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Investigating Climatic Impacts on Electric Transmission Infrastructure in Developing Countries: A Case Study of Pakistan (2020-2023)

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ABSTRACT

Pakistan's energy systems are under increasing stress due to growing demand and the frequency of climatic events. Pakistan's case is of particular interest due to its diverse climatic zones, heavy reliance on centralised energy systems, and mounting electricity demand. The paper examined how Pakistan's electrical power transmission systems are impacted by its climate, exploring vulnerabilities and resilience through a mixed-methods approach with a convergent design for comprehensive analysis and deeper understanding. Statistical analysis revealed significant relationships between climatic disruptions on the power system. Resilience calculated by resilience lost index (RLI), estimated down time index (EDTI), mean time to repair (MTTR) and mean time between failures (MTBF) showed a significant loss of resilience due to climatic disruptions. Proportional and qualitative analysis nuanced similar results. The paper highlighted need for enhanced planning, investment in climate-resilient infrastructure, technological incorporations and proactive policy measures to mitigate environmental risks, vulnerabilities and future endeavors in the domain for understanding the behavior of a system.

Keywords: climatic impacts; energy security; interdisciplinary approach; sustainable development; transmission systems.

INTRODUCTION

Energy security is increasingly becoming a strategic instrument in global power politics, where nations leverage energy resources and infrastructure as tools of coercion to achieve geopolitical objectives. Major energy-producing states often use control over energy supply chains, such as oil, gas and electricity, as leverage to influence the policies and actions of energy-dependent nations. Energy embargoes, pricing manipulations and selective supply are employed as tools of economic and political pressure. The 1973 oil embargo by OPEC and, more recently, Russia's control over Europe's gas supplies during the ongoing Ukraine-Russia conflict underscore the centrality of energy in global power dynamics.

Pakistan, being situated at the crossroads of energy-importing and transit states like TAPI (Turkmenistan, Afghanistan, Pakistan and India gas pipeline) or CASA (Central Asia South Asia power project), etc., energy remains not just an internal concern but a factor that shapes countries' geopolitical standing. Pakistan's reliance on international partnerships such as those with China and Arab countries highlights the delicate balance between cooperation and dependency in the energy domain. The implication of energy security for Pakistan's socio-economic development cannot be undermined. As one of the most populous republics worldwide, Pakistan's demand for electricity has increased exponentially over the past few decades. A secure and resilient energy sector is thus pivotal for the state, not only for mitigating vulnerabilities to external coercion but also for maintaining sovereignty, growth and asserting influence in complex international security dynamics, particularly in geographical zones like South Asia where nuclear armed states in close proximities are locked in perpetual state of security dilemma.

As electrical energy is a crucial core component of countries energy security, which is pivotal for Pakistan, the state has been struggling for since long time in the electrical energy domain to resolve the challenges and improve the performance. The structure of Pakistan's electric energy systems is deeply interconnected where disruptions in one component can trigger cascading effects across the entire system causing a series of blackouts/disconnects across the country crippling all the activities. Transmission systems which are often underappreciated in wider discourses on energy security are taken as referent object in the study, the national electric transmission system of Pakistan connects generation sources with regional distribution companies through a widespread network of high-voltage transmission lines of 500kV and 220kV, along with various grid stations dispersed across the landscape thus acting as Jesus-nut for the electrical systems.

Understanding the vulnerabilities in Pakistan's electric transmission sector is critical for understanding the country's energy security challenges. Despite its very important role, systemic inefficiencies in the transmission sector impair the sector's performance, and with significant risks to national resilience and security. During the last five years alone, losses in the electric transmission and dispatch segments combined to approximately 500 billion Pakistani rupees (approx. 1781 million USD), 3,500 gigawatt-hours of energy were lost. The transmission sector serves as a major contributor to the circular debt crisis of Pakistan, which today in 2025 stands at almost 2.5 trillion Pakistani rupees (approx. 8909 million USD) (Source: National Electric Power Regulatory Authority (NEPRA) annual report 2024).

These impacts contribute to a trillion rupees circular debt in the energy sector, forcing the country to import electricity and exhibit energy dependency that, in return, inflates foreign exchange pressures, shaping trade relations and undermining the economic security of Pakistan. Furthermore, rising energy import bills to be paid in foreign currency, i.e., dollars, result in increasing Pakistan's trade deficit, weakening fiscal stability and sovereignty. Hence, the climatic impacts have roots in grave problems in societal, economic, environmental, human-centric security and states' political and regional standings in the region. Pakistan is one of the most affected nations in the world concerning climate change due to extreme climatic settings, which are persistent in the diverse climatic landscape of the country. [refer to Appendix 2]. Extreme efforts are required by policymakers, stakeholders and systems operators to cater for the

diverse climatic impacts. One of the suggestions is decentralised policies and measures applicable to a particular geographic landscape the system operates.
As noted in "Redesigning the Future" 1974, Prof. Russell L. Ackoff has stated, *"We have also come to realize that no problem ever exists in complete isolation." The reason is that every problem affects other problems, and so, every problem is a single problem of a set of interrelated problems*" As the electric transmission segment serves as a critical component within the energy sector, many of technical and non-technical factors impact the operational efficiency of the transmission systems however this study focuses on the challenges faced by Pakistan's electric transmission sector due to climatic impacts from 2020 to 2023. This study aims to conceptualize/highlight the role of climatic impacts on Pakistan's electric energy transmission department.

LITERATURE REVIEW

The connection between climate change and energy security stances very complex interactions. According to Iyke (2023), there is a clear finding of how climate change increases the risk of energy security, although the same can be mitigated, especially among countries with lower corruption & slower population growth, by clean energy investment. In the short to medium term, climate policies can reduce risks & increase resilience to energy systems, rendering energy supply less dependent upon fossil resource availability & GDP growth (Cherp et al., 2016). The effect of climate variables on electricity demand is seasonally and regionally dependent, and developing countries may become more sensitive, above all as the consumption of electricity develops. Energy production is also sensitive to climate, especially for so-called natural resources related to power production like solar panels and wind turbines (Fadelli & Kalashnikova, 2020).

It has been demonstrated that climate impacts the reliability and performance of electrical transmission systems. Overhead transmission lines tend to suffer more outages and failure rates as a result of extreme weather events (Kondrateva et al., 2020). Insulator performance may degrade due to climatic factors such as wind, lightning and pollution, which could double the risk of back flashover in HVDC systems (Wadie, 2023). Moreover, artificial intelligence applications are being explored for softening the impacts of climate on power systems. With continued changes in climate impacting the power system, it is important to incorporate these effects into models characterizing decarbonization pathways and transmission system adaptation to future environmental conditions (Jakhar & Raj, 2023).

Extreme weather events, exacerbated by climate change, pose significant threats to power transmission systems. These events, including storms, floods, and extreme temperatures, can damage infrastructure and cause widespread outages (Abdel-Fattah & Sigurðsson, 2023; Entriken & Lordan, 2012). Climate poses significant challenges to electricity transmission infrastructure. Rising temperatures are projected to reduce transmission capacity by 1.9-5.8% and increase peak electricity demand by 4.2-15% by mid-century (Bartos et al., 2016). These impacts could lead to substantial increases in infrastructure costs, with annual climate-related expenditures potentially rising by up to 25% (Fant et al., 2020). Geophysical hazards such as storms, floods, and earthquakes can severely damage transmission networks, causing widespread blackouts (Komendantova, 2016). Extreme weather events like storms, floods, and earthquakes can severely impact electrical transmission systems in South Asia and globally. Floods and heavy rainfall can damage overhead lines, underground infrastructure, and transformer stations, leading to widespread power outages (Komendantova, 2016; Souto et al., 2022).

Joshi et al. (2021) discuss the need for improved reliability and resilience in South Asia's power sector, driven by increasing electricity demand and the integration of renewable energy sources, while also addressing the challenges posed by extreme weather events. Jakhar and Raj (2023) review the broader implications of climate change on power systems, noting that environmental changes affect power quality and transmission, and advocate for incorporating these factors into decarbonization models. However, climate hazards pose risks to electricity networks, with even small increases in wind storm intensity potentially leading to significant demand losses (Fu et al., 2018). Electricity transmission in China has significant environmental impacts, including water consumption and carbon emissions. From 2010 to 2016, carbon emissions and water consumption related to transmitted electricity increased substantially (Li Liu et al., 2020).

In India, seasonal changes and extreme weather conditions affect corona losses in high-voltage transmission networks, with varying impacts across different regions (Ghosh et al., 2018). Indonesia's experience demonstrates that weather-related disruptions primarily affect distribution networks, while transmission networks are vulnerable to lightning strikes (Handayani et al., 2019). These impacts result in financial losses for utilities and necessitate adaptation measures. In India, transmission constraints limit inter-regional electricity trade, reducing market competitiveness during congested hours. Expanding transmission capacity could significantly increase market surplus and improve overall efficiency in the power sector (Ryan, 2017). These findings underscore the importance of climate-resilient infrastructure and grid integration for reliable electricity supply.

THEORETICAL BACKGROUND

General Systems Theory (GST) pioneered by Prof. Ludwig von Bertalanffy, is a framework that highlights that "*systems must be understood not only in terms of their components but also in relation to the purpose they serve*". The paragraph, cited in Joe Kelly (1969), Organizational behaviour. p. 270. "*A problem never exists in isolation; it is surrounded by other problems in space and time. The more of the context of a problem that a scientist can comprehend, the greater are his chances of finding a truly adequate solution*". Russell L. Ackoff (1971) Towards a System of Systems Concepts In: Management Science. Vol.17. pp.661-671. Wrote "*The systems approach to problems focuses on systems taken as a whole, not on their parts taken separately. Such an approach is concerned with total-system performance even when a change in only one or a few of its parts is contemplated because there are some properties of systems that can only be treated adequately from a holistic point of view. These properties derive from the relationship between parts of systems: how the parts interact and fit together*".

If analyzing the power transmission systems with respect to the Russell Ackoff framework, these components work together toward the goal of delivering reliable electricity. The system is "purposeful" as described by Russell Ackoff, meaning it uninterruptedly interacts with external inputs such as energy demand and climatic surroundings and adjusts its operations to maintain functionality. Pakistan's power transmission is taken as a system, then climate acts as an external input that disrupts the system's equilibrium. Both GST and Russell Ackoff underline the role of feedback loops in system behaviour. These loops either stabilize or destabilize a system in response to external inputs. Climatic stressors create positive feedback loops by intensifying infrastructure weaknesses as each event causes more damage, increasing the vulnerability to the next disruption. Negative feedback mechanisms, such as improved maintenance protocols or climate-resilient designs or technological incorporations, help the system return to equilibrium.

MATERIALS AND METHODS

a. Study design, data collection, scope and limitations.

This study adopts a mixed-methods qualitative and quantitative approach. The design used was a convergent mixed method. Data used in quantitative research is primary and collected from fieldwork. The data collected for the qualitative approach involved interviews, literature review and scanning of records. Data was grouped into three broader segments: North, Centre and South. This ensured a comprehensive sample for representing the issue. The study spans the evaluation from 2020-2023, ensuring enough data to identify trends and patterns.

This study used primary data obtained from observations, records and semi-structured interviews/surveys. The set of data is based on an exhaustive and extensive survey of the location, the geographical locations included for collection were in three groups: north, center and south. The cities included were 50 from all four provinces of Pakistan, and the setup studies in those locations were 82. In metropolitan or big cities, more than one setup was taken into consideration, keeping in view the importance of the installation.

In study, data of National Disaster Management Authority, Provincial Disaster Management Authority, Baluchistan Irrigation Department, Ministry of Climate Change, Ministry of Finance, Regional Crime data by Police, data by Pakistan Bureau of Statistics, data on South Asian Terrorism portal and Official NEPRA reports was used as secondary data with an effort to conduct and record opinions of authorities through recorded interviews. The study aimed only at the transmission segment of the energy sector, and Generation, Distribution, Renewable energy, Clean Energy sources, etc., remained untouched to limit the study in certain boundaries. In order to view the system as in holistic approach, future endeavours in unexplored arenas will be fruitful.

One of this study's limitations is the absence of comprehensive data sets on financial and physical efforts undertaken or the cost of efforts like loss of human lives and finances incurred on operations or efforts/energies invested in these domains due to certain policies and restrictions on sharing of such data by the relevant authorities. Hence concept remains to develop relationships between climatic impacts and energy sector.

The data which was collected involved five main climate impacts, i.e., heavy rain/floods, wind/hurricanes, heatwaves, fog/smog, and heavy snowfall. The environmental conditions like landslides, earthquakes, impacts of weak structures (theft at electric pylons weakens the structure and on slight disturbance of climate, the pylon collapses) were not catered in the data sets. The impacts are all termed as disruptions to the system; the disruption here means the anomaly created from default settings, like, for example, a half-collapsed pylon or a sagging conductor due to hurricane impact on the neighbouring structure, etc. The time taken to restore the system depends largely on the environmental contexts, logistical aspects, terrain and accessibility, etc., as in flood conditions, time may be prolonged to weeks. Hence, the time taken on average for the restoration of the system to default settings is termed as resolution time. The attributor conditions, like heat waves, in addition to putting stress on the system, also couple with increased demand for electricity, causing the system to have frequent disruptions. these attributing conditions were not catered for in the analysis of data.

b. Analytical framework

Total disruptions to the system were noted, and those caused by climatic impacts. Causes of disruptions were segregated as climatic, technical or other impacts, etc. and analysis was made after layering the data collected. In quantitative analysis, data was analyzed in terms of graphical representation and by using statistical models through statisty app tool. However, for authentication of efforts, proportion analysis and system metrics were calculated on available data sets to see the impact on the resilience of the system. Additionally, case studies and interviews from key stakeholders and authorities were performed with narrative analysis instead of coding or thematic analysis to get a deeper understanding, like the nexus of climate with other variables in the system. Resilience metrics were calculated to measure system performance and reliability: FOR (Frequency of Failures). CADI (Customer Average Duration Index) and MTTR (Mean Time to Repair). MTBF (Mean Time Between Failures). EDTI (Electricity Distribution Index). Availability Metrics. RLI (Reliability Index).

RESULTS AND DISCUSSION

Statistical analysis shows important patterns in power interruptions, along with how long they take to fix and how stable the system remains. (Complete Stata Data as Appendix I)

Climate-Induced Disruptions: The power system saw 115.17 climate-related disruptions each year, but dealt with 163.67 disruptions from other sources every year. Our findings show that the system suffered 278.83 separate disturbances annually. The system spent most of its repair hours fixing climate-induced problems, reaching an average of 3,612.17 hours per year and a record high of 9,158 hours when conditions were at their most extreme. System Variability and Trends: The large standard deviations, 61.93 for climate disturbances and 80.13 for other disruptions, show widespread differences in how response and resolution systems work. The large number gap demonstrates that environmental damage and recovery efforts swing dramatically between different years, showing unstable performance over time.

ANOVA show an effect size (η^2) of 0.57, meaning 57% of the variation in results can be explained. This is considered a large effect. The F-statistic is 17.93, and the p-value is again less than 0.001, which means the factor being tested has a significant impact on results. Cohen's f^2 is 1.3, which is well above the threshold for a strong effect, indicating a very large effect size. Welch's ANOVA F-statistic is 14.62, with a p-value of less than 0.001, confirming that the results are statistically significant. Repeated Measures ANOVA effect size (η^2) is 0.69, indicating 69% of the variability in results can be attributed to the factor tested. This also represents a large effect. The F-statistic is 25.02, with a p-value of less than 0.001, which again shows a strong, significant effect. All of the tests (ANOVA, Welch's ANOVA) show strong statistical significance with large effect sizes, indicating that factors being tested have a substantial impact on outcomes.

Proportional analysis: shows the proportion of disturbances to the system caused by climatic reasons from 2020-23. Figure 1 below is showing year-wise trend of climate-related disruptions on the system in a graphical representation. Year-wise proportion of climatic disruptions on total disruptions is graphically represented in Figure 2 below. Factors of physical security & technical disruptions, also aging infrastructure, are considered in the total year-wise proportion of climatic disruptions on total disruptions.

Year	North	Center	South
2020	45.76%	39.81%	51.83%
2021	36.50%	35.29%	47.11%
2022	36.08%	43.41%	43.42%
2023	31.29%	37.96%	40.85%

Table 1: Proportion = Disruptions due Environmental Reasons / Total Disruptions x 100

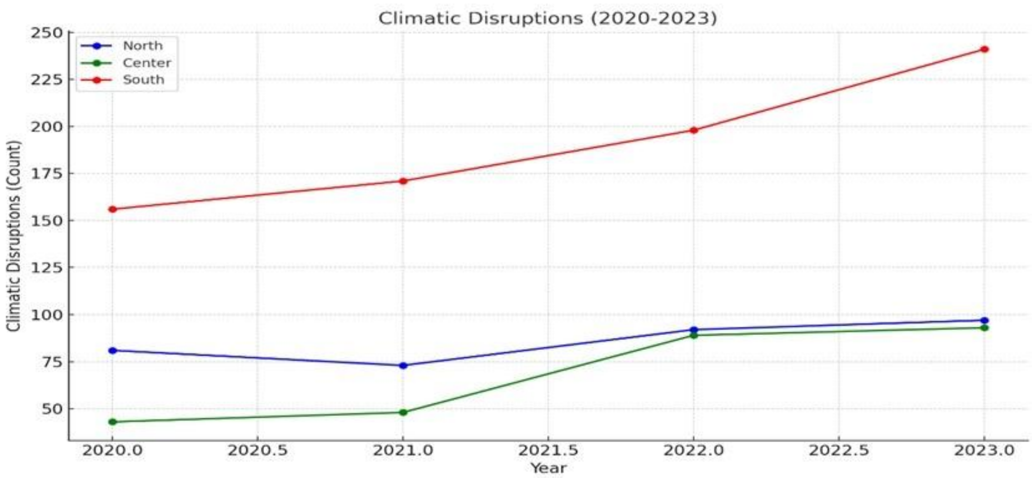

Figure 1 Yearly Climatic Disruptions

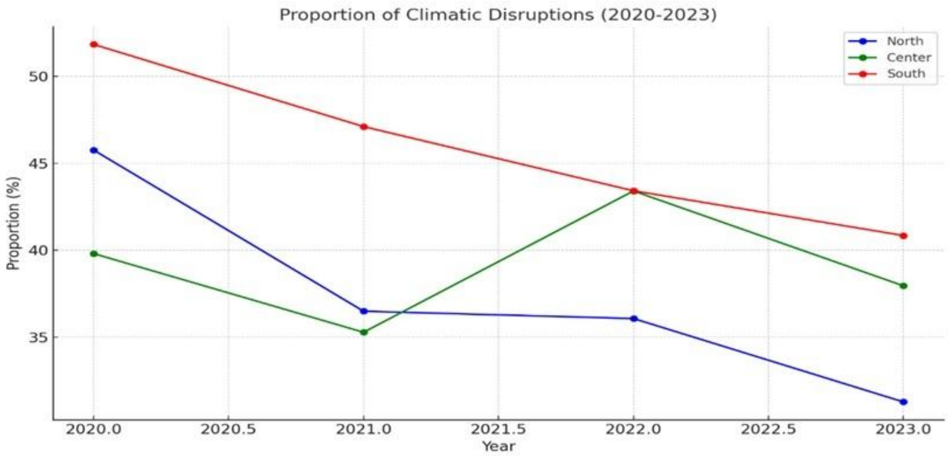

Figure 2 Yearly Proportionate of Climatic Disruptions

Yearly Trends: The percentage of incidents caused by climate effects decreased through the period 2020 to 2023. The North region witnessed a decline in disruptions from 45.76% in 2020 to 31.29% in 2023. The lower disruption numbers may not prove better system performance because the actual increase in ageing infrastructure failures and technical problems needs examination.

Regional Disparities: During 2020, the South region faced climate disruptions at 51.83% while the Central and Northern regions maintained lower climate-impact percentages. Problems across different regions show we need specific plans to handle environmental issues in each area.

Proportion analysis reveals important trends in climatic disruptions across regions. South consistently experiences the highest number of disruptions in its absolute count and proportion are steadily increasing, though the proportion decreases slightly after 2021. This indicates that while total disruptions rise in South, other factors such as technical, aging infrastructure, or security disruptions are contributing more heavily, as demonstrated by the author of this paper earlier in the work published in Pakistan Social Sciences Review (Mohsin & Kazmi, 2024, p.781). In contrast, North and Center show modest increases in the number of disruptions, with North seeing a steady decline in proportion, suggesting a shift in causes of disruptions away from climatic reasons in recent years. The climate is also having a unique nexus with physical security incidents in the country, as demonstrated by the author of this paper earlier in work published in Asian Development Studies (Mohsin & Kazmi, 2024, p. 1368).

Performance and Resilience metrics

MTTR (Mean Time to Repair): Average time taken to repair a fault and restore the system to normal operation. This metric depicts the efficiency of the repair and restoration process after a disruption. Lower MTTR indicates quicker repairs, enhancing resilience. MTTR = Total Time Consumed in Year / Total Number of Disruptions.

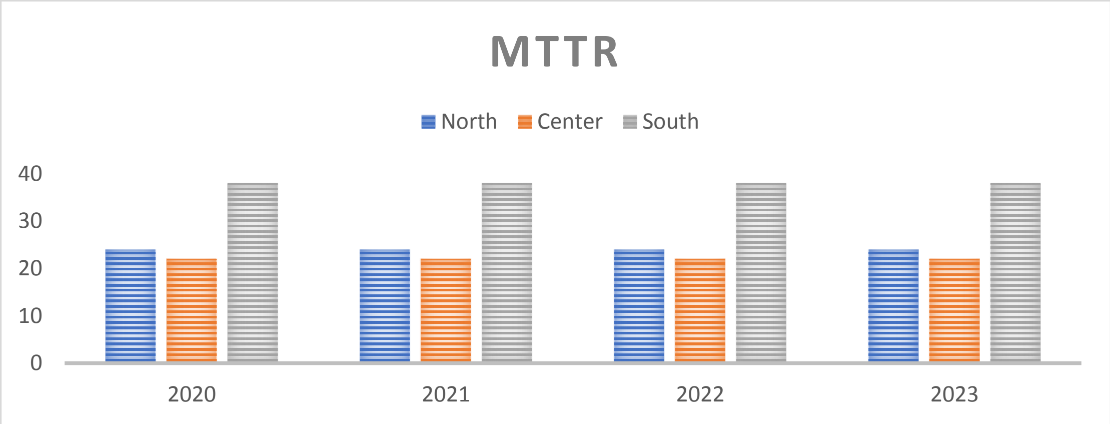

Figure 3

MTBF (Mean Time Between Failures) is the average time between two successive failures or disruptions. MTBF gives insight into a system's reliability by indicating how long the system operates without failure. Higher MTBF values indicate a more reliable and resilient system. MTBF = Total Operating Time / Number of Disruptions.

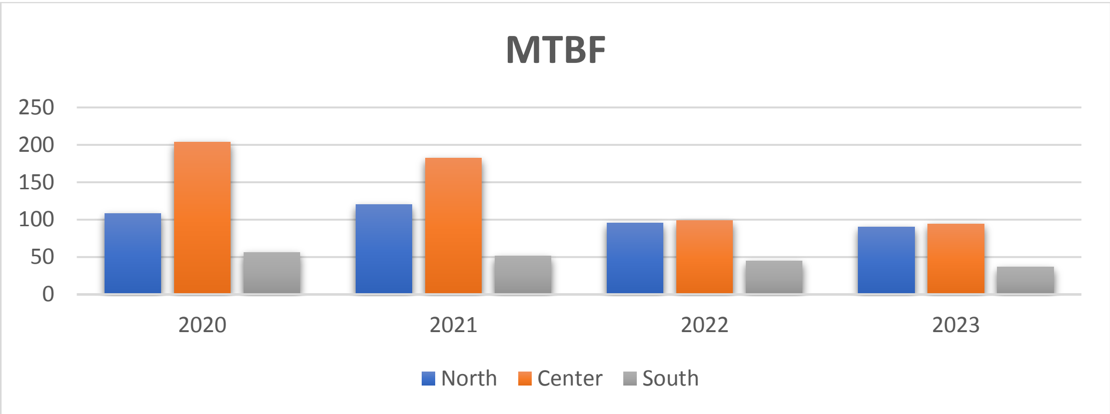

Figure 4

EDTI (Expected Down Time Index): Predicts the expected downtime of a system based on historical failure and repair data. This metric gives insight into how long the system might be down in the future EDTI = MTBF × (1− MTTR/ MTBF).

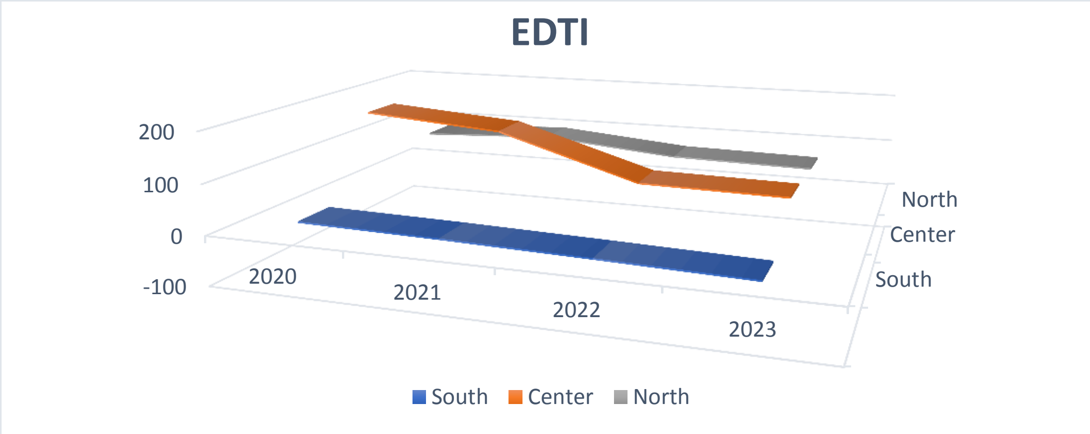

Figure 5

Availability (A): The proportion of time the system is available and operational out of total time. This metric shows how often a system is available and can serve to its full potential. Availability =MTBF/ MTBF + MTTRA.

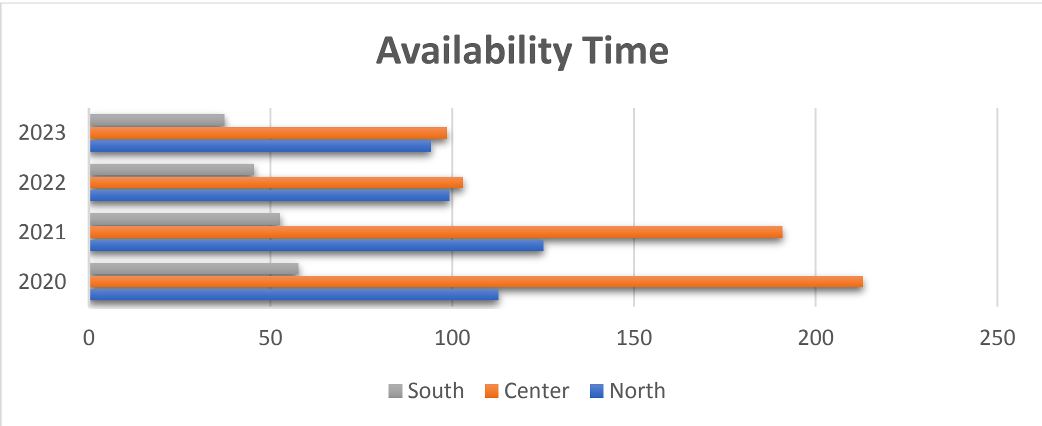

Figure 6

Resilience Loss Index (RLI): This metric attempt to quantify how much resilience a system has lost over time due to disruptions. It gives an idea of the proportion of time the system is compromised or down due to issues. A higher value indicates greater loss of resilience. RLI = Total Time Consumed in Disruptions / Total Available Time

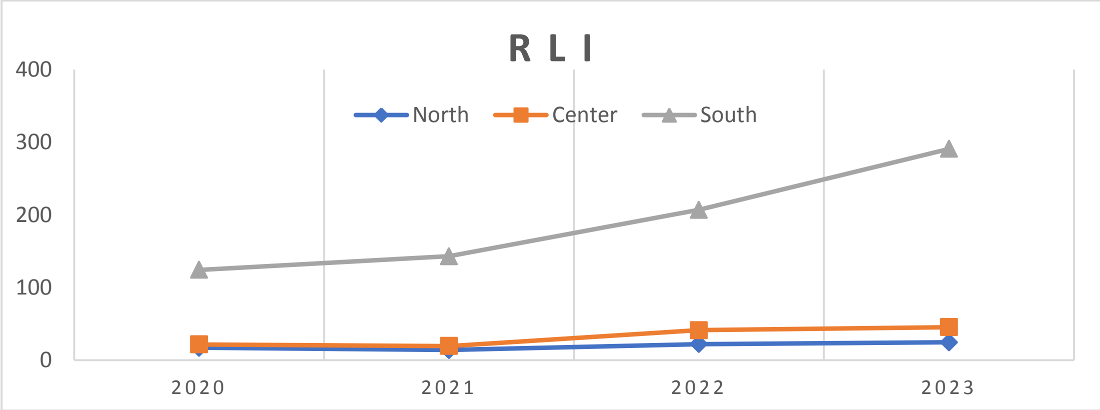

Figure 7

System metrics clearly showed that while climatic impacts are on the rise, so does it affect the transmission system and have a significant impact on the resilience of the system. MTTR showed higher numbers due to the context of problems like floods, snow, etc., which cannot be rectified in short intervals. MTBF and EDTI are predicting trends for the future in terms of climatic impacts. Availability and RLI clearly show the impact on the resilience of the system by climatic factors.

Outcomes of case studies

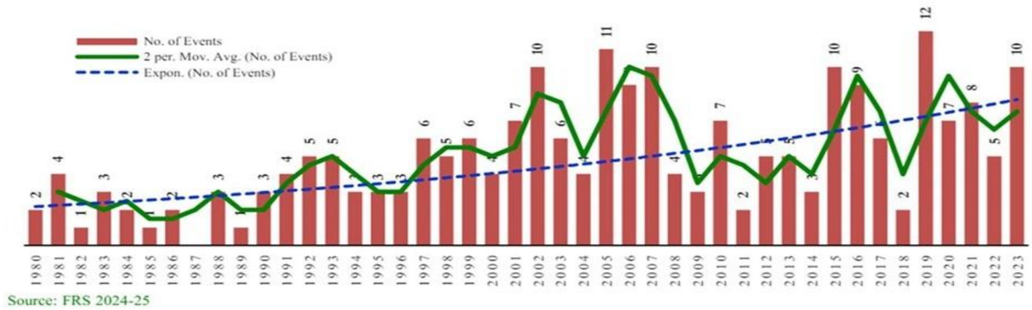

Figure 8

Climatic events continue to increase at Pakistan (Figure 8. Number of major climatic events at Pakistan increasing trend: Source, FRS 24-25) which significantly impact the resilience and reliability of the system, few of the events are mentioned below as case studies to comprehend the magnitude and impact of these disturbances to the system. To know the historical pattern and reasons total of 10 case studies were considered meriting inclusion in the domain of the paper among them crux of few studies is illustrated in table below,

Table 2: Case Studies

Location and Date	Impact	Reason
Jamshoro grid station in Sindh in May 2014	Disruptions in power transmission across Sindh and the corridor of Baluchistan.	Overheating and increased demand damaged critical outfit.

220 kV transmission line near Gaddani power plant Baluchistan September 2014	This incident resulted in the tripping of multiple transmission lines, disrupting electricity supply to Karachi and parts of Sindh.	Exacerbated by environmental stress of heating.
Muzaffargarh grid station January 2015	A massive power outage across most of Pakistan, affecting nearly 80% of the country the fault collapsed the national grid.	Aggravated by environmental stress due temperature conditions.
Multiple Grid Failures Karachi June 2015	Power loss in mega city during swirling 49 C, death toll from the heatwave exceeded 1,200.	Heatwave in Karachi caused a massive swell in electricity demand, leading to widespread grid failures and power outages across the megacity.
Chashma Nuclear Power Plant (C1 and C2) tripped due to a fault in the national transmission system, September 2016.	This incident caused power outages across northern Pakistan, affecting major cities like Islamabad, Peshawar, and Rawalpindi	Not proven but possible environmental stress on the transmission line as per an expert.
Skardu, Gilgit-Baltistan, caused the collapse of several transmission lines January 2017.	Leaving residents without electricity during freezing temperatures.	Heavy snowfall in Skardu, Gilgit- Baltistan
500 kV transmission line tripped, May 2018.	The breakdown affected Punjab, Khyber Pakhtunkhwa, and Azad Jammu and Kashmir. The fault originated in the Guddu-Muzaffargarh power line, triggering a cascading failure that led to a nationwide blackout.	Heat and demand causes
Transmission line of the Neelum-Jhelum Hydropower project in the Azad-Jammu-Kashmir region collapsed, July 2020.	This incident led to power shortages in AJK and northern Punjab.	Due to landslides caused by heavy rainfall.
Guddu Transmission Line Fault and	The resulting blackout affected the entire nation, including major urban	The fault at Guddu was due to cyclonic winds, which

Nationwide Blackout in Pakistan January 2021.	centres leaving millions without power for over 18 hours.	caused cascading failures throughout the country's power transmission network.

Case studies revealed that a failure in the energy system has significant national security implications, particularly in resource resource-scarce country like Pakistan, where energy infrastructure is closely tied to national stability and national resilience. The blackouts caused by climatic effects highlighted how a single point of failure in the transmission system can lead to widespread disruption of power, affecting not only essential services like healthcare, water supply, and telecommunications but also the country's ability to respond to emergencies. Hospitals and emergency services struggle to function without a reliable power supply, further endangering lives during climatic emergencies. Prolonged power outages also expose vulnerabilities that could be exploited by adversaries or terrorist groups to further destabilize the region. Case studies clearly show a strong impact of climatic conditions on the power systems, hampering their performance, reliability and resilience.

Outcomes of Interviews conducted with key positions at Pakistan's Transmission sector, including General Manager, Chief Engineer and Chief Security Officer, revealed a nuanced understanding of the interplay between climate impacts and the transmission sector of the energy system. They key outcomes from the interviews is as follows:
Extreme rainfall events, floods and heatwaves not only compromise the integrity of transmission structures but also exacerbate social pressures and economic implications. Prolonged exposure to climate stressors weakens transmission towers and substations, leading to frequent outages and costly repairs. Moreover, power disruptions during peak demand periods, especially in extreme summers or post-monsoon floods, intensify public dissatisfaction, impact industrial output and put additional strain on government resources. The critical need for flexible design and technology upgrades in transmission systems to withstand climatic stressors. Maintenance challenges vary widely due to Pakistan's diverse geography, ranging from arid deserts to flood-prone plains and high-altitude regions. Sindh alone, the length of transmission lines is extensive, spanning over 6000km and 18000 pylons, making it nearly impossible for maintenance patrolling teams to conduct regular inspections. Without addressing fundamental design flaws and strategically relocating critical grids away from high-risk climatic zones, power disruptions will persist, leading to escalating repair costs and service inefficiencies. Significance of integrating physical security measures with climate adaptation strategies, a more engaged community could serve as a frontline defense against threats. Climate-induced vulnerabilities, such as weakened infrastructure due to flooding or excessive heat, also create opportunities for criminal activities like cable theft and vandalism. Deploying community-based security personnel in high-risk rural zones could significantly reduce transmission-related crimes.

The growing frequency of climatic impacts is placing an increasing burden on Pakistan's power transmission infrastructure. Climate change is not just about rising temperatures but also about the unpredictability of weather patterns, leading to sudden and extreme stress on transmission systems. The need for a multi-disciplinary approach to addressing these challenges, including policy-level interventions and public awareness campaigns to foster energy resilience. Climate, community dynamics, and power transmission are interconnected in complex ways. On one hand, extreme weather events disrupt power supply, affecting livelihoods and economic stability, while on the other, the community itself plays a role in either mitigating or exacerbating these challenges. Community-based adaptation strategies such as localized microgrids, sustainable energy sources, and awareness programs could help build climate resilience.

Experts revealed that disruption of power transmission due to climatic factors has profound economic and social consequences. Resilient energy transmission systems are indispensable to mitigate cascading failures. A robust transmission system capable of isolating faults and maintaining stability under stress is crucial for national security. Ultimately, blackouts serve as a reminder that energy infrastructure is not just an economic or technical issue but a matter of national security. Improving resilience in transmission systems is critical for Pakistan to secure its energy future and ensure stability in the face of both internal and external threats. Thus, similar results as earlier analysis was evident where climatic impacts are exacerbating extreme impacts on the system and its dimensions.

Discussion

Policy analysis revealed crucial observations, as during data collection or interaction with officials, it was witnessed that authorities and the government lack attention to the National Climate Change policy. The lack of will and practical steps to mainstream climate measures in the steps undertaken was evident same needs to be incorporated starting the planning phase of projects, like importing climate resilient metallic braces for pylons instead of normal local-made stuff. The climatic impacts need to be considered at the planning phase of projects in the PC-1 stage.

Transmission of electric energy in Pakistan starts from Generation Companies (GENCOs) through the National Transmission and Despatch Company (NTDC), ending at Distribution Companies (DISCOs). NTDC operates 220kV, 500kV and 660kV transmission lines and grid stations, The power is further handed over to DISCO's which transmit it by further stepping down to 132kV, 64kV lines and grid stations. The National Electric Power Regulatory Authority (NEPRA) overall monitors and controls the power in the country through system operators and the National Power Control Centre (NPCC). As per the official State of Industry Report issued by NEPRA 2023, the DISCOs in the country cumulatively faced a loss of energy not served in the Transmission and Dispatch department equivalent to 442,944 million rupees (USD 1.5 Bn approx.) in the last five years (reasons not specified by the authorities, Figure 9). The companies of South, i.e., Sindh Electric Power Company (SEPCO) and Quetta Electric Supply Company (QESCO), are showing the highest losses. This aligns with the findings of this study, which was done on NTDC, that the transmission component of South is severely impacted by climatic changes.

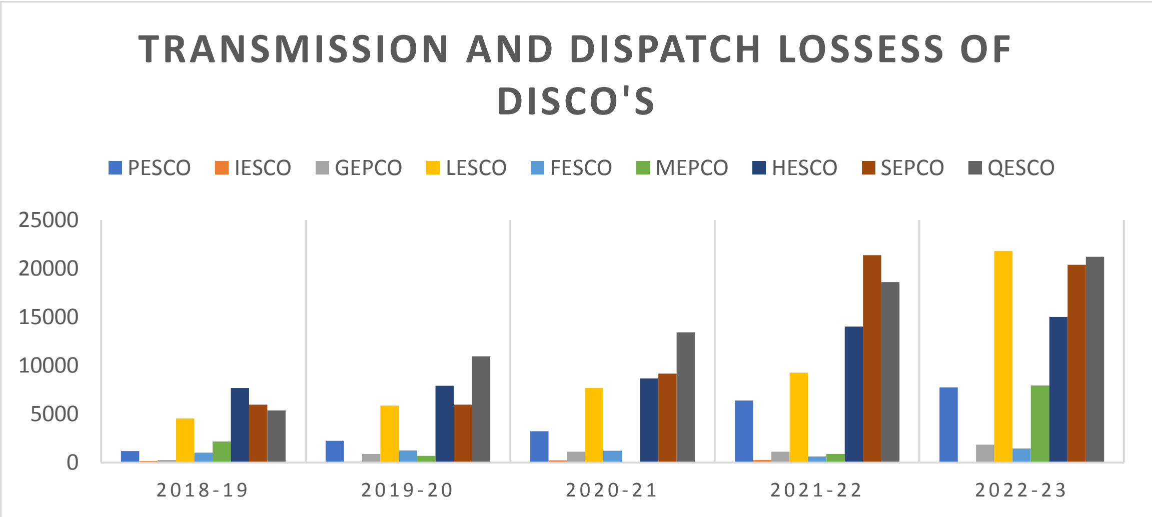

Figure 9

Addressing challenges faced by the transmission sector requires a deeper understanding of the underlying vulnerabilities and root causes to inform targeted strategies for mitigation. Pakistan's current electric transmission sector faces significant challenges in maintaining this resilience in the face of climatic impacts as electric power transmission sector is immensely affected by these climatic impacts in the from of intense heatwaves, torrential rains to floods, hurricanes/cyclones etc. vulnerability of power systems to climate-induced disruptions is becoming a grave problem.

Pakistan's economy is bearing the costs of inefficiencies in the transmission sector. The circular debt crisis of PKR 2.3 trillion in 2022 is attributable to power losses and inefficiencies, as shown by quantitative data included in the NEPRA reports, as well as field surveys. About 40 percent of this debt is associated with inefficiencies in the transmission and distribution network. While quantifying the economic burden associated with transmission inefficiency based on field data and NEPRA reports. Fuelled by unpaid capacity payments and power theft, circular debt has reached well over Rs. 2.5 trillion, crippling the energy sector's ability to remain financially viable. Grid operators said delayed payments to independent power producers (IPPs) in turn lead to cascading liquidity crises that hamper investment in modernization and maintenance.

However, the potential for economic stability in the transmission sector remains huge, despite challenges. A trend analysis of regions using upgraded transmission systems (Matiari-Lahore HVDC line) reveals that gains of 5% in loss reduction and a 10% increase in industrial productivity occurred within two years of commissioning. If such projects were expanded, they could enhance the economic output and energy efficiency.

The southern regions' disproportionate vulnerability to climate disruptions can be understood through both environmental social and structural lenses. These areas often experience higher temperatures, erratic rainfall, and more frequent flooding, but this environmental stress is compounded by historical underinvestment in infrastructure, political marginalization and governance gaps. Furthermore, the communities residing in the area are generally harder pressed in economic terms than those of central or northern regions. The intersection of climatic exposure with weak institutional presence and inadequate resource allocation exacerbates their fragility. This aligns with systems thinking, where vulnerabilities are not merely systematic but interact with the environment which generally in this case are shaped by political economy and socio-spatial inequalities. A good approach may be to embed community engagement protocols and localized response systems into national transmission strategies also the strategies for preventing theft and damage during climate events.

The finding that 51.83% of climate-related disruptions occur in southern regions resonates with the qualitative insights shared by an expert during the interviews, who pointed to structural design limitations in transmission towers and substations located in flood-prone and high-heat zones. For instance, vulnerability of uninsulated conductors and poorly elevated installations in areas like Sukkur and Hyderabad regions that also showed higher disruption rates in the quantitative data. This synergy between field-level testimony and numerical trends supports the argument for region-specific design adaptations rather than one-size-fits-all infrastructure models. While upgrading infrastructure to climate-resilient standards is critical, such recommendations must be financially feasible. Given Pakistan's fiscal constraints, particularly in the energy sector where circular debt and funding limitations persist, policy proposals must prioritize cost-effectiveness. A phased implementation strategy, guided by risk assessment scores and disruption frequency, may provide a more practical pathway. Additionally, case studies from similarly situated economies such as Bangladesh's shift to elevated substations in cyclone-prone zones or Vietnam's modular grid design in flood zones can offer scalable and budget-conscious frameworks for adaptation.

CONCLUSION

In conclusion, nature's power play continues to challenge Pakistan's energy sector, with the right strategies and right investments state can transform these challenges into opportunities for building a more resilient and sustainable energy future. This paper analysed the intersection, impact, and feedback mechanism of two grave issues Pakistan is facing, i.e., Climatic and Energy. As per Prof. Russell L. Ackoff works "the systems approach to problems focuses on systems taken as a whole, not on their parts taken separately", the results of study conducted through convergent mix methods showed strong significant impact of climatic disruptions on transmission component, one cannot just limit study of systems performance without accounting the external inputs on the system like impacts of climate. As termed by Ackoff, "such an approach is concerned with total system performance, even when a change in only one or a few of its parts is contemplated because there are some properties of systems that can only be treated adequately from a holistic point of view".

To reduce the impacts of climatic events on power transmission systems, several strategies can be considered by policymakers. Include structure upgrades, policy reforms and integration of climate-flexible technologies into the energy sector. Investing in the modernization of transmission infrastructure is pivotal for enhancing the adaptability of power transmission systems. The use of advanced technologies, such as heat-resistant conductors and braces, dust-resistant insulators, and erosion-resistant metals, can extend the reliability and resilience of transmission systems. Decentralizing the power transmission system by incorporating microgrids and distributed energy generation can enrich adaptability to climatic disruptions. Microgrids, which operate in isolation from the central grid, can give localized power during emergencies, reducing reliance on long-distance transmission lines that are vulnerable to climatic damage. Incorporating climate threat assessments into the design and construction of power transmission structures and regulations by focusing on climate change policies and frameworks. Regular maintenance and monitoring of transmission infrastructure are critical for preventing failures during climatic events. The use of remote sensing technologies like drones and satellite imagery can enhance monitoring of transmission lines and identify vulnerabilities before they lead to power outages.

Building on Ackoff's systems theory framework, this paper suggests that climatic challenges in the transmission sector are not isolated disruptions but part of an interlinked system of vulnerabilities, feedback loops and dependencies. To help in the practical solutions, a system dynamic modelling approach may offer critical understandings by simulating how various interventions such as policy reforms, infrastructural changes or resource reallocations can influence long-term system resilience. Through dynamic modelling the policymakers can visualize cascading effects of climate events and test potential responses in a controlled, predictive manner. Furthermore, decentralization strategies by emphasizing localized control, microgrids and climate-responsive infrastructure can be theoretically grounded in complex adaptive systems. These frameworks highlight the importance of modularity, feedback and local adaptability as central features of resilient infrastructure systems. By integrating these theoretical perspectives, decentralization is not merely a logistical suggestion but a systems-informed adaptive strategy that aligns with contemporary resilience and governance models.

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APPENDIX - I

STATA DATA

Descriptive statistics and system metric outcomes.

The descriptive statistics as per Table 3 & 4 carried out on the data set.

Table 3: Descriptive Statistics for data gathered on climate induced disruption to system.

#	Disruptions Environmental	Disruptions other	Total Disruptions	Average resolution time climatic disruptions (Hrs)	Total time consumed in year (Hrs)
Mean	115.17	163.67	278.83	3612.17	4593.5
Median	92.5	148.5	250	2127	3867.5
Mode	43	65	108	946	1296
Std.D	61.93	80.13	138.2	2835.57	2783.36
Variance	3835.24	6420.42	19099.4	8040470	7747098
Min	43	65	108	946	1296
Max	241	349	590	9158	10620
Range	198	284	482	8212	9324
Interquartile Range	80.75	86.25	129	4174.5	2877
Skew	0.9	1.16	1.09	0.99	0.97
Kurtosis	-0.14	1.4	1.09	-0.59	0.53
Mean ± Std.	115.17 ± 61.93	163.67 ± 80.13	278.83 ± 138.2	3612.17 ± 2835.57	4593.5 ± 2783.36

Table 4: Descriptive Statistics for system metrics of resilience calculated on data gathered.

#	MTBF	EDTI	Availability	RLI
Mean	98.37	70.37	102.42	63.81
Median	94.71	71.71	98.83	21.52
Mode	36.35	-1.65	37.31	4.44
Std. Deviation	51.89	57.78	54.54	78.14
Variance	2692.14	3337.96	2975.03	6105.91
Minimum	36.35	-1.65	37.31	4.44
Maximum	203.72	181.72	212.98	245.49
Range	167.37	183.37	175.68	241.05
Interquartile Range	56.19	70.19	59.37	91.6
Skew	0.94	0.66	0.93	1.46
Kurtosis	0.42	-0.04	0.41	1.29
Mean ± Std.	98.37 ± 51.89	70.37 ± 57.78	102.42 ± 54.54	63.81 ± 78.14

Results of ANOVA

η^2	η_p^2	Cohens f^2
0.57	0.57	1.3

f^2	Classification
0.02	weak effect
0.15	moderate effect
0.35	strong effect

	Sum of Squares	Df	Mean Squares	F	p
Factor	226879034.67	4	56719758.67	17.93	<.001
Residual	173986160.67	55	3163384.74		
Total	400865195.33	59			

Effect Size

η^2	η_p^2	Cohens f^2
0.57	0.57	1.3

Welch's ANOVA

	F	df1	df2	p
Welch-Test	14.62	4	25.64	<.001

ANOVA with Repeated Measures

	Type III Sum of Squares	Df	Mean Squares	F	p	η^2
Treatment	226879034.67	4	56719758.67	25.02	<.001	0.69
Residual	99763271.73	44	2267347.08			

According to Cohen (1988) limits for size of effect are .01 (small effect), .06 (medium effect), and .14 (large effect). Cohen, J. (1988). Statistical Power Analysis for the Behavioural Sciences. Hoboken: Taylor and Francis.

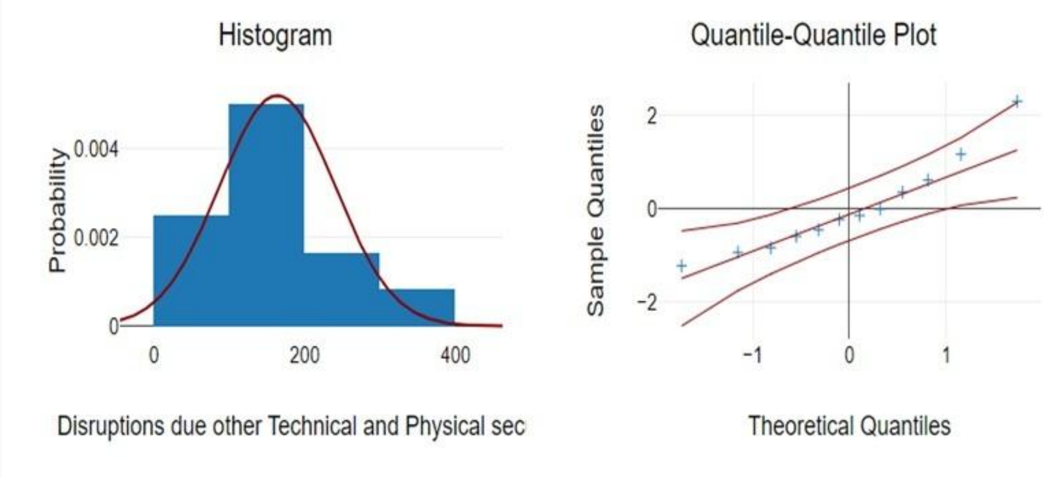


Figure 10

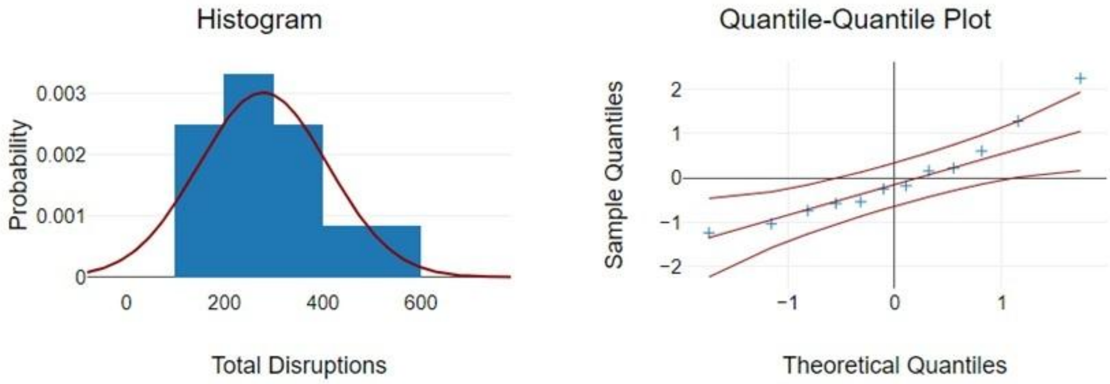


Figure 11

Figures above show the statistical depiction of Histogram and Quantile-Quantile Plots for the disruptions noted in the system due to environmental reasons and due to technical or other reasons.

1

COMPLETE DATA SET

Region	year	Disruptions due Physical Security	Disruptions due reasons (Environmental)	Total Disruptions	Average resolution time for physical security disruptions	Total time consumed in resolving / year	FOR frequency of outages or failures	CAIDI Customer Average Interruption Duration Index / MTTR mean time to repair	MTBF mean time between failures.	EDTI Expected down time index.	Availability	RLI resilience lost index.
NORTH	2020	96	13	109	1632	1853	0.010971429	17	91.25	74.25	96.61764706	16.8913242
	2021	127	33	160	2159	2720	0.014497717	17	68.97637795	51.97637795	73.03381195	29.56165018
	2022	163	51	214	2771	3638	0.018607306	17	53.74233129	36.74233129	56.90364489	48.69635337
	2023	213	69	282	3621	4794	0.024315068	17	41.12676056	24.12676056	43.54598177	83.15348174
Centre	2020	65	12	77	780	924	0.007420091	12	134.7692308	122.7692308	146	5.342465753
	2021	88	27	115	1056	1380	0.010045662	12	99.54545455	87.54545455	107.8409091	9.792202318
	2022	116	46	162	1392	1944	0.013242009	12	75.51724138	63.51724138	81.81034483	17.01496312
	2023	152	73	225	1824	2700	0.017351598	12	57.63157895	45.63157895	62.43421053	29.21475237
South	2020	145	41	186	2610	3348	0.016552511	18	60.4137931	42.4137931	63.77011494	40.92826244
	2021	192	74	266	3456	4788	0.021917808	18	45.625	27.625	48.15972222	71.76121125
	2022	258	92	350	4644	6300	0.029452055	18	33.95348837	15.95348837	35.83979328	129.5766402
	2023	349	119	468	6282	8424	0.039840183	18	25.10028653	7.100286533	26.4947469	237.1036049
TOTAL	2020	306	66	372	5022	6125	0.034931507	16.41176471	28.62745098	12.21568627	30.37177595	165.3508839
	2021	407	134	541	6671	8888	0.046461187	16.39066339	21.52334152	5.132678133	22.83648798	292.1202247
	2022	537	189	726	8807	11882	0.06130137	16.40037244	16.31284916	-0.087523277	17.3075125	508.8541754
	2023	714	261	975	11727	15918	0.081506849	16.42436975	12.26890756	-4.155462185	13.01590168	900.9748452

APPENDIX - II

PAKISTAN'S CLIMATIC LANDSCAPE

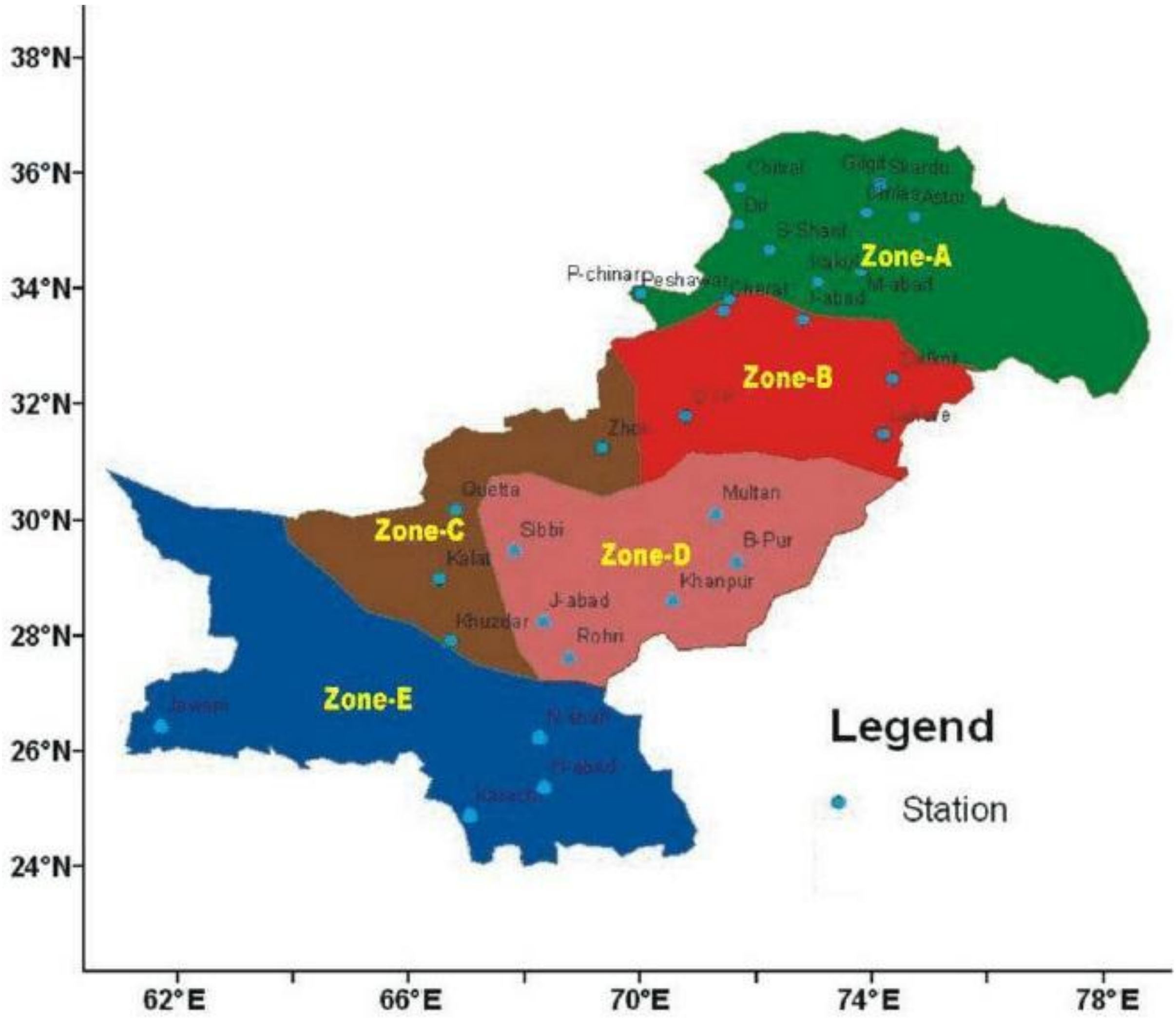
The topographical region of Pakistan's power transmission network covers a wide cluster of climatic zones. Whereas the south faces seriously warm, clean storms, and storms, the north's transmission lines must withstand sharp cold and a part of snow. Whereas western districts as often as possible confront dry spells, eastern areas are subject to regular flooding.

Extensive heatwaves often as possible happen in Pakistan, particularly in the southern areas of Sindh and Punjab, where highs of over 45°C are common. The control lattice is under colossal strain amid these strongly warm waves as a result of a spike in demand for power. Expanded loads on transformers and transmission lines result in overheating, which harms crucial components and causes breakdowns and power outages. The strain that warmth puts on the control network moreover accelerates the weakening of the transmission foundation, particularly the insulators and conductors, which lose strength and efficiency when exposed to high temperatures for amplified periods of time.

The Monsoon season starts from June to September, bringing huge rainfall in different areas of Pakistan, which ultimately leads to flooding. During this time, transmission lines, substations, and other crucial infrastructure in flood-prone regions are amazingly defenseless. Substations are vulnerable to flooding, which can cause hardware damage and hinder the supply of power, particularly in the event that they are located near streams or in low-lying zones. Within the sloping zones of northern Pakistan, where transmission towers are built on soak territory, flooding also increases the hazard of avalanches. Overwhelming precipitation destabilizes the soil, causing towers to break down and delaying control blackouts in the affected zones. Monsoon-induced increments in dampness accelerate the erosion of metallic transmission framework components, shortening their life expectancy and raising the risk of auxiliary failure.

High-speed windstorms and typhoons are common within the territories of Sindh and Baluchistan, particularly during the summer. Since tall winds can mechanically harm overhead control transmission lines, these storms pose a genuine hazard to them. Effective blasts make control lines influence, which can lead to line clashes and brief circuits, which impede the stream of power. Windstorms have the extraordinary capacity to topple transmission towers, resulting in broad blackouts. Clean storms make an additional issue since they diminish the detection capacity of transmission attacks by covering them in clean particles. Electrical streams may twist over as a result of this "flashover" ponder, which can result in control power outages and interference.

In Pakistan's northern sloping locale, especially in Gilgit-Baltistan and Khyber Pakhtunkhwa, flooding, cold waves, and snowfall pose a significant challenge. When snow builds up on transmission lines, the weight of the lines increases, causing towers to hang and, in some cases, collapse. These issues are made more lamentable by the ice course of action on conductors and towers, which incorporates weight and comes almost in assistant dissatisfaction that draws out power outages in blocked off zones. Transmission system efficiency is lessened by cold climate since the conductor electrical resistance rises at lower temperatures.



Qasim, *et. al*. (2014). Spatiotemporal Variations and Trends in Min and Max Temp of Pakistan. 4. 85-93.

Description.

Zone A comprises have cold climate and high mountains, situated in the North. These are hilly stations located between 34^{o}N to 38^{o}N in the Himalayan Hindukush.

Zone B has a mild cold climate and sub mountains, located 31 to 34 °N.

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Zone C is cold in winters and hot in summers. Mostly mountainous stations with high elevations from mean sea level 27 to 32°N and 64 to 70 °E.

Zone D hottest and driest zone, where highest maximum temperatures are recorded in Sibbi and Jacobabad.

Zone E: coastal cities near to Arabian Sea. The coastal part comprises only a small part of this region, and the climate above the coastal parts is Balochistan as well as Sindh province, which is arid.

APPENDIX - III

Visuals of Climatic Impacts in Pakistan Transmission Sector

High temperatures cause fires in equipment and wild growth at grid stations, which damage the underground cables.

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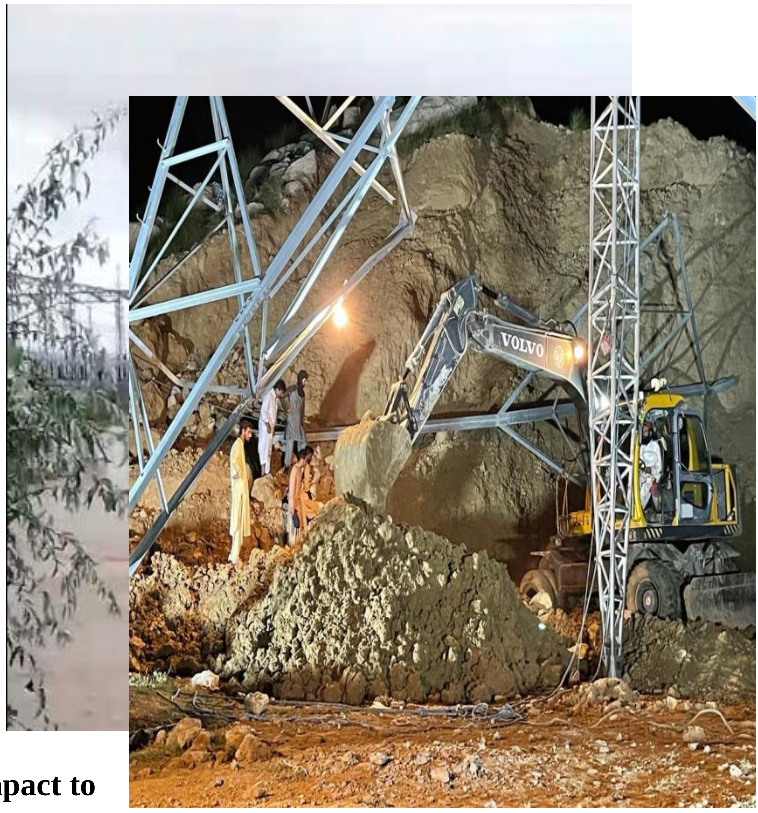
Impact to infrastructure by floods



Impact to electric pylons due cyclonic winds and thunderstorms


Tower#313

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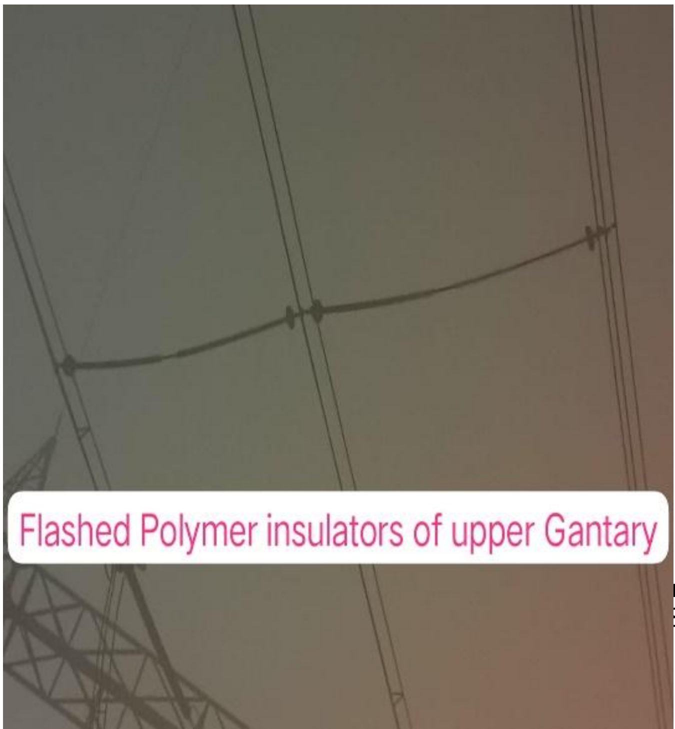
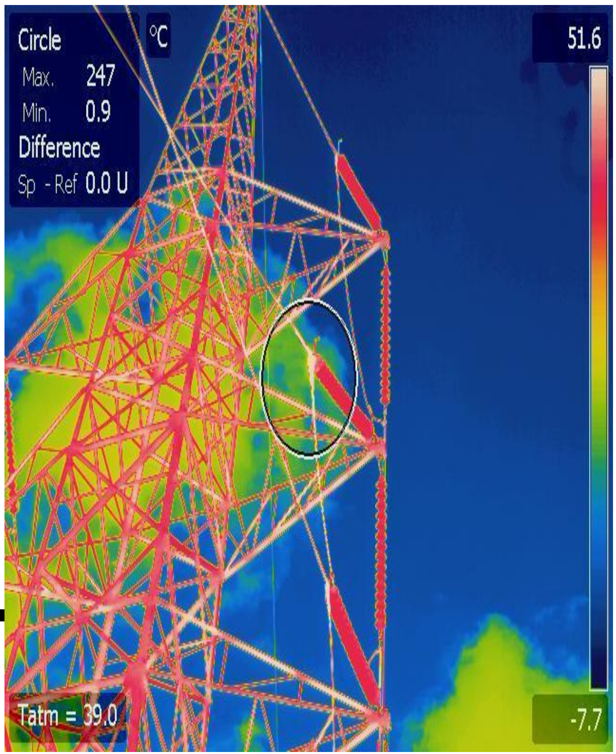
Impact due dust / smog causing flashovers. Thermal camera depicting temperature of 247°C





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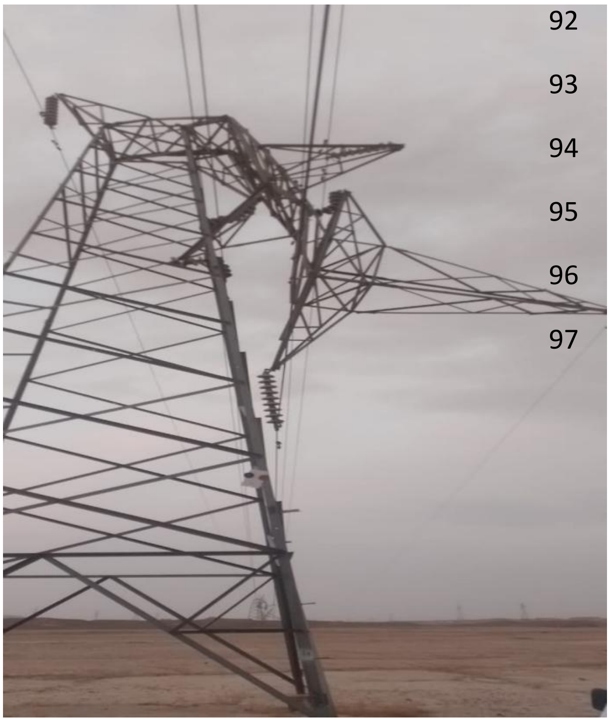
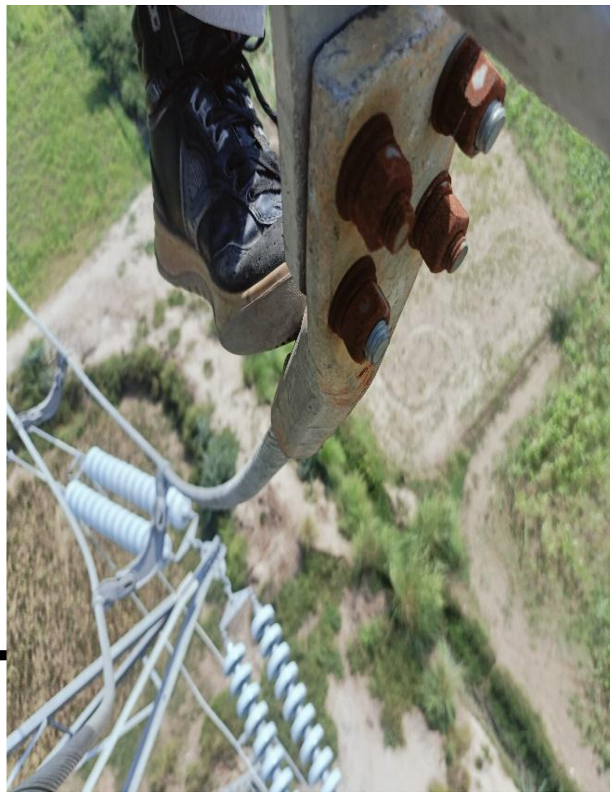
Conventional and Non-Conventional Warfare

Impact caused by erosion and rusts resulting in collapses





Impact Caused by Avalanches and Heavy Snow fall