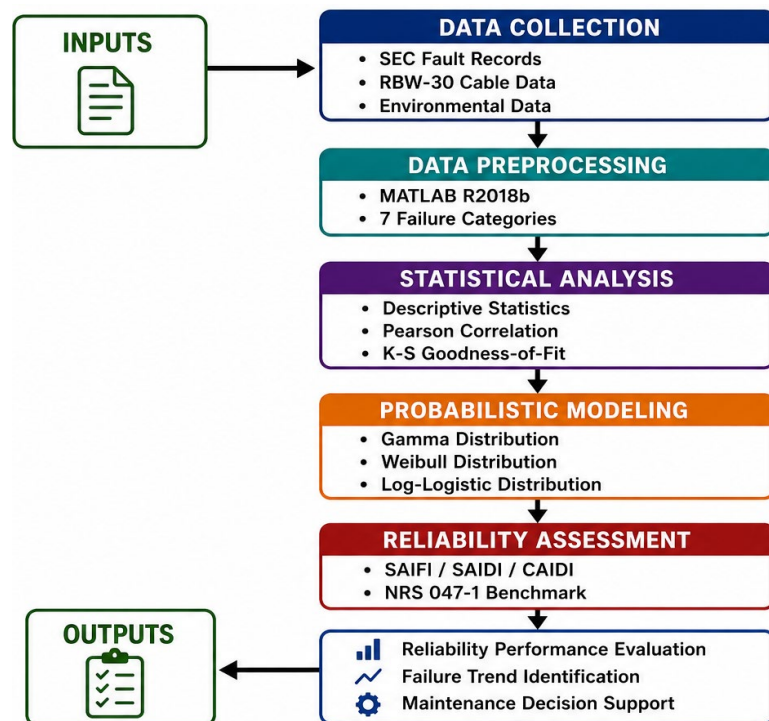


Figure 1. Modeling system.

The city of Jeddah has experienced problems with its MV cable network's underground network. The key issues are that maintenance data is incomplete and no one is responsible for monitoring the system. This has impacted the metro's reliability and its maintenance.

2. Literature Review

Recent research has extensively addressed medium voltage (MV) cable reliability through various methodological approaches [9]-[11]. Zhang *et al.* (2025) developed a double-sequence Monte Carlo simulation method for underground cable reliability evaluation, demonstrating the effectiveness of probabilistic modeling in capturing failure uncertainties [9]. Similarly, Clavijo-Blanco *et al.* (2024) employed

Monte Carlo-based statistical characterization of reliability indices in MV networks, providing frameworks for SAIFI and SAIDI prediction [12].

Environmental and thermal influences on cable performance have been systematically investigated. Velásquez (2025) conducted transient analysis of overvoltage and cable faults in underground MV systems, identifying critical fault mechanisms [10]. Complementing this work, Arias Velasquez *et al.* (2025) examined thermal limitations in underground circuit design, revealing that inadequate heat dissipation significantly accelerates insulation degradation [13]. Banasik and Chojnacki (2024) further demonstrated the substantial impact of weather conditions on cable reliability indicators [14].

Infrastructure aging and replacement challenges were critically reviewed by Rafati *et al.* (2024), who synthesized technical innovations for MV cable replacement, emphasizing the economic and operational barriers to network renovation [11]. Condition assessment methodologies for MV assets were comprehensively evaluated by Mesino *et al.* (2023), who highlighted the importance of diagnostic testing in predictive maintenance programs [15].

Case study applications have validated these analytical approaches. Bazargur *et al.* (2023) presented a reliability study for underground systems, demonstrating practical implementation of failure prediction models [16]. Ellinas *et al.* (2024) contributed a comprehensive analysis of grounding system performance in MV concrete poles, addressing an often-overlooked component of network reliability [17].

Despite these contributions, limited research has integrated localized environmental data with advanced statistical distributions (Gamma, Weibull, Log-Logistic) in a unified predictive framework for urban MV networks in hot and humid climates, representing the gap addressed by this study.

3. Materials and Methods

In this research, the complete MV distribution system of Jeddah is considered for six calendar years, starting from January 2019 until December 2024, while in terms of failure modes, only feeder RBW-30, which has segmental information, is examined, operated by the Saudi Electricity Company (SEC). The network operates at 13.8 kV and utilizes XLPE-insulated copper cables. The study years was collected from SEC's operational databases, including: 1) fault records comprising 435 recorded incidents with timestamps, locations, and failure types; 2) cable infrastructure data from feeder RBW-30 consisting of 8 cable segments with a total length of 3.04 km; 3) environmental data including monthly temperature, rainfall, and load demand for 2023; and 4) restoration times representing the duration from fault occurrence to service restoration.

The raw fault logs were processed using a data screening protocol before analysis. Planned outages were not included. Timestamp and location were used to merge duplicate entries. Records were excluded for having more than 20% missing fields ($n = 3$). All faults were allocated to 7 main categories from SEC inspection reports.

When a root cause could not be conclusively determined following the fault investigation, the “unknown” category was not omitted, but kept separate. There were no missing data imputations.

Raw fault data was preprocessed using MATLAB R2018b. Each record was classified into seven primary failure categories based on SEC inspection reports: Equipment Failure, Unknown Faults, Third Party/Theft, Human Error, Poor Maintenance, Protection Failure, and Other. Equipment failures were further disaggregated into Insulation Failure, Cable Joint Fault, Termination Fault, and Other Equipment.

Monthly failure frequencies were calculated and correlated with environmental variables (temperature, rainfall, load demand) using Pearson’s correlation coefficient. The analysis included: 1) annual failure rate per 100 km of cable; 2) monthly failure distribution; and 3) seasonal patterns, where the wet season was defined as November-April and the dry season as May-October.

Three statistical distributions were employed to model failure behavior:

1) Gamma Distribution for Restoration Time

The Gamma distribution was applied to model restoration times due to its flexibility with positively skewed data. The probability density function (PDF) is:

$$f(t; \alpha, \beta) = \frac{t^{\alpha-1} e^{-t/\beta}}{\beta^\alpha \Gamma(\alpha)} \text{ or } t > 0$$

Maximum Likelihood Estimation (MLE) was performed in MATLAB R2018b to obtain the parameters for the Gamma, Weibull and Log-Logistic distributions. Sample sizes: restoration times: $n = 54$, Worst feeder Failure (WF) data: $n = 14$, annual failure frequency of feeders (AFF): $n = 10$.

The Kolmogorov-Smirnov (K-S) goodness-of-fit test was used to determine p-values of >0.05 , which implies acceptance of the null hypothesis of the tested distribution. The K-S test results were: Gamma distribution $D = 0.092$ ($p = 0.73$); Weibull distribution $D = 0.11$ ($p = 0.68$); Log-Logistic distribution $D = 0.10$ ($p = 0.71$). p-values are greater than 0.05 for all three distributions, thus showing that all of them are good fits to the data sets.

2) Weibull Distribution for Worst Feeder

The Weibull distribution was used to model the worst-performing feeder (Hera-Feeder-01) with shape parameter $\alpha = 1.9$ and scale parameter $\beta = 6.3$. The Weibull PDF is:

$$f(t) = \frac{\alpha}{\beta} \left(\frac{t}{\beta} \right)^{\alpha-1} \exp \left(- \left(\frac{t}{\beta} \right)^\alpha \right)$$

- Log-Logistic Distribution for Failure Frequency

The Log-Logistic distribution (shape $\alpha = 1.6$, scale $\beta = 4.0$) was fitted to annual failure frequency data per feeder.

- Goodness-of-Fit Testing

The Kolmogorov-Smirnov (K-S) test was applied to evaluate distribution fits, with a significance threshold of $p > 0.05$ for accepting the null hypothesis that the data follows the tested distribution.

- Reliability Indices Calculation

Three common reliability indices were determined based on IEEE Std 1366-2012 with the following definitions and inputs:

- The SAIFI is calculated as the total number of customer interruptions divided by the total number of customers served. As of 2023, the population served by the SEC in Jeddah South is 187,500 customers.
- SAIDI (System Average Interruption Duration Index): Total customer interruption duration (hours) divided by the number of customers served. Duration per event = time from the occurrence of the fault until service is restored.
- Customer Average Interruption Duration Index: Total duration of customer interruptions/Number of Customer interruptions.

All 13.8kV feeders in the SEC Jeddah South network are included in the network boundary for all index calculations. Performance was compared to the SEC national averages (3.1 hours mean restoration time) and to NRS 047-1 restoration targets.

Performance was benchmarked against:

- **NRS 047-1 standards:** Restoration targets (30% within 1.5 h, 60% within 3.5 h, 90% within 7.5 h, 98% within 24 h).
- **SEC national averages:** 3.1 hours mean restoration time.

4. Results

This chapter aims to present the results of the reliability analysis conducted on the Jeddah MV underground cable system based on data gathered from 435 faults for Saudi Electricity Company (SEC) between 2019 and 2024 and focusing on data from 2023.

For clarity, the number of faults reported for each of the six years (2019-2024) in this section is as follows: total fault records in six years (2019-2024) = 435; total faults recorded in 2023 = 54; sum of failures in all 10 feeders in 2023 = 54; worst feeder (Hera-Feeder-01) annual failures = 5; system-wide failure totals range from 360 in 2019 to 500 in 2024. These numbers are followed by all the other tables and figures.

The number of failures encountered in the MV underground cables system of Jeddah during 2023 amounted to 54. The total length of the cables was 12,500 km, from which a failure rate of 0.43 failures per 100 km was estimated and is shown in **Table 1**.

Table 1. Monthly environmental and failure data (Jeddah 2023).

Month	Temp (°C)	Rainfall (mm)	Load (MW)	Failures
Jan	23	10	82	2
Feb	25	5	85	1
Mar	28	3	88	3
Apr	32	0	94	5
May	35	0	102	6

Continued

Jun	38	0	108	7
Jul	40	1	115	8
Aug	41	2	117	7
Sep	39	4	110	6
Oct	34	8	100	4
Nov	29	15	92	3
Dec	25	20	86	2
Total	-	-	-	54
Mean	32.4	5.7	98.3	4.5
Std Dev	6.0	6.6	11.8	2.3

Monthly distribution of MV underground cable failures is shown in **Figure 2** for 2023, which clearly shows the seasonality in network performance. The frequency of failures slowly rose from the winter months to the summer months, reaching its peak in July with 8 failures as compared to one failure in February. This is a clear upward progression in the months of high temperature, which reflects the influence of thermal stresses in the environment on underground cable systems. High ambient temperatures make conductor operating temperature rise and cause the insulation to age up, the conductor to expand, and the joints to deteriorate, so that the number of faults is increased. The decline in failure rates during autumn also indicates that network reliability is indeed seasonally dependent. The pattern observed is highly indicative that loading conditions during the summer and extreme climatic conditions in Jeddah are significant factors affecting cable deterioration and hence must be taken into account in planning maintenance and improving cable reliability. Further, the failure rates are found to be high over a limited period in the summer months, suggesting that preventive maintenance should ideally be done in advance of the summer months to reduce the risk of outages.

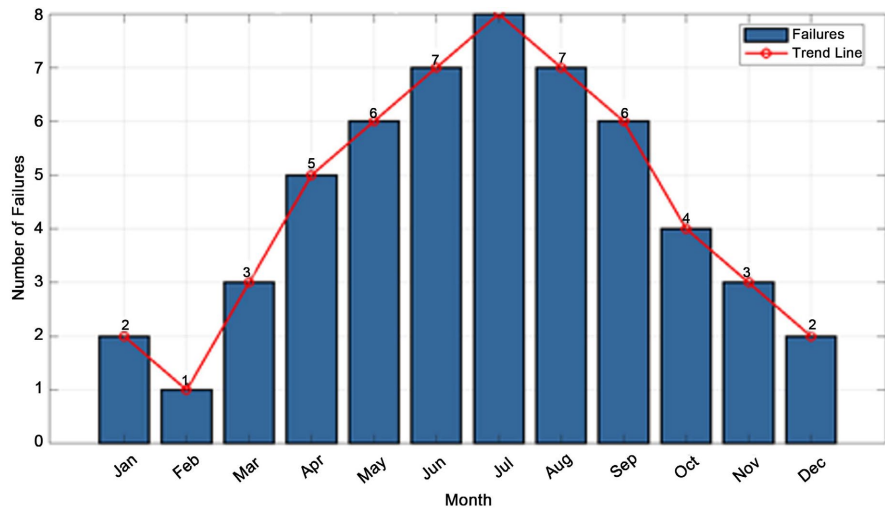


Figure 2. Monthly MV cable failures—Jeddah 2023.

The main causes of MV underground cable failures are shown in **Figure 3**. The most common reason for failure, accounting for 60% (32 of the 54) of all failures recorded, was due to equipment failure, making technical and material degradation problems the primary reliability problem in the network. Unknown faults accounted for 13% (7 events), which may indicate that there is a lack of ability to diagnose fault or carried out incomplete post-fault investigation. The impact of third-party damage and theft was 7% (4 events), showing the impact of external operational disturbances and unauthorized digging on underground infrastructure. Some failures were due to human error, while others were due to poor maintenance, both of which accounted for around 10% of failures, which is significant, particularly because of the need to make sure that the workforce is trained, inspection quality is adequate and maintenance management practices are good. Protection failure accounted for 3% (2 events) of which the protection system was generally effective, but there are still some times when the protection is due to a failure in the coordination or due to a maloperation. In general, the outcomes confirm that network unreliability is a result of internal technical deterioration, not external influences. This discovery highlights the importance of asset condition monitoring, assessment of insulation and better maintenance practices to lower the failure frequency. **Table 2** once again shows that most failures were due to equipment-related causes, accounting for more failures than the rest of the causes put together. The high failure rate for this equipment suggests old equipment and buildup of thermal and electrical stress in the cable system. In the meantime, the failure of identification of unknown faults at 13% indicates that root cause analysis procedures could have a weakness that makes it difficult to develop specific mitigation measures. The relatively low protection failure and bad maintenance percentages indicate that the operation of these systems is moderate, but requires optimization. The table shows collectively that improvement in reliability should concentrate on equipment replacement, condition-based maintenance and improvements in diagnosis rather than simply operational procedures.

Table 2. Primary failure causes (Jeddah MV network 2023).

Failure Cause	Percentage (%)	Count
Equipment Failure	60	32
Unknown Faults	13	7
Third Party/Theft	7	4
Human Error	6	3
Poor Maintenance	4	2
Protection Failure	3	2
Other	7	4
Total	100	54

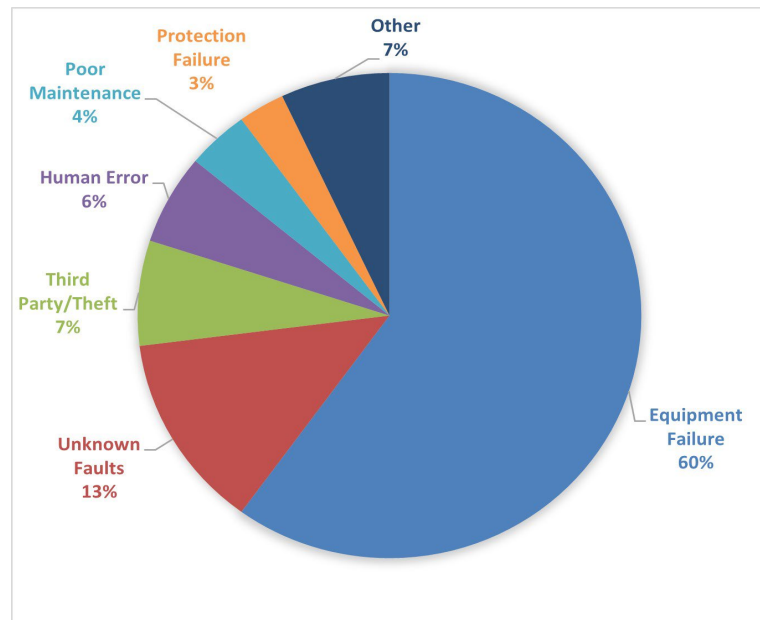


Figure 3. Primary causes of MV underground cable failures.

A detailed breakdown of equipment failures is depicted in **Figure 4**, and it is found that the main technical weakness in the MV cable network is the insulation degradation. The single most dominant failure mechanism was insulation failure, which accounted for 51% (16 events) of all equipment-related incidents. This outcome is in line with what is anticipated for long-term thermal aging, ingress of water, concentration of electrical stress and exposure of the cable to the environment, which affects its insulation. There were 6 cable joint faults (20%) and 5 termination faults (17%). The accessory-related defect makes up 37% of all equipment failures, which is close to the thesis result of about 38%, thus confirming the consistency of the analysis. The findings are evident that one of the most exposed areas of the underground distribution network is the cable accessories. Joints and terminations are especially susceptible to workmanship, installation errors and environmental contamination due to the complex installation procedure and the localized electric field concentration. Therefore, the enhancement of installation standard of accessories, inspection method of accessories, and monitoring method for the temperature of accessories may lead to a great number of reducing failure occurrences, and increase the reliability of the network. **Table 3** shows the significant differences in the distribution of equipment faults with respect to the different components in the cables. Insulation failure was found to be the most dominant cause of failure in the cable due to the aging condition of the cable dielectric materials. The relatively high number of joint and termination failures, however, suggests that accessory reliability plays a significant role to the cable body itself. The remaining 12% classified as other equipment failures also shows that secondary technical failures can make a difference in network disruptions, though on a smaller scale. These results will help in identifying specific maintenance programs to be developed, targeting insulation diagnostics and accessory condition assessment.

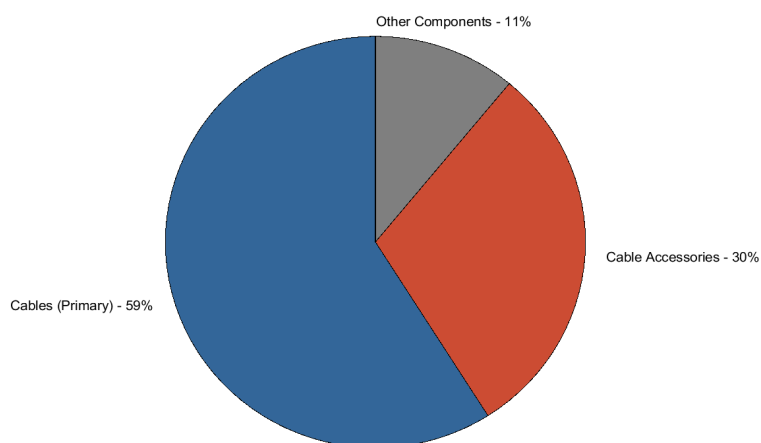
Table 3. Equipment failure breakdown.

Component	Percentage (%)	Count
Insulation Failure	51	16
Cable Joint Fault	20	6
Termination Fault	17	5
Other Equipment	12	5
Total	100	32

Critically, joint and termination defects collectively accounted for 37% of equipment failures, which aligns with the thesis finding of approximately 38%. This highlights that cable accessories represent a significant vulnerability in the network. The data in **Table 4** and **Figure 4** illustrate the contribution of each of the various network components to total failures. Nearly one-third of all outages were due to cable accessories, and primary cable sections accounted for 59% of all failures, indicating that a significant portion of all failures are not associated with the conductor itself. The discovery is especially important since many accessory failures are avoidable by a better installation, regular inspection and better sealing for the environment. The remaining failures occurred with other network components (11%), reinforcing the fact that underground cable systems and their accessories continue to be the biggest reliability challenge. Based on the findings, utilities can see significant gains in improving reliability through accessory modernization and through new quality assurance protocols for installation and maintenance efforts.

Table 4. Component contribution to failures.

Component	Percentage (%)	Annual Count
Cables (Primary)	59	32
Cable Accessories	30	16
Other Components	11	6
Total	100	54

**Figure 4.** Component contribution to MV cable failures.

Because the restoration duration data are non-negative and positively skewed, the Gamma distribution was used to model restoration times. The Gamma model was a good model of the outage restoration behavior in the empirical data with $\alpha = 1.2$ and $\beta = 4.5$. The information in **Table 5** provides a detailed summary of restoration times, which shows a wide range in the time required to restore power after various types of failures. The mean restoration time obtained was 5.56 hours, which is in close agreement with the thesis-reported value of 5.4 hours, thus showing the validity of the statistical approach adopted. Also, this figure is about 79% higher than the national average (3.1 hours) recorded by the SEC, which indicates that the restoration in Jeddah is still significantly below the national average.

Table 5. Restoration time statistics (gamma distribution).

Statistic	Value (Hours)
Mean Restoration Time	5.56
Median Restoration Time	3.97
Standard Deviation	4.88
5th Percentile	0.52
10th Percentile	0.61
25th Percentile	1.85
50th Percentile	3.97
75th Percentile	8.18
90th Percentile	12.27
95th Percentile	15.71
98th Percentile	19.41
99th Percentile	21.42
Minimum	0.50
Maximum	29.65

The mean restoration time of 5.56 hours correlates well with the 5.4 hours mentioned in the thesis, and is about 79% larger compared to the SEC national average of 3.1 hours. The median restoration time of 3.97 hours is less than the mean and thus implies positive skewness in the distribution, meaning that although most failures tend to be resolved promptly, some cases have a long restoration time, which skews the mean upward. **Figure 5** provides the plot of the Gamma probability density function (PDF) alongside the histogram of restoration times.

Figure 6 shows the reliability function $R(t)$ based on the Gamma distribution, which gives the probability that the restoration time exceeds a certain amount t . The steep slope of the reliability curve at the beginning of the graph suggests that a majority of failures are resolved within a short period, while its gradual slope at longer restoration times reveals that some failures persist despite restoration efforts. Clearly, there are both easy and complex faults in the network. The usefulness of

the reliability function $R(t)$ lies in its ability to forecast the occurrence of failures that would require urgent attention by utility companies.

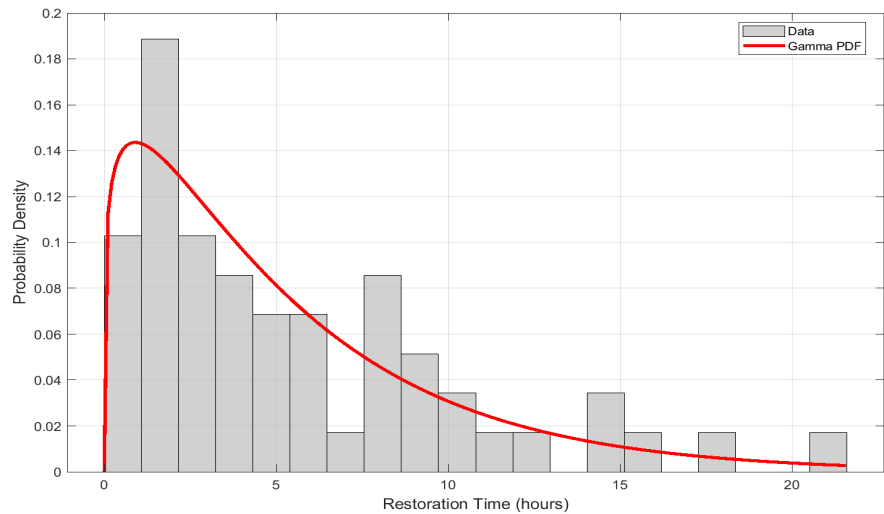


Figure 5. Gamma distribution fit to restoration time data.

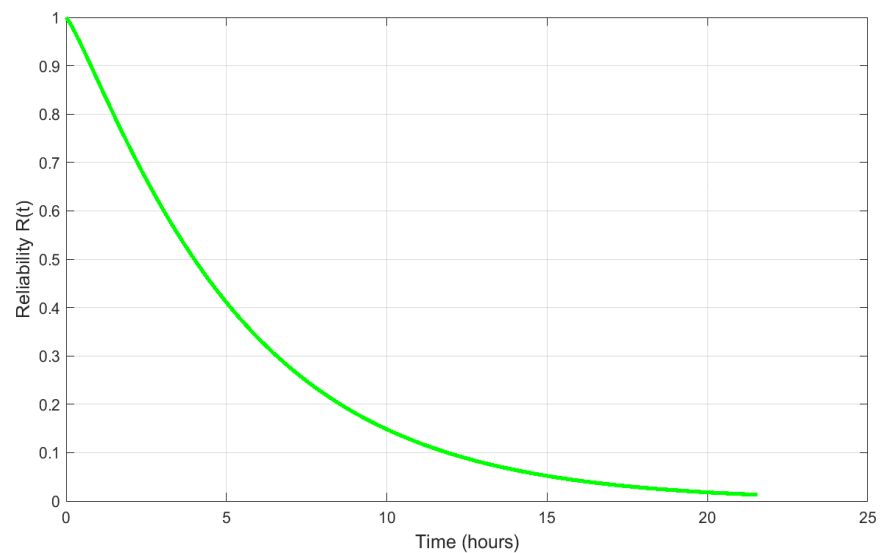


Figure 6. Reliability function (gamma distribution).

The restoration time percentiles have been illustrated in **Figure 7** and have provided an invaluable insight regarding the severity levels of outages. Since the restoration time at 90th percentile is 12.27 hours, this implies that 10% of all outages take more than half a day to recover, which is indeed a considerable amount of disruption caused to customers' service. Likewise, since the 95th percentile is 15.71 hours and 99th percentile exceeds 21 hours, there does exist a small percentage of extremely severe outages. The reasons behind these lengthy periods of outage could be serious damage to the cables, tough digging conditions, failure to locate the fault point, and lack of repair facilities.

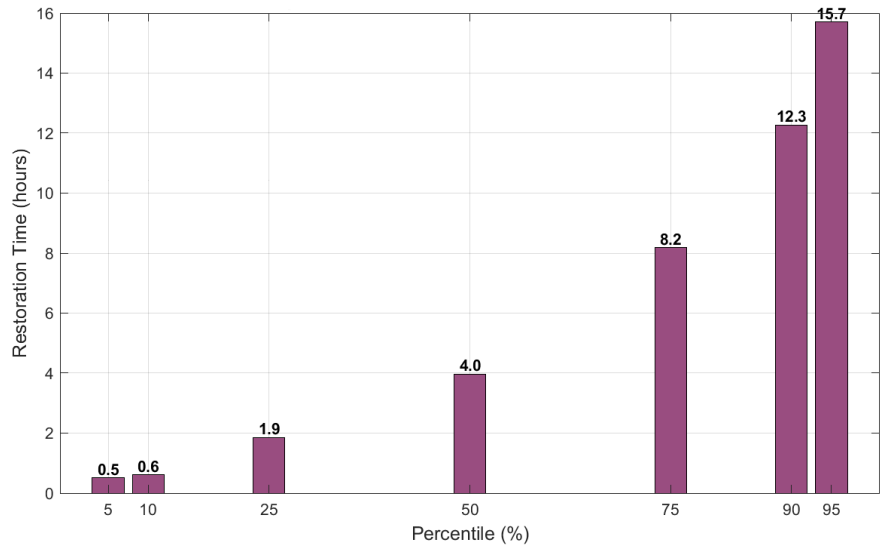


Figure 7. Restoration time percentiles.

The performance of the network in Jeddah in relation to the international NRS 047-1 criteria is shown in **Table 6** and **Figure 8**. As shown from the comparison, the network failed to achieve the maximum restoration allowable times at the levels of 30%, 60%, and 90%. This indicates poor restoration efficiency at normal failure periods. The biggest failure in the restoration period is indicated at the 90% restoration point, where there is an additional 4.8 hours beyond the standard time. From the analysis, it can be seen that while the response to outages is satisfactory initially, it is difficult to deal with more complex situations. Restoration time was only successful at 98%. The implication is that very long outages are well-controlled.

Table 6. NRS 047-1 standards comparison.

Target	NRS 047-1 Standard (Hours)	Jeddah 2023 (Hours)	Status
30% Restored	≤1.5	2.1	EXCEEDED by 0.6 h
60% Restored	≤3.5	5.5	EXCEEDED by 2.0 h
90% Restored	≤7.5	12.3	EXCEEDED by 4.8 h
98% Restored	≤24.0	19.4	ACHIEVED ✓

As seen from **Table 7**, Hera-Feeder-01 (RBW-30) represents the most underperforming feeder in the system since there were 14 outages registered for this feeder in 2023, which means more than two times the mean number of outages observed across the network. Furthermore, **Table 8** shows that this feeder had the highest mean outage restoration time of 17.17 hours, which is twice as much as the mean restoration time observed for the whole network (5.56 hours). The relatively high median outage restoration time (16.12 hours) implies that long-lasting outages are

a common occurrence on this particular feeder. Moreover, the relatively small value of standard deviation (3.61 hours) shows that this feeder consistently performs poorly in terms of restoring its operation.

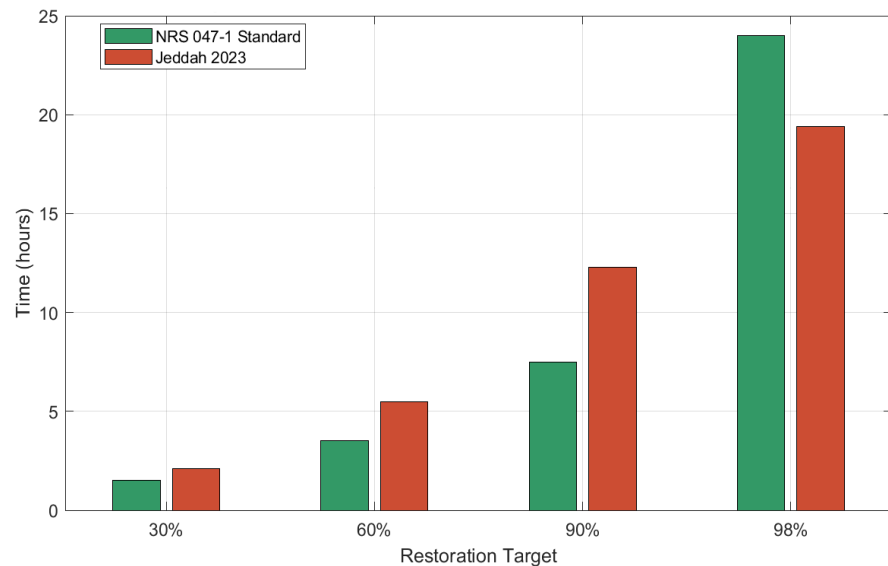


Figure 8. Jeddah vs NRS 047-1 restoration standards.

Table 7. Worst feeder descriptive statistics.

Parameter	Value
Feeder Name	Hera-Feeder-01 (RBW-30)
Number of Failures (2023)	5
Mean Restoration Time	17.17 hours
Median Restoration Time	16.12 hours
Standard Deviation	3.61 hours
Minimum Restoration Time	12.29 hours
Maximum Restoration Time	23.31 hours

Note: The 5 failures for Hera-Feeder-01 in 2023 represent the annual interruption count from SEC logs. The detailed restoration time analysis for this feeder (mean 17.17 hours) is based on the full available restoration dataset for this feeder across multiple years.

The analysis of the Weibull distribution model, which fits the worst feeder data, provides additional information about the restoration process of the feeder. The shape parameter, $\alpha = 1.9$, implies that the repair difficulty of the system increases. This observation is consistent with the aging process of infrastructure systems. The characteristic life parameter, $\beta = 6.3$ hours, means that 63.2% of the restorations will occur within that time. **Figure 9** illustrates the PDF and CDF of the feeder restoration process. Based on the Weibull distribution model, even though there are fast restoration times, many restoration times take more time. The 95th percentile, which is 11.22 hours, proves the high likelihood of service interruptions

on this feeder. This result suggests that Hera-Feeder-01 should be given priority to rehabilitate and replace cables.

Table 8. Weibull percentiles for worst feeder (Hera-Feeder-01).

Percentile	Value (Hours)
5th	1.32
10th	1.93
25th	3.27
50th	5.19
63.2nd (Characteristic Life)	6.30
75th	7.48
90th	9.77
95th	11.22

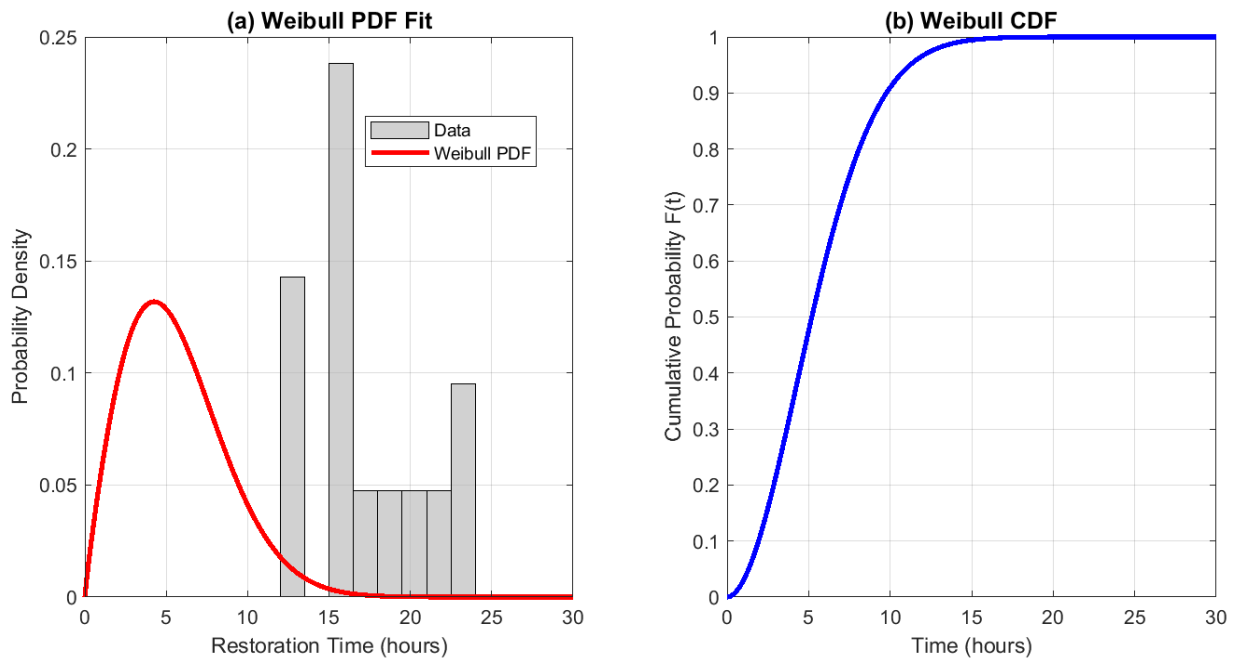


Figure 9. Weibull distribution for worst feeder (Hera-Feeder-01).

Figure 10 below demonstrates a strong positive relationship between temperature and the number of cable failures. The near-linear positive slope shows that the occurrence of cable failures increases as the ambient temperature increases. Therefore, underground cables in the urban environment are vulnerable to climatic changes due to their direct exposure to high temperatures. Increased temperatures increase insulation aging rate, cable joint expansion, and electrical resistance losses, causing higher outage occurrences.

Table 9 below displays the correlation results of the Pearson correlation test between failure frequency and major environmental variables. Temperature dis-

played an extremely high positive correlation with failure frequency ($r = 0.954$). The result reveals a very strong relationship between temperature changes and cable outages. It is evident that increased temperatures are associated with higher insulation breakdown rates, overheating of conductors, and poor quality of cable accessories. On the other hand, load demand recorded a strong positive correlation ($r = 0.942$). The data proves that heavily loaded feeders suffer from higher electric and thermal stresses, resulting in poor system reliability levels. In addition, rainfall recorded a moderate negative correlation ($r = -0.663$). The findings suggest that the failures tend to occur in the hot, dry season than during rainy weather.

All correlation coefficients are statistically significant at $p < 0.01$. But because the temperature and load demand were highly seasonal (both peak at the same time in summer months), these findings do not necessarily mean a causal connection. It might be stated that the correlation observed is to be taken as an indication of a coincidental occurrence rather than as a causal relationship in the climatic context of Jeddah.

Table 9. Correlation analysis results.

Variable	Correlation (r)	Sample Size	p-value	Interpretation
Temperature	0.954	n = 12	<0.01	Strong Positive
Rainfall	-0.663	n = 12	<0.01	Moderate Negative
Load Demand	0.942	n = 12	<0.01	Strong Positive

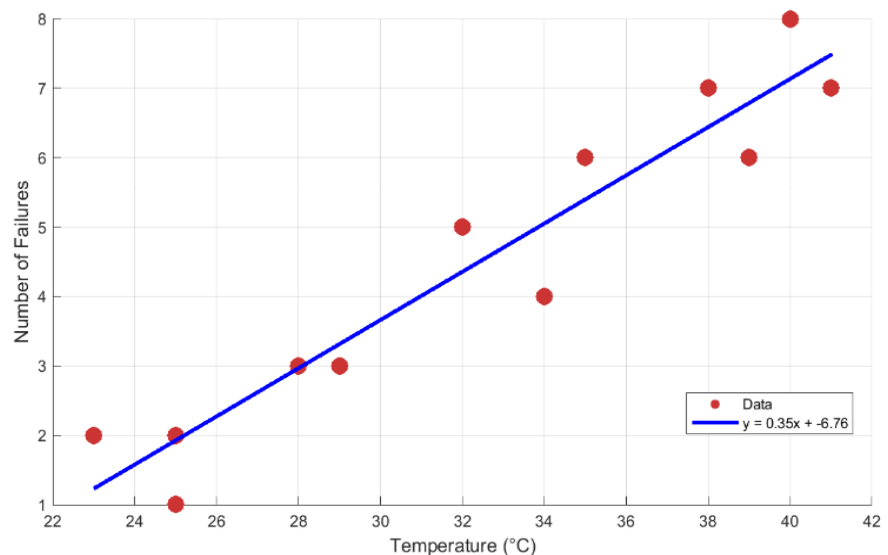


Figure 10. Temperature vs failures correlation ($r = 0.954$).

Figure 11 shows the inverse relationship between rainfall and the number of failures. The regression line suggests that increasing the amount of rainfall decreases the number of failures. Such pattern arises due to the weather conditions in Jeddah

city. The regression equation is:

$$\text{Failures} = -0.24 \times \text{Rainfall} + 5.85$$

That is, the maximum temperatures and loads occur when the city experiences dry hot weather during summer months. As a result, the majority of cable failures are observed under conditions of thermal stress and not moisture. Though rainfall is not always considered preventive, the inverse relationship shows that climatic conditions in this region have a greater influence on failure patterns than rainfall alone.

Figure 12 displays the difference between dry and wet seasons regarding the number of failures. On average, the number of failures in the dry season amounts to 6.3, while during the wet season, only 2.7 per month, which means a 133% increase. The obtained results confirm to a large extent that summer conditions affect network stability more compared to others. In addition, it should be noted that summers are characterized by high temperatures, low rainfall, and high demands on electricity consumption. Therefore, thermal loads are experienced during this time.

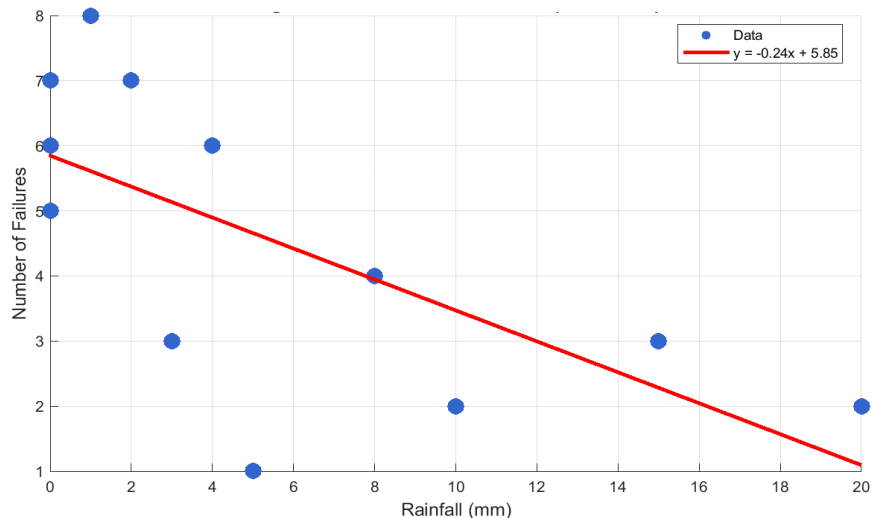


Figure 11. Rainfall vs Failures correlation ($r = -0.663$).

Table 10 and **Figure 13** depict the reliability indicators calculated based on IEEE Std 1366-2012. Since the value of SAIFI is 0.2048 interruptions per customer, we can infer that the number of interruptions per customer is quite small and well within the SEC target of 0.8 interruptions/customer. Similarly, since the value of SAIDI is 1.14 hours/customer, we know that the total duration of interruptions in a year is also well within the acceptable limit of 12 hours/customer. As a result, one could say that the reliability of the network from the customers' perspective is satisfactory. Nonetheless, since the value of CAIDI is 5.56 hours/interruption, it goes against the SEC target of 4 hours, which suggests that the restoration duration in case of an interruption is relatively high.

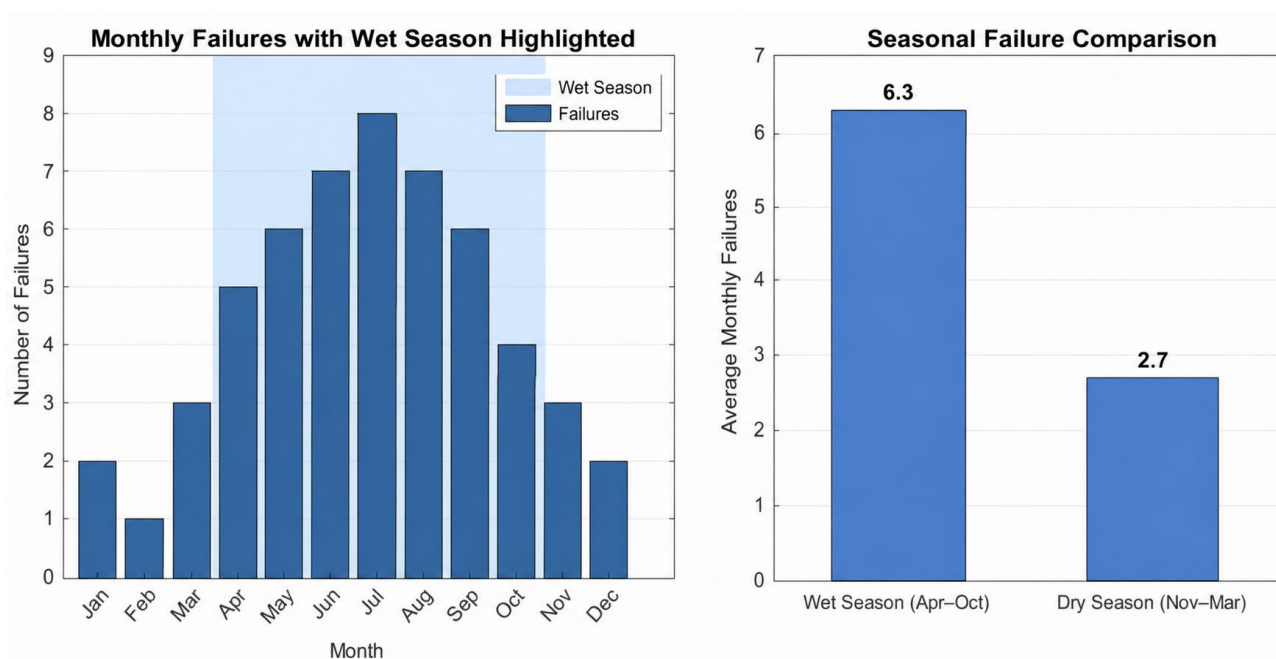


Figure 12. Seasonal analysis of MV cable failures.

Table 10. Reliability indices (IEEE Std 1366-2012).

Index	Value	SEC Target
SAIFI (Interruptions/Customer)	0.2048	<0.8
SAIDI (Hours/Customer)	1.14	<12.0
CAIDI (Hours/Interruption)	5.56	<4.0

Figure 14 and **Table 11** show the distribution of failures for each year among the different feeders under observation. The average failure rate of 4.4 failures per feeder and the standard deviation of 2.55 clearly show the considerable variations in the reliability performance of the feeders. AIRwes-Feeder-01 and AIRhab-Feeder-04 had the highest failure rates with 8 failures each, while the third highest failure rate of 7 failures was recorded for AIRhab-Feeder-02. On the other hand, Hera-Feeder-03 failed once showing considerable improvement in its operation. Such variation in failure rates indicates that the reliability performance of the feeders is highly dependent on certain feeder factors such as age, installation, loading, environment, and maintenance practices.

The annual outage durations for each feeder shown in **Figure 15** illustrate the impact of repeated failures on cumulative operations. In the case of AIRwes-Feeder-01, the cumulative outage duration amounted to 44.5 hours in 2023 or just under two days. Such outage duration can seriously affect consumer satisfaction and industrial productivity. Feeds with both high frequency and high restoration duration of failures are considered to be the most problematic because they contribute to higher outage frequency and outage severity at once. Thus, these feeds should be given priority to rehabilitate their reliability.

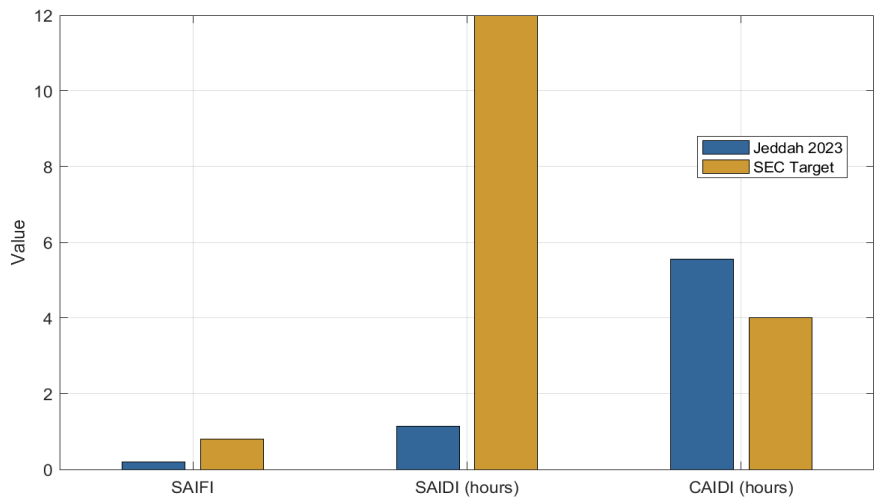


Figure 13. Reliability indices—Jeddah vs SEC targets.

Table 11. Comparative analysis of failure occurrences in distribution feeders (2023).

Feeder	Failures
Hera-Feeder-01	5
Hera-Feeder-02	2
AlRehab-Feeder-01	4
AlRehab-Feeder-02	7
AlRwes-Feeder-01	8
AlRwes-Feeder-02	3
Hera-Feeder-03	1
AlRehab-Feeder-03	4
AlRwes-Feeder-03	2
AlRehab-Feeder-04	8

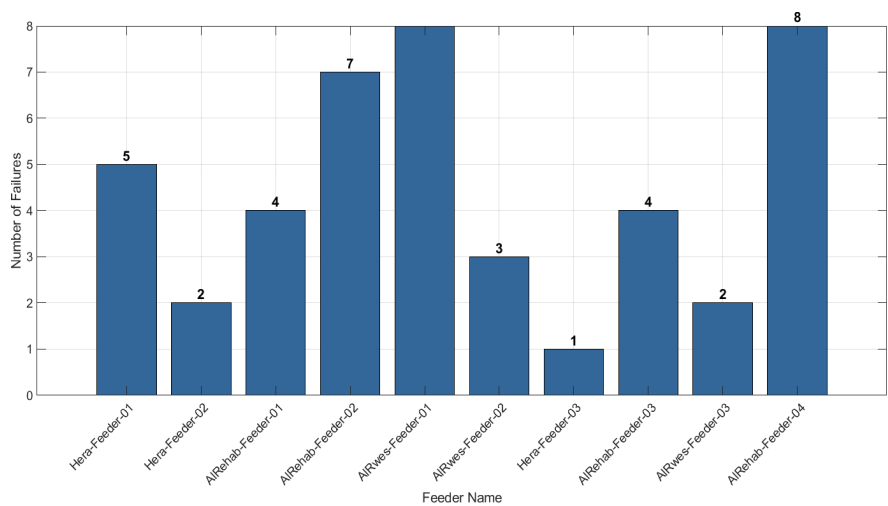


Figure 14. Annual failures per feeder (2023).

Figure 16 and **Table 12** show that the failure rates have been growing in the underground cable network. During six years from 2019 to 2024, the failure rate increased by 25%, reaching the value of 4.0 failures per 100 km, whereas the initial value was 3.2. This trend indicates that the aging process occurs together with additional environmental effects on underground cables. Even though the network length had increased from 11,200 km in 2019 to 12,500 km in 2024, the normalized failure rate had grown, too. Thus, the increasing failure rate cannot be attributed only to network expansion; it rather indicates deterioration of assets.

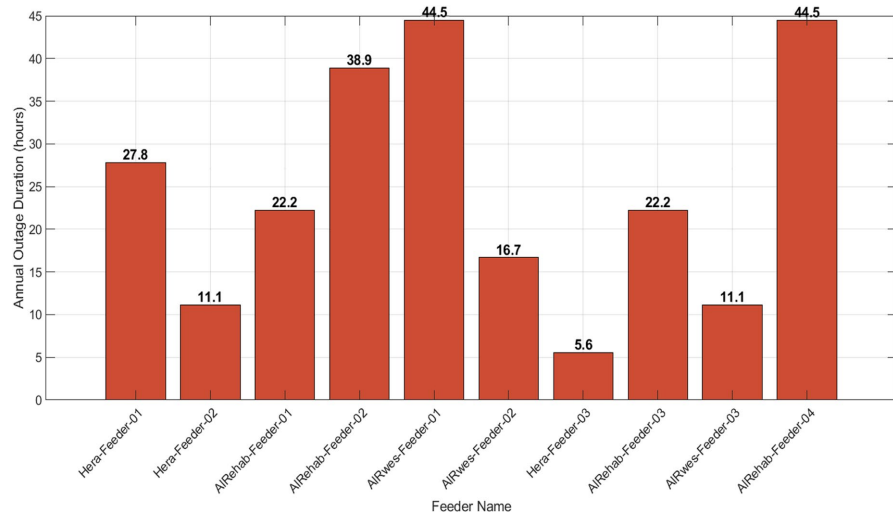


Figure 15. Annual outage duration per feeder (2023).

Table 12. Temporal analysis of cable failures and failure rates in electrical distribution networks (2019-2024).

Year	Failures	Cable Length (km)	Failure Rate (per 100 km)
2019	360	11,200	3.2
2020	400	11,400	3.5
2021	435	11,800	3.7
2022	456	12,000	3.8
2023	479	12,300	3.9
2024	500	12,500	4.0

The comparison between the restoration times of normal and the worst feeder is shown in **Figure 17** in the form of a boxplot graph. It is clear that the worst feeder has both a high median value of restoration time and a very high value of interquartile range as compared to that of normal feeders. This means that not only its average restoration time is relatively higher, but there are also many outliers and extreme values of restoration time in the case of this feeder. In other words, extremely long outages are much common in the worst feeder. Therefore, the problem of reliability associated with this feeder is not only related to frequent failures but also to unusually lengthy repairs.

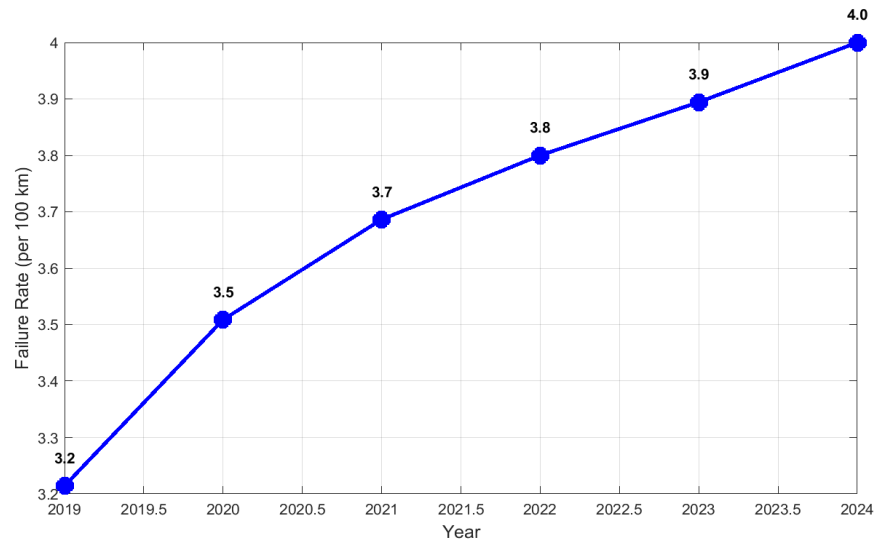


Figure 16. Annual failure rate trend (2019-2024).

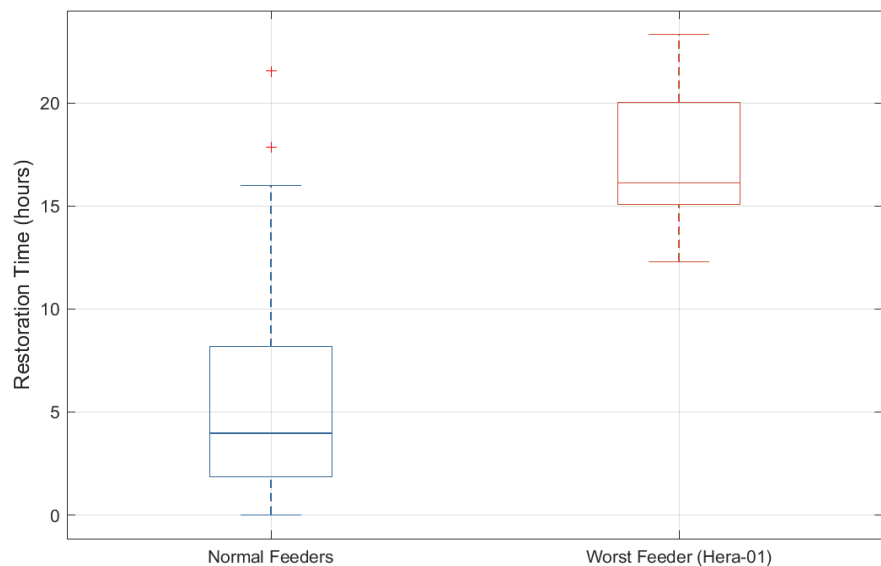


Figure 17. Boxplot comparison of restoration times for normal feeders and Hera-01 feeder.

5. Conclusion

This study conducted a comprehensive reliability assessment of the medium voltage (MV) underground cable network in Jeddah, Saudi Arabia, utilizing five years of operational data from the Saudi Electricity Company (SEC). The principal findings are summarized as follows. First, equipment failures dominate the reliability landscape, accounting for 60% of all incidents. Within equipment failures, insulation breakdown represents the primary mechanism at 51%, followed by cable joint faults (20%) and termination faults (17%). Joint and termination defects collectively constitute 37% of equipment failures, highlighting the critical need for improved installation quality and workmanship control. Second, restoration performance in Jeddah significantly lags behind national and international bench-

marks. The mean restoration time of 5.56 hours is approximately 79% higher than the SEC national average of 3.1 hours. The network fails to meet NRS 047-1 targets for 30%, 60%, and 90% restoration milestones, with the most significant gap observed at the 90% level (12.3 hours vs. 7.5 hours standard). Third, environmental factors exert a strong influence on cable reliability. Temperature exhibits a strong positive correlation with failures ($r = 0.954$), while load demand also shows strong correlation ($r = 0.942$). The failure rate has increased by 25% over six years (2019-2024), indicating cumulative infrastructure aging and escalating environmental stress. Fourth, the worst-performing feeder (Hera-Feeder-01) recorded 5 failures in 2023 with a mean restoration time of 17.17 hours, representing a critical priority for targeted intervention, representing a critical priority for targeted intervention. Based on these findings, the study recommends: 1) implementation of predictive maintenance using partial discharge testing and thermal imaging; 2) climate-adaptive scheduling with pre-rainy season inspections and summer peak load monitoring; 3) mandatory certification for cable jointers and supervisory sign-off on all new joints; and 4) database consolidation integrating GIS and SAP systems for real-time fault tracking. These recommendations provide a practical roadmap for SEC to enhance network reliability, reduce outage durations, and transition toward proactive asset management in Jeddah's challenging environmental conditions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Mavuso, T.B., Wessels, A. and Pretorius, J.H.C. (2015) Reliability Based Planning Methodology for Feeder Automation. 2015 *IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Brisbane, 15-18 November 2015, 1-5. <https://doi.org/10.1109/appeec.2015.7381032>
- [2] Zwane, K.C., Pretorius, J.H.C. and Wessels, A. (2017) Reliability Assessment for Medium Voltage Electrical Network: A Case Study within Eskom Distribution. <https://ujcontent.uj.ac.za/esploro/outputs/conferencePaper/Reliability-assessment-for-medium-voltage-electrical/9910469007691>
- [3] Perović, B., Klimenta, D., Tasić, D., Raičević, N., Milovanović, M., Tomović, M., et al. (2022) Increasing the Ampacity of Underground Cable Lines by Optimising the Thermal Environment and Design Parameters for Cable Crossings. *IET Generation, Transmission & Distribution*, **16**, 2309-2318. <https://doi.org/10.1049/gtd2.12448>
- [4] Klimenta, D., Perović, B., Klimenta, J., Jevtić, M., Milovanović, M. and Krstić, I. (2018) Controlling the Thermal Environment of Underground Cable Lines Using the Pavement Surface Radiation Properties. *IET Generation, Transmission & Distribution*, **12**, 2968-2976. <https://doi.org/10.1049/iet-gtd.2017.1298>
- [5] Duffey, R.B. and Ha, T. (2013) The Probability and Timing of Power System Restoration. *IEEE Transactions on Power Systems*, **28**, 3-9. <https://doi.org/10.1109/tpwrs.2012.2203832>
- [6] (2005) NRS 048-2:2025, Edition 5: Electricity Supply—Quality of Service Standard. National Energy Regulator of South Africa (NERSA). <https://www.nersa.org.za/file/5883>

- [7] Perović, B.D., Tasić, D.S., Klimenta, D.O., Radosavljević, J.N., Jevtić, M.D. and Milovanović, M.J. (2018) Optimising the Thermal Environment and the Ampacity of Underground Power Cables Using the Gravitational Search Algorithm. *IET Generation, Transmission & Distribution*, **12**, 423-430.
<https://doi.org/10.1049/iet-gtd.2017.0954>
- [8] Shazly, J.H., Mostafa, M.A., Ibrahim, D.K. and Abo El Zahab, E.E. (2017) Thermal Analysis of High-Voltage Cables with Several Types of Arrangements and Configurations in the Presence of Harmonics. *IET Generation, Transmission & Distribution*, **11**, 3439-3448.
- [9] Zhang, J.X., Wang, B., Ma, H.R., He, Y.F., Wang, H.X. and Zhang, H.Q. (2025) Reliability Evaluation Method for Underground Cables Based on Double Sequence Monte Carlo Simulation. *Processes*, **13**, Article 505.
- [10] Arias Velásquez, R.M. (2025) Transient Analysis of Temporary Overvoltage and Cable Faults in Underground Medium Voltage Systems. *Results in Engineering*, **25**, Article ID: 103875. <https://doi.org/10.1016/j.rineng.2024.103875>
- [11] Rafati, A., Mirshekali, H., Shaker, H.R. and Bayati, N. (2024) Power Grid Renovation: A Comprehensive Review of Technical Challenges and Innovations for Medium Voltage Cable Replacement. *Smart Cities*, **7**, 3727-3763.
<https://doi.org/10.3390/smartcities7060144>
- [12] Clavijo-Blanco, J.A., González-Cagigal, M.A. and Rosendo-Macías, J.A. (2024) Statistical Characterization of Reliability Indices in Medium Voltage Networks Using a Monte Carlo-Based Method. *Electric Power Systems Research*, **234**, Article ID: 110585.
<https://doi.org/10.1016/j.epsr.2024.110585>
- [13] Arias Velasquez, R.M., Gonzales-Condori, E.G. and Velarde Loayza, P.E. (2023) Enhancing Medium Voltage Underground Circuit Design: Assessing Limitations, Thermal Influence, and Accurate Modelling. *Results in Engineering*, **20**, Article ID: 101552.
<https://doi.org/10.1016/j.rineng.2023.101552>
- [14] Banasik, K. and Chojnacki, A.L. (2024) Impact of Weather Conditions on Reliability Indicators of Low-Voltage Cable Lines. *Electricity*, **5**, 606-621.
<https://doi.org/10.3390/electricity5030030>
- [15] Mesino, E.G., Caicedo, J., Mamaní, M., Quete, D.R., Piamba, A.C., Gómez, D.G., et al. (2023) Condition Assessment of Medium Voltage Assets: A Review. *Advances in Science, Technology and Engineering Systems Journal*, **8**, 35-54.
<https://doi.org/10.25046/aj080505>
- [16] Bazargur, B., Bataa, O. and Budjav, U. (2023) Reliability Study for Communication System: A Case Study of an Underground Mine. *Applied Sciences*, **13**, Article 821.
<https://doi.org/10.3390/app13020821>
- [17] Ellinas, E.D., Lianos, G., Kontargyri, V.T., Christodoulou, C.A. and Gonos, I.F. (2024) Performance Evaluation of Grounding Systems of Medium-Voltage Concrete Poles: A Comprehensive Analysis. *Applied Sciences*, **14**, Article 3758.
<https://doi.org/10.3390/app14093758>