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RESEARCH PAPER

The Unseen Costs: Physical Security and its Impact on Energy Security

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ABSTRACT

The energy security of the state is in fact the National Security of the state. The components of energy systems are integrally interwoven in such a way that impact on one component cause cascading effects on all the others. Electric transmission systems are often underappreciated in the broader discourse on energy security, emphasizing the need for in-depth scrutiny. This study focuses on interdisciplinary approach to see the energy security through a holistic lens for studying the energy systems as an entity rather than as a collection of parts under the umbrella of General System Theory. The study used triangulation approach for validating the data and reducing bias. The results predicted future reparations and energies / concentration required as per actual encumbrance of threats faced by energy security towards strategic approach in enhancing National Security posture for effective balance in region of South Asia.

KEYWORDS Energy Security, Interdisciplinary Study, Physical Security, Resilience, System Theory

Introduction

Though Pakistan is struggling in multiple dimensions encompassing its national security, however issues of energy security are considered priority and a concern of power corridors, as the energy security of the state have geopolitical implications, the concern of global community in this aspect cannot be ruled out. Pakistan is endeavoring to safeguard its energy security by engaging the foreign companies mostly based on China for building Dams and upgrading the existing energy infrastructure or adding the renewable energy projects like wind / solar to increase the potential of national grid to support the increasing demand at domestic and industrial levels for uninterrupted low-cost power. This approach by the state is undertaken to ensure the balance of power in the region of South Asia having crucial military powers in close proximities.

Pakistan's energy sector is facing numerous challenges that threaten its stability and socio-economic development therefore impacting the national security posture. As the industries in Pakistan face closures due high-cost energy as raw material and also the interruptions causing delay of orders, the economic activities have started shifting to other states like many of textile energy which is shifted to Bangladesh. This caused issues of Economic Balance of Power which has direct relationship with the military posture for safeguarding the National Security.

While focusing on the induction of new energy systems, the vulnerabilities of the existing system also need to be relooked. The power transmission component of the national energy security of Pakistan is the most crucial component in energy system, which is acting as lynchpin to join the power generation systems with the power distribution system. The system at present is facing numerous issues with respect to its resilience and reliability. The enhancement of energy security through resilient transmission networks is a critical area of investigation and core agenda under United Nations Strategic Development Goals "Ensure access to affordable, reliable, sustainable and modern energy for all.". This study aims to assess the role of Pakistan's transmission lines in supporting national energy security, focusing on the vulnerabilities of the system. Understanding the interconnections within Pakistan's energy landscape requires grounding this study in Systems Theory, which views the energy sector as an interconnected system of components.

The impact of Physical Security under social sciences was tested upon to see the significant impact on resilience of transmission infrastructure of electric energy component an engineering discipline. The seminal works of Prof. Russell L. Ackoff and Prof. Ludwig von Bertalanffy provided theoretical foundation for this study, which postulates that the interactions among different components of the energy system must be examined holistically to appropriately address the challenges encountered.

The behaviour of a system cannot be fully understood by only analysing its individual parts; the interactions and relationships between parts are crucial. Thus, pronouncing the importance of an interdisciplinary approach, breaking down the boundaries between sciences. A problem never exists in isolation; it is always surrounded by other problems in space and time. The more of the context of a problem that a scientist can comprehend, the greater are its chances of finding a truly adequate solution. Vulnerability of system for physical security threats was checked at the most crucial component transmission system which is acting as lynchpin to join the power generation systems with the power distribution system.

Efforts were made to pinpoint specific threat zones with respect to physical security within the transmission component of electricity system. In conjunction with data collection and analysis by triangulation, the research involved the analysis of specific case studies that documented historical physical security incidents of disruptions within the transmission segment. The key stakeholders and hierarchy involved in operations and maintenance were interviewed to further enhance the understanding of the crucial issue. Through these efforts aim was to uncover the underlying causes of such disruptions and evaluate the effectiveness of existing response mechanisms employed to mitigate the impacts.

Literature Review

Energy security is increasingly recognized as a critical component of national and regional security frameworks. the energy security of a state is in fact the national security of that state. (Fîță & Grigorie, 2021; Abbas & Alqama, 2020). It encompasses reliable access to energy resources, control over energy transportation and the ability to maintain economic stability (Fîță & Grigorie, 2021). The concept gained prominence following the 1973 oil embargo, highlighting the intricate relationship between energy, economy, and national security (Abbas & Alqama, 2020).

Energy security is multifaceted, involving economic, environmental, social, and technological dimensions that vary across countries and time periods (Kurian & Vinodan, 2013). While some studies emphasize its importance in geopolitics and economics, others question its actual impact, noting weak correlations between energy, economic, and security indices for many countries (Mara et al., 2022). Nevertheless, ensuring energy security remains a high priority for governments and international regimes, particularly in regions like South Asia, where it is crucial for economic development and political stability (Kurian & Vinodan, 2013).

Energy security is a multifaceted concept crucial for developing countries, encompassing access to modern energy services for both the poor and rapidly growing industrial sectors (Kuik et al., 2011). Developing nations face unique challenges, including insufficient capacity, high energy intensity, and rapid demand growth (Cherp et al., 2012). Many low-income countries experience overlapping vulnerabilities, making them particularly insecure (Cherp et al., 2012). To enhance energy security, developing countries should focus on energy efficiency (Kaygusuz et al., 2015).

A comprehensive approach considering energy poverty, environmental implications, and economic dependence is necessary to address the diverse energy security concerns faced by different countries (Krishnan, 2016). Pakistan's energy security has been a significant concern, with the country importing nearly a third of its energy resources (Malik et al., 2020; Malik et al., 2019). Studies using the 4As framework (availability, applicability, acceptability, and affordability) revealed that Pakistan's energy security improved initially from 2011 to 2014 but deteriorated in the following years (Malik et al., 2020; Malik et al., 2019).

The electric energy transmission sector plays a crucial role in ensuring energy security (Dołęga, 2019). While progress has been made, challenges remain in achieving sustainable growth in the electricity sector, with variations across economic, environmental, and social dimensions (Sarangi et al., 2019). Overall, the development of robust transmission infrastructure and effective policies are essential for ensuring energy security. To enhance energy security, investments in energy production and transmission, promotion of energy efficiency, grid modernization for renewable integration, and energy market reforms are recommended (Ayoo, 2020). Effective planning requires consideration of topographical, geographical, environmental, social, and political factors (Reddy et al., 2017).

The application of General Systems Theory (GST) to energy security has gained traction in recent research. GST provides a framework for understanding complex systems, including energy systems (Pérez & Razz, 2009). In the context of energy security, researchers have proposed models that consider availability, affordability, efficiency, and acceptability of energy systems (Narula, 2018). A systematic approach to energy security assessment has been developed, incorporating parameters such as system integrity, structure, functions, relationships, processes, and materials (Sukhodolia, 2019).

Physical security of power transmission infrastructure is crucial for maintaining grid reliability and resilience. Substations are vulnerable to malicious physical attacks, necessitating threat assessment methods and operator decision support (Jing Xie et al., 2014). Physical security threats to power transmission infrastructure can have severe consequences, including system instability, load interruptions, and cascading failures (Sadeghian et al., 2022). Researchers have developed methodologies to assess the vulnerability of power systems to various threats, including explosions and terrorist attacks, by analysing damage mechanisms and component susceptibility (Brewer et al., 2015).

The increasing interconnectedness and automation of these systems have created new vulnerabilities to equipment failures, human error, climate change, and terrorist attacks (Truscott, 2009). The resilience of critical energy infrastructures is essential for societal well-being and state functionality, necessitating strategies based on predictability, flexibility, and adaptability (Fîță et al., 2022). As uncertainty regarding safe access to reliable energy supplies at reasonable prices increases, energy security remains a crucial aspect of national security (Matsui & Kryukova, 2021).

Theoretical Framework

The work of Russell L. Ackoff an American organizational theorist professor and pioneer in the field of operations research, systems thinking and management sciences gave the foundations to what in the modern times called General System Theory, Russell. L. Ackoff, in his work "The development of operations research as a science" Operations Research Vol 4. (June 1956) pp.265-295. "The development (rather than the history) of operations research as a science consists of the development of its methods, concepts, and techniques. Operations research is neither a method nor a technique; it is or is becoming a science and as such is defined by a combination of the phenomena it studies". Further in 1959 his work shed light on deeper insights as "In the words of a practitioner of operational research something new has been added. The tendency to study systems as an entity rather than as a conglomeration of parts is consistent with tendency in contemporary science no longer to isolate the phenomena in narrowly confined contexts, but rather to open interactions for examination and to examine larger and larger slices of nature. Under the banner of systems research (and its many synonyms). These research pursuits and many others are being interwoven into a cooperative research effort involving an ever-widening spectrum of scientific and engineering disciplines".

General system theory was a work by Ludwig von Bertalanffy Professor at University of Alberta Edmonton) Canada introduced in his renowned work published in 1968 in a book General System Theory Foundations, Development, Applications. This is the seminal book where Bertalanffy formalized General Systems Theory, laying out its principles and applications across various scientific disciplines. The main idea which the author wrote in the book was that "In the narrower sense (G.S.T.), trying to derive, from a general definition of "system" as a complex of interacting components, concepts characteristic of organized wholes such as interaction, sum, mechanization, centralization, competition, finality, etc., and to apply them to concrete phenomena.

Further explaining this theory 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 these parts interact and fit together"

These works are foundations of this research where the National Energy Security of Pakistan is viewed as a system which needs holistic approach and the components of this energy security was dissected and a small component of power transmission system was viewed as a factor on which the interdisciplinary factors like physical security in social sciences discipline has impact. The relationship of these parts is explored in this research study as to how they interact and fit together in this system.

Material and Methods

This study adopts a qualitative and quantitative approaches to analyse the relationship between security incidents (thefts, breaches, incidents) called to as disruptions in the system and system downtime (time taken for repair and maintenance to restore system to default settings) in Pakistan's energy transmission infrastructure. The triangulation approach is selected for enhancing credibility and viability in addition to reducing the bias in the study.

The data collected covers a broad geographical spread of 82 installations across 50 cities in Pakistan. This ensured a comprehensive sample for representing security incidents in both urban and rural transmission setups. The study spans four years, ensuring enough data to identify trends and patterns over time.

Quantitative analysis: The data collected was assembled in three regions, North, Center and south for the years 2020 till 2023. The total physical incidents termed as disruptions were calculated on time required at different regions for resolution. The statistical analysis for regression and correlation was carried out on the available data set. The resilience of the system was calculated in terms of Frequency of Outages / failures, MTTR mean time to repair, MTBF mean time between failures, EDTI expected down time index, Availability of system at that particular area and RLI resilience lost index.

Qualitative analysis: through interviews and case study of terrorist attack on Sheikh Mohammadi Power Grid Station Peshawar 2013, aligning with the triangulation methodology, five semi-structured interviews were conducted, narrative analysis was carried out.

Results and Discussion

Table 1
Descriptive Statistics:

Variable	Mean	SD	Range
Total Disruptions	217.83 disruptions	111.31	77 disruptions to a maximum of 468
Average Resolution Time	2685.58 hours	1605.13	780 hours to 6282 hours
MTBF (Mean Time Between Failures)	65.64 hours	31.01	25.10 hours to 134.77 hours
Availability	70.20%	33.80%	26.49% to 146%.
RLI (Resilience Lost Index):	59.92	66.37	5.34 to 237.10

Total Disruptions and Total Time Consumed: Strong positive correlation (0.982), meaning that more disruptions lead to significantly more total time consumed. Total Disruptions and MTTR: Moderate correlation (0.554), suggesting a relationship between more disruptions and longer repair times. MTBF and Total Disruptions: Strong negative correlation (-0.882), indicating that as the number of disruptions increases, the mean time between failures decreases (less reliability). Availability and Total Disruptions: Strong negative correlation (-0.877), meaning that more disruptions significantly reduce system availability. RLI and Total Disruptions: Strong positive correlation (0.956), showing that higher disruptions correspond to a higher resilience lost index. MTBF and Availability: Almost perfect positive correlation (0.9998), meaning that as MTBF increases, system availability also increases significantly.

Results showed that there is a strong relationship between disruptions and negative system impacts, including more time consumed, lower MTBF, lower availability, and higher resilience loss. Availability and MTBF are highly dependent on each other, indicating that a more reliable system (higher MTBF) tends to have better availability. The resilience lost index (RLI) increases substantially with disruptions, highlighting the importance of reducing system failures to maintain resilience.

The regression model provided further insights into data as Key findings were:

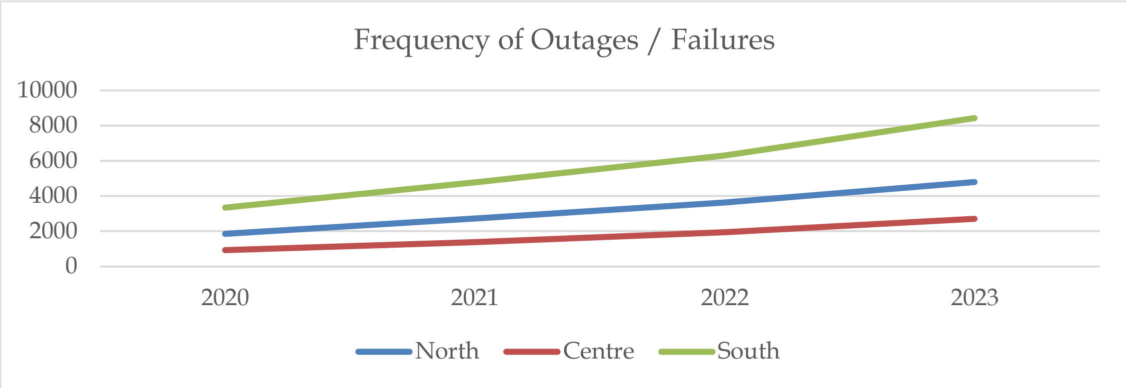
Year: As time progresses, disruptions and total time consumed appear to increase, indicating possible aging infrastructure or worsening physical security conditions enhancing the downtimes and reducing the resilience.

Region: The regions have significant effects, with the South showing a much larger influence on the total time consumed compared to the North and Center.

System Performance and Resilience metrics:

FOR (Frequency of Outages or Failures): Measures the rate at which outages occur in a system over a given time period.

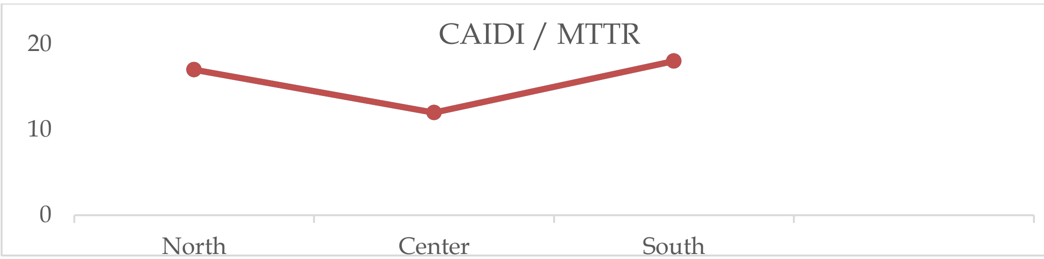
FOR = Number of Disruptions / Total Operating Time (in hours or days)



This metrics provides a view of how frequently the system experiences outages due disruptions in the system caused by physical security, this chart help assess stability of the system. Higher FOR values decreases the systems resilience.

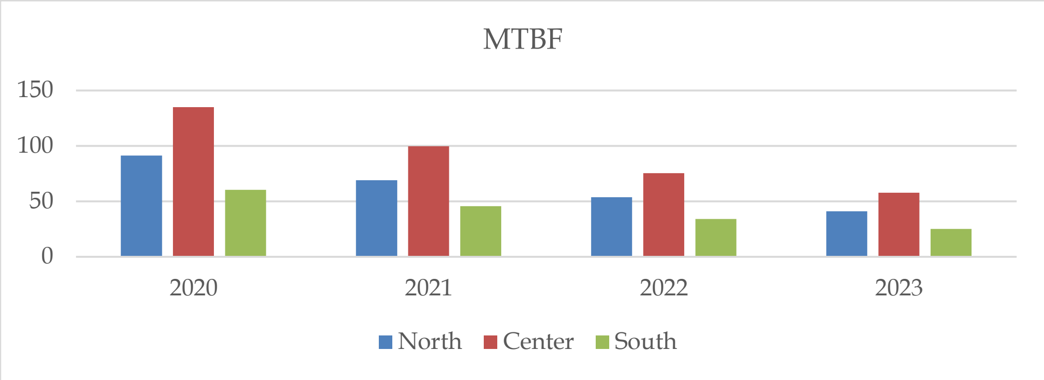
CAIDI (Customer Average Interruption Duration Index) or MTTR (Mean Time to Repair): The average time taken to repair a fault and restore the system to normal operation.

MTTR=Total Time Consumed in Year / Total Number of Repairs or Disruptions



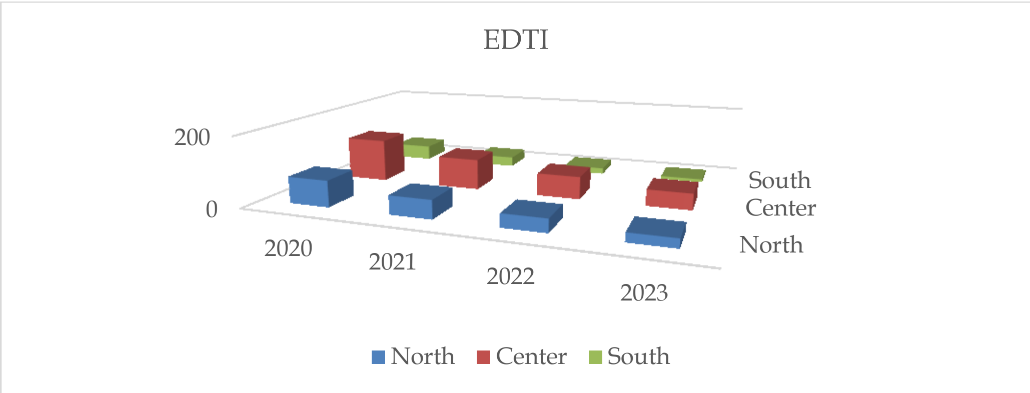
This metric depicting the efficiency of the repair and restoration process after a disruption. Lower MTTR indicates quicker repairs, enhancing resilience.

MTBF (Mean Time Between Failures): is average time between two successive failures or disruptions. MTBF = Total Operating Time / Number of Disruptions



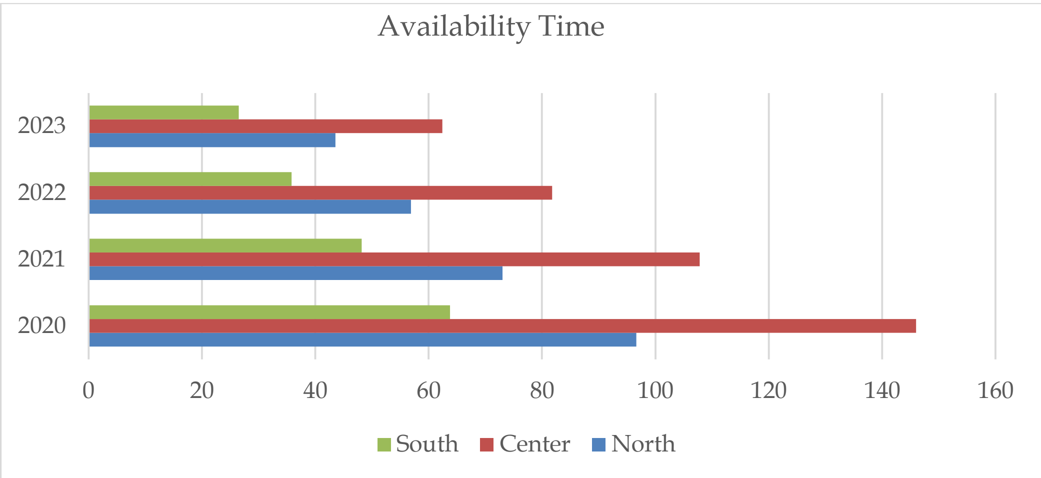
MTBF gives insight into the system's reliability by indicating how long the system operates without failure. A higher MTBF indicates a more reliable and resilient system.

EDTI (Expected Down Time Index): Predicts the expected downtime of the system based on historical failure and repair data. EDTI = MTBF × (1− MTTR/ MTBF)



This metric gives insight into how long the system might be down in future events, based on past performance. This is used to predict the systems elasticity as well for the future operational planning's.

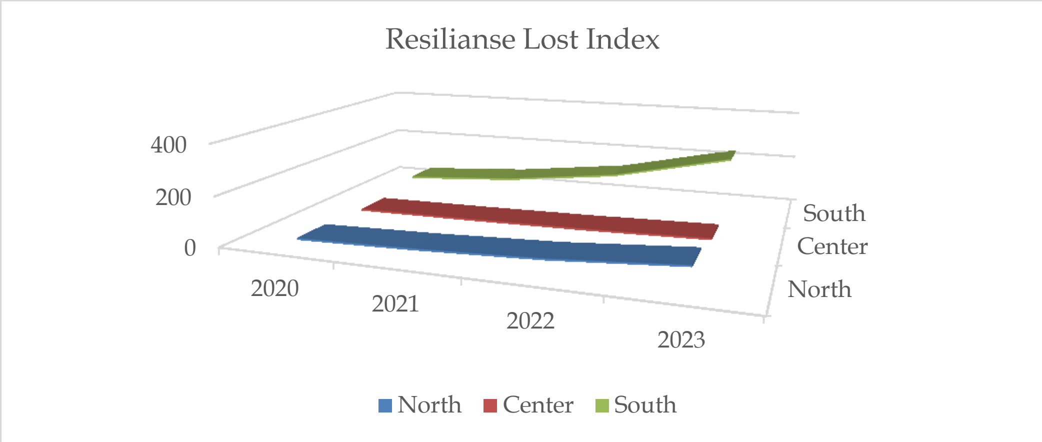
Availability (A): The proportion of time the system is available and operational out of the total time. Availability = MTBF / MTBF + MTTRA



This metric shows how often the system is available and can serve with full potential. It is an important measure of overall system resilience.

Resilience Loss Index (RLI): This metric attempt to quantify how much resilience the system has lost over time due to disruptions.

RLI = Total Time Consumed in Disruptions / Total Available Time



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.

The General Manager (Asset Management) explained how the economic downturn has led people to steal iron braces from electric pylons and copper materials from grid stations. He elaborated on the challenges of system restoration, highlighting issues related to accessibility, resource availability, travel time, and security concerns in sensitive areas. He noted that the deployment of community guards in these sensitive regions has significantly reduced system downtime over the past year.

The Chief Engineer (Asset Management) discussed the losses faced by the company due to issues like power evacuation, energy loss, and financial setbacks. He also described the impact of power outages on communities, especially in urban areas and at critical installations such as hospitals. He outlined the difficulties encountered in rerouting power through alternative methods and activating backup systems when downtime exceeds critical thresholds. Additionally, he emphasized the costs of hiring extra security and the logistical challenges of accessing areas under repair, given that the total length of the transmission line in the southern region exceeds 6,000 km.

The Resident Engineer explained the repair process from the moment an incident is first reported to its resolution. He highlighted the repeated incidents in hotspot areas, where organized gangs operate, posing significant challenges to repair teams. While he praised the role of security in preventing many incidents, he noted the impracticality of guarding such an extensive infrastructure, with more than 6,000 km of transmission lines and over 18,000 pylons in the southern region. He mainly addressed the administrative challenges associated with managing such a vast network.

The Chief Security Officer provided an overview of the security environment in the country, mentioning the presence of various extremist and terrorist groups. He described the use of explosives in certain areas to disrupt power, often driven by unknown agendas or reasons he chose not to disclose. He linked the theft of electric pylons in the northern and southern regions to the poor economic conditions of local populations. In some cases, recovered materials revealed that stolen items were being used for construction by local residents, offering a new perspective on the issue. He detailed the efforts of security teams, who work closely with local authorities and police to manage these vast areas.

The Director of Threat Assessment & Operational Planning provided insights into potential hotspot areas and the various causes of disruptions observed in those regions. He emphasized the importance of strategic planning in reducing both downtime and costs. Additionally, he highlighted the role of technological advancements in security, which have been crucial in minimizing damage and improving the cost-effectiveness of security measures.

The interviews highlighted the critical role that physical security plays in maintaining energy security and minimizing downtime. The General Manager's account underscores the impact of economic pressures on infrastructure vulnerability, while the Chief Engineer and Resident Engineer illustrate the significant challenges of system restoration, especially in hotspot areas. Security efforts, though impactful, face limitations due to the vast geographical spread and resource constraints. It also provided insights on the complex and evolving security landscape, shaped by external threats and local economic conditions. Collectively, these findings offer a nuanced understanding of how physical security failures directly contribute to operational disruptions.

Sheikh Mohammadi Grid Station is a critical infrastructure component of Pakistan's power transmission network, located in Peshawar. It plays a key role in delivering electricity to Khyber Pakhtunkhwa (KPK) province, which includes densely populated urban areas and essential installations such as hospitals, government buildings, and military facilities.

On the night of February 25, 2013, the Sheikh Mohammadi Grid Station was subjected to terrorist attack by militants. The assailants, armed with rocket-propelled grenades (RPGs), automatic weapons, and explosives, launched a direct assault on the grid station with the intention of crippling the power supply to large portions of KPK. The attackers breached the perimeter of the station under the cover of darkness, using explosives to disable key transmission lines and transformers. The intensity of the assault overwhelmed the security personnel stationed at the grid, resulting in the death of several security guards and injuries to others.

The attack resulted in a complete blackout across Peshawar and surrounding areas, leaving millions of residents without electricity for an extended period. Essential services, including hospitals, emergency response systems, and water supply stations, were disrupted, creating a humanitarian crisis that lasted several days. The economic loss was significant, as the blackout affected industries, businesses, and daily economic activities. The damage to the infrastructure required weeks of repairs to fully restore power to the affected regions, placing a financial burden on the government and power authorities. The cost of repairs was estimated to be in the millions of rupees, not to mention the longer-term economic losses due to the interruption of electricity-dependent industries.

This incident underlined need for more robust security protocols at critical energy infrastructure sites. The event also exposed the inadequacy of backup power systems and challenges faced in restoring power after a significant attack on the grid. Given the prolonged downtime and the delay in recovery, the attack demonstrated how physical security failures at key nodes in the energy transmission network can have cascading effects on the stability of the power system and broader national security.

Conclusion

This study emphasizes the importantonce of physical security in the energy security by analyzing the significant impact on the resilience and reliability of the system conducted on the electrical transmission systems in Pakistan. The study also gave another perspective that although physical security measures are essential, they need to be evaluated in combination of socio economic and environmental settings for giving the holistic picture which was the basic theme of study for evaluating the interdisciplinary approach as per the works Prof. Russell L. Ackoff and Prof. Ludwig von Bertalanffy on General Systems Theory.

Recommendations

The policy makers should focus on the holistic strategies to tackle the issues of physical security measures as the transmission line length in just one zone of south is exceeding 6000KM in total and with more than 18000 electric pylons.

The policies should be focusing on needs for legislation to curb the practice of sale or use of the materials used in electric transmission systems in similar context as done for the materials used in railway systems. Securing the resilience of Pakistan's energy infrastructure is crucial not just for the nation's energy security but also for its overall economic stability and growth. Hence, immediate measures are needed to enhance the infrastructure's resilience to physical risks.

The results also indicate the importance for stakeholders to focus on incorporating physical security threats in the planning and maintenance of electric transmission infrastructure. This involves putting resources into cutting-edge technologies, enhancing physical security measures. Moreover, examining how physical security measures interact with vulnerabilities causes by the climatic impacts which can trigger the situation in already volatile areas in terms of floods, internal population displacement etc. this could offer a better understanding of constructing energy systems that are more resistant. This study established the strong significant relationship of physical security measures and energy security of the state which in turns effect the national security posture having geopolitical implications in the region.

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