



Addis Ababa University

**Investigation on Unexplained Faults in Transmission Lines:
A Comprehensive Study on Pollution-Induced Outdoor
Insulation Problems on Ethiopian Transmission System, and
GIS-based Pollution Severity Mapping**

Doctoral Dissertation

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A dissertation submitted to the Graduate School of Electrical and Computer Engineering in partial fulfilment of the requirements for the Degree of Doctor of Philosophy (PhD) in Electrical Engineering (Electrical Power Engineering).

January 2025

Addis Ababa University.



Addis Ababa University

School of Graduate Studies

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

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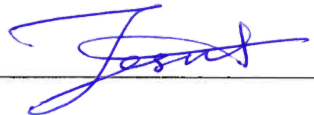
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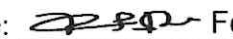
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To My Parents and Beloved Family.

Declaration

This Ph.D. dissertation is the result of my own work. Any material used from other sources has been clearly identified, properly acknowledged, and cited in accordance with academic standards.

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Abstract

Excessive unexplained outages on transmission lines significantly impact Ethiopian power system and, consequently, the national economy. Resolving these issues requires accurately identifying the root causes of outages and adopting appropriate mitigation strategies as a proactive approach. Such an approach, incorporating improved design and maintenance practices, is more cost-effective in the long term and ensures that critical issues are prioritized. Therefore, in line with addressing the challenges resulting from excessive unexplained outages on transmission lines, this dissertation presents the investigation of pollution-induced outdoor insulation problems in Ethiopian transmission system and develops a GIS-based pollution severity map for the whole country, including the estimation of site pollution severity parameters on carefully selected locations.

Statistical analysis of the unexplained faults on power transmission lines operating at 132 kV, 230 kV, and 400 kV was the first focus area of this research. Long-term fault records, from 2015 to 2022, were analyzed for identifying the main probable root causes of these outages by combining fault time stamp data with known fault characteristics as well as with information on local climatic and environmental conditions. Out of the total number of 8,891 registered fault records, 4,231 (47%) were unexplained. Among these unexplained outages the analysis attributed 19% of them to lightning, 27% to pollution events, 11% to fires, and 43% to external interferences.

Furthermore, this research places a particular emphasis on pollution-induced flashover of insulators, a major factor contributing to unexplained outages in the Ethiopian power transmission network. A detailed and refined methodology was developed to identify faults caused by insulation pollution flashover, that associated fault characteristics with local meteorological and environmental conditions. Results reveal that 24.7% of the previously unexplained faults were likely caused by pollution-induced flashovers. The analysis showed that porcelain insulators exhibit the highest pollution-induced flashover intensity. Silicone rubber insulators also have performed unsatisfactorily in Ethiopian conditions, indicating the need for improved insulator selection and sizing practices that consider the local climatic and environmental conditions.

The analysis allowed us to assess the outdoor insulation design practices. It highlights the lack of systematic use of service experience, site pollution measurements, and laboratory tests in the practices used for insulator selection. Recommendations to the Ethiopian Electric Power (EEP) are formulated that aim at improving this process and request paying more attention when addressing the pollution related challenges.

The study further evaluated the site pollution severity of selected sites in Ethiopia and developed a GIS-based pollution severity map for the country. It was conducted at 364 selected sites along existing

overhead transmission lines and substations, and other key locations for future grid expansion. Two site pollution severity evaluation methods were used: analysis of climatic and environmental conditions, and analysis of operational service experiences of existing transmission lines alongside of local meteorological parameters. The map incorporates local pollution sources and requires validation through ground-based measurements. As part of estimating the severity of environmental pollution, the study focused on assessing the ambient particulate matter (PM_{2.5}) levels. It analyzed annual mean satellite-based PM_{2.5} density for Ethiopia from 1998 to 2022 using ArcGIS for spatial data processing and Inverse Distance Weighted (IDW) interpolation to create a concentration surface map. The analysis revealed an increasing trend in Ethiopia's average annual mean PM_{2.5} density. The North-East grid region had the highest annual mean PM_{2.5} density (34.13 µg/m³), while the Southeast and South regions had the lowest. A strong correlation was found between high PM_{2.5} density areas and frequent pollution-induced flashovers. This is the first standardized pollution severity map for the Ethiopian power grid, serving as a baseline for future updates.

Keywords: Ethiopian power transmission system; Power transmission reliability; Root cause analysis, Unexplained faults; Pollution flashover; Outdoor insulators; Silicone rubber polymeric insulators; Site pollution severity; GIS-based pollution severity map; Particulate matter, Climatic conditions of Ethiopia

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List of Abbreviations

ACAG	Atmospheric Composition Analysis Group
DDDG	Directional Dust Deposit Gauge
DEM	Digital Elevation Model
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
ESDD	Equivalent Salt Deposit Density
GERD	Grand Ethiopian Renaissance Dam
GIS	Geographic Information System
GWR	Geographically Weighted Regression
IDW	Inverse Distance Weighted
IEC	International Electrotechnical Commission
MISR	Multi-angle Imaging Spectroradiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MTBF	Mean Time Between Flashover
NSDD	Non-Soluble Deposit Density
PFO	Pollution Flashovers of Insulators
PM	Particulate Matter
SDD	Salt Deposit Density
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SES	Site Equivalent Salinity
SPS	Site Pollution Severity
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Program
USCD	Unified Specific Creepage Distance
WMO	World Meteorological Organization

Acknowledgments

First and foremost, I am deeply thankful to God, the Almighty, whose blessings and guidance provided me with wisdom and resilience throughout this journey. His strength carried me through the challenging moments and led me to complete this study successfully.

I would like to express my heartfelt gratitude to my esteemed supervisors, Prof. Stanislaw M. Gubanski and Dr. Mengesha Mamo, whose support, guidance, and expertise have profoundly shaped this research. It has been a genuine privilege to work under your supervision, gaining from your experience, unique perspectives, and thoughtful feedback. Thank you for your encouragement and for challenging me to grow throughout this journey. I truly look forward to future opportunities to collaborate with you. I would also like to extend my deep appreciation to Dr. Dan Windmar, my industry internship supervisor at STRI, ABB Voltage Technology and Testing Laboratory in Ludvika, Sweden. His expert guidance and support during my time there were instrumental in helping me gain practical experience within an exceptional setting.

I am sincerely grateful to the management and academic staff of the School of Electrical and Computer Engineering within Addis Ababa Institute of Technology at Addis Ababa University. Their diligent management of the Ethio-Sweden capacity-building project, of which this research is a part, provided me with essential resources and opportunities, and I am truly grateful for the support I received in being part of this project. My gratitude extends as well to Bahir Dar University, particularly the Faculty of Electrical and Computer Engineering at Bahir Dar Institute of Technology, whose support and encouragement greatly enriched my study journey.

I extend my sincere appreciation to the faculty and staff of the Division of Electric Power Engineering in the Department of Electrical Engineering at Chalmers University of Technology in Gothenburg, whose support played a significant role in making my research visit both successful and productive. I am particularly grateful to Prof. Yuriy Serdyuk and Dr. Xiangdong Xu, whose essential courses and invaluable insights provided a solid foundation for my research. I also extend my thanks to Annie Grundevik for her kind and constant support during my time at Chalmers University. The collaborative and supportive nature of this research community has substantially contributed to my academic and personal development.

I would like to gratefully acknowledge the financial support provided by the Swedish International Development Cooperation Agency (Sida), which funded my research visits to Chalmers University of Technology and facilitated my internship at the STRI ABB High Voltage Laboratory. This support was vital in enabling my research, training, and professional development.

My appreciation also goes to the staff members of Ethiopian Electric Power (EEP) for their collaboration, sharing of expertise and practical insights, facilitating field visits, and assisting with data collection, all of which contributed significantly to the quality and depth of this research.

Finally, I am deeply grateful to my friends and colleagues for their steady encouragement, moral support, and understanding throughout this journey. To my parents and beloved family, your unwavering love, encouragement, and support were my strength during even the most challenging times. Thank you for everything.

CHAPTER 1

1. Introduction

1.1 Background

A stable and reliable supply of electrical energy is essential for societal well-being and economic growth. The growing demand for reliable electricity is primarily driven by ongoing industrial expansion, rapid technological progress, and rising standards of living. As economies expand and populations grow, ensuring a stable and uninterrupted power supply becomes essential. This requirement leads to substantial investments in energy infrastructure, encourages innovation in energy technology, and necessitates strategic planning to maintain efficient and resilient power systems. Therefore, ensuring the robustness of power infrastructure is essential for supporting sustainable economic development and global competitiveness (Jenkins & Ekanayake 2017; Todorović et al. 2023; Zohuri 2016).

The reliability of electrical power networks has become a central concern for both utilities and policymakers. Maintaining an uninterrupted power supply is critical for economic activities and customer satisfaction. Utility companies today face mounting pressure to expand their generation capacity, upgrade aging infrastructure, and make transmission and distribution systems more efficient. Balancing these demands while keeping operational costs in control is challenging, and it is further complicated by the need to identify and prevent failures that could lead to unplanned outages and service interruptions.

Transmission lines, which carry electricity over long distances from power plants to substations and, finally, to end-users, play a crucial role in the power system. Their reliability is critical, any disruptions can trigger large-scale power outages, affecting millions and causing immediate inconvenience and potentially significant financial losses for both utilities and their customers. Insulators, critical components of the transmission and distribution systems, play a key role in providing mechanical support for conductors and ensuring that they are electrically insulated from surrounding structures and the ground thereby preventing unwanted current flow that could lead to outages. These insulators are designed to withstand high voltages stress while subjected to severe mechanical and environmental stresses, preventing electrical discharge (flashovers) and ensuring the safe and continuous operation of the power grid. The integrity of these components is therefore critical, as they serve as the front line of defense against outages, ensuring the consistent delivery of power (Jean & Weiser, 2022).

Excessive unplanned outages or unexplained faults on transmission lines can have far-reaching effects, extending beyond mere inconvenience. They can severely affect multiple dimensions of power systems

and the broader economy. For instance, frequent outages increase the volume of Energy Not Served (ENS), resulting in revenue loss for utilities and dissatisfaction among consumers. Beyond lost income, these frequent interruptions degrade overall power quality, leading to voltage sags, surges, and harmonic distortions that can damage sensitive equipment and shorten its lifespan. The cumulative effect of these outages strains the power grid, increasing the likelihood of cascading outages and potentially causing system-wide failures. These disruptions result in increased operating and maintenance costs and potential damage to commercial and industrial equipment, which can deter investment and hinder economic growth (Alam et al. 2018; Landegren et al. 2019; Lawton 1996; Novosel 2013; Poudineh & Jamasb 2017; Wijayatunga & Jayalath, 2008). These challenges underscore the importance of proactively addressing the issues posed by unexplained faults and unplanned outages in transmission lines. Utilities must identify and mitigate these risks to maintain a stable and resilient electricity supply.

Despite significant advancements in technology and operational practices, the performance of transmission lines can still be compromised by various external factors often causing unplanned outages. A large share of these unplanned outages stem from natural events, extreme weather like lightning, high winds, storms, heavy rain, snow, and ice can all damage transmission components and lead to disruptions. Environmental factors such as pollution, corrosion, wildfires, wildlife interference, and overgrown vegetation also play a role, each posing a unique threat to the reliability of transmission lines, adding more risks to an already complex system. These issues are further compounded by internal and operational problems, including equipment failures, insufficient maintenance, manufacturing defects, human error, and even theft and vandalism can also cause faults. These internal and external factors collectively increase the system's overall vulnerability to unexpected outages, which can be challenging to manage and predict due to their complex origins (Bin et al., 1998; Koval & Chowdhury, 2005; Liang et al., 2020; Volpov & Katz, 2016; Volpov & Kishcha, 2017).

A comprehensive understanding of these fault causes, combined with mitigation strategies, is essential. Historical fault data analysis, improved design practices, and predictive maintenance are among the tools utilities can use to strengthen transmission system resilience. Addressing the root causes of outages not only reduces their frequency but also optimizes resource allocation, ensuring the prioritization of critical areas (Tutt et al., 2012; Wijayatunga & Jayalath, 2008; Zidan & El-Saadany, 2015).

Among the various causes of unexplained faults, pollution-induced flashovers of insulators stand out as a significant challenge, particularly in areas with high levels of environmental pollution. When contaminants such as dust, salt, or industrial pollutants accumulate on insulator surfaces, wet conditions can cause these pollutants to form a conductive layer, leading to electrical surface

discharges, or flashovers. These flashovers can result in service disruptions, power outages, equipment damage, and increased maintenance costs, all of which compromise grid stability (Liang et al., 2020; Nigris, 2022, 2020; Volpov & Kishcha, 2017; Zhiyi, 2016).

Local environmental and meteorological conditions have a significant impact on the likelihood of flashovers. Factors like relative humidity, temperature, rainfall, wind speed and direction all play a role, influencing the rate of pollution accumulation and wetting, both of which affect the probability of a flashover. A detailed understanding of these variables is essential for developing strategies to mitigate pollution-related outages. Site-specific insulator selection and dimensioning can significantly improve reliability by reducing the risk of flashover. Comparative analysis of insulators operating under varying environmental conditions can yield valuable insights into their performance, guiding data-driven decisions for future insulator selection (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008; Nigris, 2020).

Evaluating site pollution severity is critical for understanding flashover risks and implementing effective solutions. Pollution severity maps, which aggregate data on local climate, environmental conditions, and pollution levels, provide a comprehensive visual reference and valuable resources for utility operators and engineers. These maps help with risk assessments, insulator selection and dimensioning, and maintenance schedules, ensuring that transmission lines are equipped to withstand local environmental stresses (Denis & Schrorch, 1981; Liang et al., 2020; Pons & Jeanmaire, 2022; Nigris, 2022, 2023; Volpov & Kishcha, 2017; Zhiyi, 2016).

Given these challenges, addressing unexplained faults in transmission lines, particularly those caused by pollution-induced flashovers on high-voltage insulators, is of paramount importance. Utilities need to stay ahead of these risks to meet the rising demand for dependable, cost-effective, and sustainable electricity distribution that is also environmentally friendly.

1.2 Problem Statement

Ethiopia's national transmission network is a vital infrastructure, responsible for supplying electricity across the country and facilitates power exports to neighboring nations. The network comprises high-voltage AC transmission lines operating at 500 kV, 400 kV, 230 kV, and 132 kV, as well as a 500 kV DC line that connects Ethiopia to Kenya, enabling international power exports. Currently Ethiopia exports power to Djibouti, Sudan, and Kenya, with plans underway to extend this network to Somaliland and South Sudan. The state-owned electricity provider, Ethiopian Electric Power (EEP), is responsible for the development, construction, management, and operation of power plants and transmission infrastructure, and export of electricity. It owns and operates the national power grid, which is organized into nine operational regions to efficiently manage this extensive network: Each of

these regions faces unique environmental and climatic conditions, which present distinct challenges for maintaining the reliability of the transmission network (EEP, 2022; Parsons Brinckerhoff & EEP, 2014).

Despite considerable expansion in Ethiopia's power infrastructure in recent years, the national transmission network is experiencing a high frequency of unplanned outages and unexplained faults. Many of these faults arise from external environmental factors, which present serious reliability challenges and threaten the stability of the entire power system. The growing number of unexplained faults has led to substantial revenue losses for the utility, primarily due to the large amounts of unserved energy each year. Consumers, in turn, are subject to frequent power interruptions, degraded power quality, and voltage fluctuations, which contribute to widespread dissatisfaction and technical complications. Long-term operational data collected from Ethiopian Electric Power (EEP, 2022) has highlighted the extent of these reliability issues, showing that unexplained faults have reached critical levels that demand immediate attention from stakeholders.

A significant portion of the recorded faults occur on transmission lines operating at voltages ranging from 132 kV to 400 kV. Between 2015 and 2022, approximately 8,891 unplanned outages were recorded (EEP, 2022). These faults can be broadly grouped based on their origin into two main categories as internal system faults and external environment caused faults. Internal system faults include short circuits, overvoltage, undervoltage, overloading, protection failures, equipment malfunctions, and switching surges. External environment caused faults, on the other hand, resulting from natural and human-made factors such as lightning strikes, pollution, bird activity, fires, strong winds, accidents, wildlife interference, theft, and vandalism. Environmental factors have been recognized as major contributors to the unplanned outages occurring in the EEP transmission network. However, inconsistent fault identification and recording practices within EEP complicate the process of root cause analysis. Many environmental outages are not attributed to specific primary causes but are often recorded under generic categories such as "earth faults" or labeled as "unknown transient faults" or "no-signal." This misclassification complicates fault analysis and hinders the development of effective mitigation strategies. These ambiguously categorized faults, often referred to as unexplained faults, account for a significant portion of the total transmission line faults. In contrast, internal system faults are usually well-documented with their causes clearly identified (Desta & Wogari, 2020; EEP, 2022).

To date, no comprehensive study has examined unexplained faults on a national grid scale, across all transmission voltage levels in Ethiopia. This research aims to fill this knowledge gap by conducting an extensive analysis of unexplained faults. The study will involve systematic collection, organization,

and processing of fault data, followed by a rigorous statistical analysis to classify these faults, retrospectively, according to their most likely root causes (Desta & Wogari, 2020; EEP, 2022).

By considering Ethiopia's specific environmental conditions, this research aims to identify the factors that significantly influence the frequency of unexplained outages. By examining these specific elements, we can better understand what drives the reliability of the transmission network. For example, Ethiopia generally experiences low average wind speeds, typically below 3 m/s, which suggests that wind is unlikely to have a significant impact on the performance of transmission lines. Thus, it is reasonable to conclude that wind is not a major contributor to these outages. Similarly, while lightning strikes can cause interruptions through direct strikes or back flashovers, protective measures such as shield wires and surge arresters are in place, minimizing its impact on unexplained outages. Furthermore, lightning effects are generally confined to the rainy seasons in highland regions and are easily detected through lightning surge counts. Switching surges are also unlikely to be a significant cause of unexplained faults due to the infrequent nature of switching operations and the fact that they do not typically coincide with the timing of these faults.

Most known causes of line faults, such as transient over-voltages from lightning or switching surges, as well as mechanical stresses from winds and storms, are well understood and have been accounted for during the design phase of transmission lines. Adequate protective mechanisms and equipment have been implemented to minimize their impact, and established maintenance practices are already in place. However, environmental factors, particularly pollution-induced and bird-related insulator flashovers, have not been adequately addressed in the design phase. As a result, these factors are likely to contribute more significantly to the high frequency of unexplained outages within the EEP network compared to other known causes.

The lack of attention to pollution-related concerns during the design and maintenance phases has resulted in a considerable number of unexplained outages, undermining the reliability of transmission lines. This situation highlights the need to adopt a targeted approach to better understand and address these challenges. As Ethiopia's transmission network faces increasingly complex environmental stressors, conducting a detailed investigation into these pollution-related problems and their impact on insulator performance is essential for improving system reliability and operational efficiency. Through this research, effective strategies for enhancing the resilience and reliability of Ethiopia's power transmission infrastructure will be identified.

Preliminary investigations, based on operational reports, line patrol assessments, and maintenance records, as well as insights from EEP engineers and maintenance personnel, suggest that many outages are linked to pollution, specifically pollution-induced flashovers of insulators caused by environmental

contaminants and bird activity. However, these sources of outages are rarely documented as primary fault causes in EEP's reporting systems. This under recognition may stem from the absence of specific fault categories for pollution and bird-related flashovers in EEP's fault reporting formats and substation logbooks. Also, these faults often lack visible physical evidence, complicating identification and response efforts by maintenance teams. Consequently, these faults are often misclassified or recorded under more generic categories, making it difficult to address them directly.

Visual inspections and long-term operational records show that many insulator flashover incidents can be attributed to inadequate dimensioning and improper selection of insulators for the local environmental conditions. EEP's current practice of using uniform insulator designs across regions with diverse climatic and environmental challenges often results in unexpected failures. In regions such as agricultural lands, industrial areas, deserts, or coastal zones, insulators are exposed to varying levels of contamination, intensifying the risk of pollution-related flashovers.

This research aims to address these knowledge gaps by evaluating the performance of insulators across Ethiopia's diverse climatic and environmental conditions. The findings will provide a foundation for targeted interventions to improve the network's reliability, support the country's growing economy, and meet international energy export commitments.

1.3 Literature Review

This section provides insights into the key factors affecting the performance of transmission lines, particularly focusing on unexplained faults. It forms a crucial framework for this research and is structured into three main parts, each addressing critical aspects of the research focus. The first part explores the leading causes of unexplained faults in transmission lines, which is essential for developing effective mitigation strategies. The second part discusses the basic theory behind insulator pollution flashover, a phenomenon that affects the reliability of transmission systems. The third part presents an overview of the performance of ceramic and non-ceramic insulators under varied environmental conditions, emphasizing the importance of targeted research in this area.

1.3.1 Leading Causes of Unexplained Faults on Transmission Lines

Transmission lines play a crucial role in electrical power systems by transporting electricity over long distances. However, they are susceptible to various faults originating from both natural phenomena and human activities, making detection and mitigation challenging. To improve the reliability of the power system and reduce service interruptions, it's essential to have a thorough understanding of the main causes of these faults. This section will explore the main factors contributing to unexplained faults on transmission lines, including pollution flashover, lightning strikes, wildlife interactions, tree contact, fires, bird-related faults (commonly referred to as bird streamers), switching surges, adverse

weather conditions, and various forms of external interference such as equipment failures, animal interactions, accidents, external damage, poor workmanship, impacts from foreign objects, theft, and vandalism (Bevanger, 1994; Bin et al., 1998; Hathout & Callery, 2015; Koval & Chowdhury, 2005; Liang et al., 2020; Martin, 2016; Volpov & Katz, 2016; Volpov & Kishcha, 2017).

Among the most significant causes of unexplained faults is insulator pollution flashover. This phenomenon occurs when contaminants such as dust, salt, industrial pollutants, and other particulate pollutants accumulate on the surfaces of insulators. When these pollutants become wet due to fog, dew, or rain, they form a conductive layer that leads to leakage currents and, ultimately, electrical surface discharges, resulting in flashover events. Pollution-induced flashovers are especially common in coastal, desert, industrial, urban, mining, and agricultural areas, where pollution levels tend to be higher. Local meteorological conditions, including humidity, temperature, and rainfall, further influence the severity of this problem (Che et al., 2024; José A. Ramos Hernanz et al., 2006; Lambeth, 1971; Mavrikakis et al., 2017; Salem et al., 2022).

Another major contributor to faults in transmission lines is lightning strikes. The electrical surges generated by direct strikes to conductors or towers, as well as back flashovers, can induce transient overvoltage across insulators, resulting in flashovers and insulation breakdown. Lightning that strikes the ground near transmission lines can also induce voltages on conductors, further intensifying the risk of insulation failure. This risk is particularly pronounced in areas with frequent thunderstorms, where the incidence of lightning strikes considerably increases during rainy seasons. Although protective measures such as improving tower footing resistance, installing surge arresters, and shield wires are commonly employed to mitigate lightning effects, the unpredictable nature of these phenomena leaves power systems vulnerable to such risks (Bin, 2010; Chao et al., 2017; Li et al., 2020; Yao et al., 2014).

Fires, particularly wildfires in proximity to transmission lines, can result in unexplained outages by damaging transmission components and creating conductive paths through smoke and particulate matter suspended in hot air, ultimately leading to line-to-ground faults. The intense heat generated by fires can weaken structural components, triggering faults and widespread power outages that necessitate costly repairs. These types of faults are more common in regions susceptible to wildfire, particularly during dry and hot periods (Mitchell, 2013; Pu et al., 2015).

Bird-related faults also contribute to the incidence of unexplained outages in transmission systems. The nesting and perching behaviors of birds on transmission towers can lead to faults through several mechanisms. These faults occur in three principal ways, the first two are related to pollution (Bird pollution, or type A, and Bird streamers, or type B), while the third pertains to external interference, resulting from nesting, collisions with conductors, and bird electrocution, which are primarily

occurring on lines designed to operate at 132 kV and below. For example, droppings from larger bird species can form conductive paths between conductors and grounded structures, causing single-phase-to-ground faults and equipment damage. Bird-related faults tend to be more prevalent near bodies of water and agricultural areas, where bird populations are typically concentrated. This interaction between wildlife and electrical infrastructure underscores the need for effective management strategies aimed at reducing these occurrences and enhancing system reliability (Ding et al., 2021; Rooyen et al., 2002; Zhou et al., 2009).

Switching surges related to operational activities can also lead to unexplained outages. These transient overvoltages typically occur during the energization or de-energization of transmission lines and when switching varies power conditioning and controlling equipment, resulting in insulation breakdown and flashovers, which subsequently increase maintenance costs (Hamza et al., 2019; Shaikh et al., 2018; Vasileva & Stanchev, 2020).

External interferences constitute another major factor that can undermine the reliability of transmission lines. This category encompasses adverse weather, equipment failures, foreign object interference, animal interactions, accidents, and hardware failures. Severe weather conditions, such as strong winds, heavy rainfall, snow, ice accumulation, and extreme temperatures, can physically damage transmission lines and components, leading to a higher rate of faults. These conditions can lead to sagging conductors, increased mechanical stress on towers, insulator flashovers, conductor galloping, and, in severe cases, complete line failures, particularly in regions prone to extreme weather events. The growth of vegetation, particularly during storms, can cause branches or entire trees to come into contact with power lines, resulting in faults and subsequent outages, which incur increased maintenance costs. Implementing proper vegetation management practices is, therefore, essential for minimizing interference risk and ensuring a continuous power supply (Hathout & Callery, 2015; Martin, 2016).

Foreign objects, including balloons, kites, and tree branches, as well as animals like squirrels and rodents, can create conductive paths or cause physical damage to components through contact with transmission lines (Bevanger, 1994). Accidents, such as vehicle collisions with transmission towers or construction activities near transmission lines, can cause physical damage (Reddy et al., 2022; Yang, 2022). Additionally, hardware failures may result from aging infrastructure, manufacturing defects, or inadequate workmanship during installation and maintenance, or human error, leading to various faults and increased maintenance costs (Martin, 2016). Theft and vandalism pose substantial risks, as they can also result in significant damage to transmission infrastructure. Thieves usually steal valuable components like conductors and steel tower members, while vandals may intentionally damage equipment such as line insulators (Bevanger, 1994; Hathout & Callery, 2015; Martin, 2016; Reddy et al., 2022; Yang, 2022). Consequently, identifying the leading causes of unexplained faults on

transmission lines is imperative for developing effective mitigation strategies. By examining the complicated interactions between transmission lines, environmental stressors, wildlife, human activities, and external interference, power system operators can develop targeted interventions to reduce fault occurrences and enhance the overall reliability of transmission networks.

1.3.2 Insulator Pollution Flashover as a Cause of Faults on Transmission Lines

Insulator pollution flashover presents a considerable challenge for the reliability of power transmission systems, often leading to unexpected faults that can cause widespread outages, equipment damage and increased maintenance costs. The flashover process is a complex interaction influenced by multiple factors, including insulator surface properties, types of pollutants, local wetting conditions, and applied voltage. Understanding these interrelated factors requires studying the local climate, environment, sources of pollution, and pollutant deposition around the insulator. Additionally, visual inspections of insulator surface conditions to detect material degradation, electrical discharge marks, or surface leakage currents provide valuable data for monitoring flashover risks (CIGRE Taskforce 33.04.01, 2000; Macey, Vosloo, & de Turreil, 2004; Vosloo, 2002).

The materials from which insulators are made play a pivotal role in determining their vulnerability to pollution flashover. Insulators can be categorized as hydrophilic or hydrophobic, each reacting differently under wet conditions (CIGRE Taskforce 33.04.01, 2000). Hydrophilic insulators, generally composed of ceramic materials, tend to become completely wet when exposed to moisture, forming a continuous film of electrolyte that enhances conductivity. This characteristic makes ceramic insulators more susceptible to flashover under wet conditions. In contrast, polymeric insulators, particularly those made from silicone rubber, show hydrophobic properties that cause water to bead into distinct droplets rather than forming a continuous conductive layer. This hydrophobic behaviour can significantly reduce the risk of flashover by preventing widespread conductivity across the surface, highlighting the impact of insulator material properties on pollution flashover risks (CIGRE Taskforce 33.04.01, 2000).

The phenomenon of pollution flashover in ceramic insulators progresses through a series of sequential stages, influenced by environmental and physical factors. Initially, pollutants accumulate on the insulator surface over time, forming a layer that includes dry contaminants such as dust, salts, alkalis and industrial pollutants, as well as wet contaminants such as salt spray that appear in humid or coastal regions. Dry contaminants require a wetting process, whereas liquid contaminants like salt spray increase the immediate flashover risk by forming a conductive electrolyte layer. Subsequently, environmental factors such as fog, light rain, or melting snow wet the surface, making the pollution layer conductive, which can either trigger current flow or, in cases of heavy rain, flush soluble contaminants away or create bridging conducive to flashover. When the conductive layer forms,

leakage current begins to flow across the energized surface, generating localized heating that initiates partial drying of the layer. These uneven drying forms “dry bands,” which are non-conductive regions with high resistance, temporarily interrupt current flow, resulting in a buildup of line-to-earth voltage across them. As this voltage increases, it raises the electric field strength across the dry bands, eventually leading to a breakdown of the air gap, when it exceeds the dielectric breakdown threshold of air, approximately 3 kV/mm. These arcs, occurring across the dry bands, increase leakage current and are sustained by the resistance of undried pollution layers. If the undried sections maintain low resistance, arcs persist and propagate, eventually spanning the insulator and completing a flashover. This progressive arc development decreases overall series resistance, raising the current flow until the flashover ultimately leads to a line-to-earth fault (Che et al., 2024; CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008; José A. Ramos Hernanz et al., 2006; Lambeth, 1971; Mavrikakis et al., 2017; Salem et al., 2022).

Pollution flashovers trigger single-phase-to-ground faults, causing temporary outages. Repeated flashovers over time can deteriorate insulator materials and associated components, resulting in increased maintenance costs and potentially reducing the reliability of the power transmission network (CIGRE Taskforce 33.04.01, 2000; Macey, Vosloo, & de Turreil, 2004; Vosloo, 2002). Beyond affecting insulator surfaces by causing flashover, surface erosion, and material degradation, pollution also influences the aging and corrosion of metal fittings and connectors used in high-voltage (HV) insulators. This exposure accelerates the deterioration of metal components, compromising the overall insulator performance and resulting in premature failures that require earlier replacements and lead to increased operational costs and posing additional risks to the reliability of the power transmission network (Lambeth, 1971; Benguesmia et al., 2015; Dimitropoulou et al., 2015).

Research about insulator pollution flashover issues has been extensive and global. In China, studies have focused on pollution severity in industrial and coastal areas to address the outdoor insulation challenges posed by pollution flashovers. European countries such as Italy, France, Greece and Spain have also investigated the effects of industrial and coastal pollution on the integrity of outdoor insulation systems and grid stability. Additionally, countries such as Iran, Saudi Arabia, Egypt and Israel have also examined the impacts of desert and industrial pollution on the reliability of their transmission lines and implemented targeted mitigation measures to minimize the risks of pollution flashovers in overhead transmission systems. In South Africa and Brazil similar studies have been conducted on coastal and industrial pollution, contributing to a broader understanding of the critical challenges insulator pollution flashover pose in the reliability of power transmission systems. Global experiences indicate that a thorough understanding of pollution types, sources, and environmental factors is essential for effectively mitigating the risks associated with pollution flashovers. By

addressing these complexities, power utilities can better manage their transmission systems, enhancing both operational reliability and economic efficiency (Dimitropoulou et al., 2015; Liang et al., 2020; Nigris, 2022; Pons & Jeanmaire, 2022; Volpov & Kishcha, 2017; Wesley & Garcia, 2022; Zhiyi, 2016; Shariati et al., 2006; Abouelsaad et al., 2013; Al-Hamoudi & Al-Hamouz, 2003; Zedan & Akabar, 1991).

In addressing pollution flashover issues in high-voltage (HV) transmission lines, China's experience serves as a significant case study in the development of robust insulation strategies and technologies. Historically, pollution flashovers have posed substantial threats to grid reliability in China, especially in industrial regions, resulting in numerous outages from the 1950s to the 1990s. These pollution-induced outages reached critical levels in the 1970s and 1980s, leading to widespread power disruptions. Over time, China has successfully mitigated pollution-induced outages through targeted improvements in insulator technology, enhanced pollution monitoring, and proactive measures. Specifically, the integration of silicone rubber (SR) composite insulators since the 1980s has proven essential in enhancing insulation resilience in polluted environments. Furthermore, China's extensive research on pollution flashover mitigation has been instrumental in ensuring robust grid reliability, evidenced by the significant reduction in pollution-related outages since 2007 (Liang et al., 2020; Zhiyi, 2016).

China's comprehensive approach to managing pollution flashovers also involved proactive pollution monitoring and insulator design adjustments tailored to specific regional pollution characteristics. The establishment of over 23,390 measurement points by 2014, managed by the State Grid Corporation of China (SGCC), allowed for real-time pollution severity assessments, facilitating pollution severity mapping that identifies high-risk areas and informs maintenance and design adjustments. Additional strategies, such as ensuring insulator dimensioning exceeds typical pollution loads and studying pollution accumulation rates, allow China to maintain system resilience even under extreme conditions. The country's experience offers valuable insights for regions facing similar environmental challenges; by implementing advanced insulator technologies, establishing measurement networks, performing statistical analysis on outage events, and adapting insulator designs, other regions can enhance their transmission reliability and better manage pollution flashover risks (Liang et al., 2020; Zhiyi, 2016).

1.3.3 Performance of Ceramic and Non-Ceramic Insulators

Maintaining the integrity of insulators in high-voltage transmission systems is essential for ensuring reliable and cost-effective power grids. Their performance is influenced by factors, including physical dimensions (creepage distance, arcing distance, shank diameter, shed diameter, and profile), the type

of material, climatic and environmental conditions, as well as power system variables (power frequency and impulse over-voltages). This complexity highlights that outdoor insulators must be properly selected and dimensioned to meet pollution performance requirements and voltage withstand capability. The pollution performance of insulation is a key component of the overall insulation coordination design, and the final solution must consider all aspects of insulator performance (Abouelsaad et al., 2013; Baker et al., 2009; CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group 33.04, 1979; CIGRE Working Group C4.303, 2008; Feilat & Al-Maqrashi, 2011; Fontana et al., 2006; IEC/TS 60815-1, 2008; Jiang et al., 2016; Lambeth, 1971; Li et al., 2010; O & Gorur, 1998; Richards et al., 2003).

Ceramic insulators, including porcelain and glass, have long been popular choices due to their high dielectric strength and resilience to temperature variations. These insulators are known for their durability and ability to endure mechanical stresses and harsh weather conditions. However, they are also bulky, complex to install, and susceptible to performance degradation in polluted environments due to their hydrophilic surface properties. These limitations have led researchers and utility companies to explore alternatives, particularly in areas where environmental pollution is severe.

To address these challenges, non-ceramic insulators (NCIs), also known as polymeric or composite insulators, have become increasingly popular over the past few decades. Compared to traditional porcelain and glass insulators, NCIs offer a range of advantages, including reduced weight, easier transport and installation, improved resistance to vandalism, and enhanced performance in polluted environments. Silicone rubber (SR) and ethylene-propylene-diene-monomer (EPDM) rubber are the most common materials used in NCI housings (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group 33.04, 1979; CIGRE Working Group C4.303, 2008; Gubanski, 2005; IEC/TS 60815-1, 2008). The superior performance of these materials is attributed primarily to their surface hydrophobic properties, preventing water from spreading into a conductive layer, thereby reducing leakage current and the likelihood of flashovers in polluted or wet conditions (Gubanski, 2005; CIGRE Taskforce 33.04.01, 2000).

Silicone rubber composite insulators exhibit excellent antipollution flashover capabilities with flashover or withstand voltages 2–3 times higher than those of porcelain insulators under identical pollution and wetting conditions. In addition, polymeric coatings (primarily RTV silicone rubber) and resistive/semiconductive glazes have been adopted to enhance the performance of ceramic and glass insulators. Many investigations conducted in both laboratory and field conditions have validated this performance advantage (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group 33.04, 1979; CIGRE Working Group C4.303, 2008; IEC/TS 60815-1, 2008).

Despite their advantages, non-ceramic insulators are still susceptible to degradation over time, especially under environmental and electrical stresses. Environmental factors like pollution, ultraviolet (UV) radiation, high temperatures, humidity, chemical exposure, sand erosion, and biological growth can degrade the hydrophobic properties of their housing materials, ultimately leading to performance deterioration (Gubanski, 2005). Also, repeated exposure to electrical stress, such as corona discharges and transient overvoltage events can lead to electrical punctures and localized breakdowns which erode the surface of polymeric insulators and accelerate aging, potentially compromising their long-term reliability. While their antipollution flashover capabilities are well-documented, these aging processes raise concerns about the long-term durability of NCIs in harsh environments (Gubanski, 2005; Pylarinos et al., 2015).

Several studies have examined how ceramic and non-ceramic insulators perform under varied environmental and operational conditions. For instance, Vosloo (2002) conducted a comparative study in South Africa, assessing different insulator materials and coatings exposed to harsh marine pollution. To ensure accurate material performance comparisons, all non-material design variables such as creepage distance, connecting length, inter-shed spacing, and profile were carefully controlled across the tested insulators. The test, conducted over a one-year period with new insulators, monitored leakage current, electrical discharge (corona) activity, climatic and environmental data. Continuous observations and material analyses of the exposed insulators were performed. Statistical analysis of the peak leakage current, peak leakage current waveform, surface conductivity, accumulated electrical charge, and critical flashover voltage was conducted using multiple regression techniques correlated measured electrical performance with environmental influences. The findings indicated a strong correlation between electrical and environmental parameters, leading to a ranking of various materials and coatings based on their performance. Vosloo (2002) concluded that insulator performance under polluted conditions could largely be attributed to the insulation materials used and the environmental factors involved.

In Fernando (1999) and Fernando & Gubanski (2000), non-ceramic insulators were tested in field and laboratory settings to assess their performance in the tropical environment of Sri Lanka. Three different types of 33 kV insulators (Silicone Rubber (SR), EPDM, RTV-coated porcelain, and porcelain), both energized and non-energized, were installed at three test sites exposed to marine, industrial, and clean environments. The insulators' performance was periodically evaluated through visual inspections, hydrophobicity classification, and pollution severity measurements (ESDD and NSDD) over three and a half years. The results showed that silicone rubber and RTV-coated porcelain insulators generally preserved their hydrophobic properties, while EPDM insulators exhibited significant surface changes. Porcelain insulators experienced flashovers and displayed signs of surface degradation on multiple

occasions. Consequently, porcelain insulators were rated as the least effective, while SR and RTV-coated insulators demonstrated superior performance, with EPDM insulators showing noticeable surface degradation and loss of hydrophobicity.

Moreover, Fernando (1999) and Kumara & Fernando (2020) conducted a biological growth study on porcelain and SR insulators from Sri Lanka and Tanzania to evaluate their impact on surface material degradation and flashover performance. Laboratory tests included assessments of surface hydrophobicity, surface conductivity, and leakage current measurements under DC voltage, alongside dry and wet flashover tests. The results indicated that algae growth had a minimal impact on surface hydrophobicity and conductivity under wet conditions, suggesting that biological growth was minimally conductive. The measured leakage current was found to be in the microampere range, indicating low surface conductivity comparable to clean surfaces. However, algae contamination reduced hydrophobicity and flashover voltage in laboratory tests. The studies suggested that while biological contaminants can grow on various silicone rubber surfaces, their overall effect on insulator performance remains minimal.

Despite the growing use of non-ceramic insulators, concerns continue about their long-term electrical performance and material lifespan. The hydrophobicity of silicone rubber can recover after temporary losses due to environmental stress, but sustained degradation may lead to irreversible loss of performance (CIGRE Taskforce 33.04.01, 2000; Gubanski, 2005; IEC/TS 60815-1, 2008; Pylarinos et al., 2015). Given the widespread use of NCIs in new transmission projects across Ethiopia and other regions with similar climates, further studies are needed to assess the long-term durability of these materials in diverse environmental conditions.

1.4 Research Objectives

Based on the background developed in this research and opinions of EEP engineers and maintenance personnel, it is suggested that pollution induced insulator flashover (from both pollution flashover mechanisms; the wetting of pre-deposited pollution and instantaneous pollution such as bird streamer) is a major source of the excessive number of unexplained outages occurring in the Ethiopian electric power transmission lines. Given the recognized advantages of fault root cause identification, the research outlined in this dissertation was conducted by focusing on the following research objectives.

1.4.1 General Objective

The general objective of this research is to investigate unexplained transmission line faults in the Ethiopian transmission network and identify their root causes, with a particular focus on pollution induced flashover of insulators and to develop a GIS-based pollution severity map for the country, in

order to enable the implementation of targeted mitigation strategies, ensuring a safe and reliable operation of power transmission networks.

1.4.2 Specific Objectives

The above general objective is realized by answering the following research questions through five specific objectives:

Objective 1: To statistically analyze characteristics and patterns of unexplained faults in the Ethiopian transmission network and to identify, in retrospect, their root causes and outline appropriate mitigation measures (**Paper-I**).

The research questions that align with this research objective:

- What are the primary causes of unexplained faults in the Ethiopia transmission network, and how can they be accurately identified and categorized, in retrospect?
- How effective are current monitoring and maintenance procedures in detecting and preventing unexplained faults on transmission lines?
- What are the statistical characteristics of these unexplained faults over the years and how do they impact the fault frequency performance of lines and their percentage contribution?
- What are the spatiotemporal distributions of these unexplained faults across different EEP grid regions, and how do they correlate with environmental and climatic conditions and rainfall regimes?
- What mitigation measures can be proposed to reduce the occurrence of unexplained faults based on identified patterns and root causes?

Objective 2: To assess design practices and climatic and environmental conditions for insulator selection as well as to review outdoor insulation problems related to pollution in Ethiopian transmission and distribution systems (**Paper-II**).

This will be employed to answer the following research questions.

- What are the most common insulator material used in Ethiopian transmission and distribution systems?
- What are the most common types of insulation failures observed in the EEP transmission and distribution systems, and what are their primary causes?
- How effective are current insulator materials and design practices for outdoor insulators used in the EEP transmission in mitigating pollution-induced flashovers, and what improvements can be made?

- How do local climatic and environmental conditions impact the performance and prolonged life of outdoor insulators on transmission lines in Ethiopia?
- What environmental pollution factors, including pollution type and levels, influence site pollution severity class and the selection criteria for outdoor insulators in different EEP grid regions?
- How effective are the existing maintenance strategies in reducing pollution related insulation problems across different EEP grid regions?

Objective 3: To identify pollution induced insulator flashovers in Ethiopian power grid and investigate their geographical and temporal distribution to identify the most affected regions and transmission lines as well as to evaluate the performance of various insulator types installed in the network (**Paper-III**).

With this objective in mind, it is possible to answer the following research questions.

- What are the methods to identify, in retrospect, the pollution induced unexplained faults?
- What are the characteristic patterns and conditions for pollution induced flashover?
- How can the EEP grid regions be classified based on the type and severity level of pollution they experience and the similarities in seasons for creating conducive conditions for pollution flashover to occur?
- What are the primary sources and types of environmental pollution prevalent in each grid, and how do they vary seasonally?
- How do local meteorological conditions, such as rainfall, number of rainy days, relative humidity, temperature, and wind patterns, influence the accumulation and wetting of pollutants on insulators?
- How the spatiotemporal distribution of pollution induced flashover varies in Ethiopia?
- How does the frequency of pollution-induced flashovers of insulators vary across different geographical regions of Ethiopia and what types of pollutants are most commonly responsible for flashovers?
- Which specific grid regions are identified as hotspots for pollution-induced flashovers, and what characteristics make these regions more susceptible?
- Which transmission lines experience the highest incidence of pollution-induced flashovers, and what are the common factors among these lines?
- How do composite polymeric insulator performed in the diverse (humid, tropical and desert) climatic and environmental conditions and topography of Ethiopia?

Objective 4: To examine the spatial and temporal variation of fine particulate matter (PM_{2.5}) density in Ethiopia using satellite estimates, for the application of outdoor insulator design as well as to create a PM_{2.5} density map.

To achieve this objective, the following research questions are addressed:

- What methods and tools can be used to assess fine particulate matter in Ethiopia?
- How can satellite data be processed and utilized for the analysis PM_{2.5} density and to create a comprehensive PM_{2.5} density map for specific regions in Ethiopia?
- What are the major sources of particulate matter in different regions of Ethiopia and factors affecting their spatial distribution?
- How does the spatial distribution of PM_{2.5} density vary across different geographic regions of Ethiopia over time?
- What are the temporal trends in PM_{2.5} density over different seasons and years?
- What are the implications of PM_{2.5} density variations on the performance of outdoor insulators?
- How do the PM_{2.5} density variations correlate with the distribution of pollution induced faults across grid regions of EEP?

Objective 5: To estimate the site pollution severity parameters on carefully selected locations and develop a GIS-based pollution severity map for Ethiopia.

To achieve this objective, the following research questions are addressed:

- How can the site pollution severity (SPS) parameters be accurately estimated and mapped for the Ethiopia transmission network according to IEC standard?
- What are the key climatic and environmental factors influencing pollution severity in different regions of Ethiopia? How can these factors be used to estimate site pollution severity level?
- How can long-term service experience data (e.g., outage and line patrol reports, field visual inspection, maintenance records) from existing transmission lines be used to estimate site pollution severity level?
- How do the long-term service experiences of existing transmission lines correlate with the estimated pollution severity in various locations across Ethiopia?
- Which locations in Ethiopia exhibit the highest and lowest pollution severity levels based on current data?
- What are the implications of estimated pollution severity on the maintenance and reliability of transmission lines in Ethiopia?

- How can a GIS-based pollution severity map be developed for Ethiopia, and what are its implications for the selection and dimensioning of outdoor insulators?

1.5 Scope of the Research

This study aims to conduct a comprehensive examination of the primary factors contributing to unexplained faults in Ethiopia's transmission network, particularly those originating from environmental influences. The growing incidence of such faults highlights the need to investigate their root causes and the implications for network reliability. Central to this research is an in-depth analysis of pollution-induced flashovers in insulators—an often overlooked yet critical aspect affecting transmission line performance. By addressing this area, the study seeks to provide practical insights for utility operators, ultimately enhancing the reliability and resilience of Ethiopia's power transmission infrastructure.

The primary focus of this research is to thoroughly assess the insulation challenges confronting Ethiopia's transmission and distribution networks. This will involve a detailed evaluation of the materials and design practices currently employed for outdoor insulators, with particular consideration for environmental stressors. The aim is to assess the adequacy and performance of these insulators and identify areas for improvement that could mitigate insulation failures. Through an examination of existing practices, the study intends to drive enhancements in insulator performance to better respond to Ethiopia's diverse climatic and environmental conditions.

The research will also analyze the local climate, meteorological, and environmental factors impacting insulator performance, especially in areas vulnerable to pollution. This aspect includes a geographical analysis of regions surrounding transmission corridors, with a focus on understanding how environmental conditions influence the behavior and effectiveness of different types of insulators used in transmission and distribution networks. By examining these local factors, the study aims to provide crucial insights into the unique challenges posed by Ethiopia's environmental landscape.

Additionally, the study will incorporate an analysis of long-term operational service data and records of unexplained faults within Ethiopia's power transmission network. This data-driven approach will allow for identifying correlations between environmental pollution levels and flashover occurrences. Establishing these links will contribute to a clearer understanding of how environmental stressors impact transmission line reliability.

An essential outcome of this research will be estimating pollution severity parameters and developing a GIS-based pollution severity map for Ethiopia. This map will provide utility operators with vital data for assessing pollution impacts on transmission lines, planning new installations, evaluating insulator

performance, and optimizing maintenance strategies. By visualizing pollution levels across the country, the map will enable more informed decision-making regarding insulator selection and dimensioning, tailored to the specific environmental stresses in each region, which ultimately supports a more resilient power transmission system.

The scope of this research includes all nine operational regions within Ethiopia's transmission network, encompassing areas with diverse environmental conditions such as deserts, agricultural zones, mining and industrial areas, urban centers, and near-coastal deserts. This analysis will use transmission line fault data collected over eight years (from 2015 to 2022) alongside georeferenced climatic, meteorological, and environmental data. The study will examine key meteorological patterns like rainfall, temperature, relative humidity, wind speed and direction, and solar radiation. It will also explore environmental aspects, including land use, topography, soil properties, and the distribution and concentration of particulate matter.

In summary, this research aims to address existing gaps in understanding unexplained transmission faults by examining the complex interactions between environmental stressors and insulator performance. By developing a robust framework for assessing pollution-induced flashovers and creating practical tools, such as the GIS-based pollution map, the study will contribute to the sustainable management of Ethiopia's power transmission network.

1.6 Significance of the Study

This research addresses key challenges in the reliability and performance of transmission networks, especially in regions where environmental factors, like pollution, compromise insulator functionality. Faults on transmission lines can cause extensive outages and voltage instability, resulting in operational challenges and financial burdens for both utilities and their customers. Thus, comprehensive understanding and managing the causes of these faults is essential for sustaining a stable and reliable power system.

This study is particularly important due to its focus on the statistical analysis of unexplained faults and an in-depth evaluation of design practices for outdoor high-voltage insulators. By concentrating on pollution-induced flashovers and their effects on transmission line reliability, this research aims to enhance the overall safety and performance of power systems. Analyzing transmission line fault patterns and root causes, the study aims to deliver actionable insights that enable utilities to implement more effective mitigation strategies. These insights could reduce unexpected outages, thereby improving service quality and customer satisfaction.

With an improved understanding of fault causes and patterns, utilities (EEP and EEU) can make well-informed decisions on resource allocation, ultimately reducing maintenance and enhance operational

efficiency. Evaluating insulator design practices alongside an analysis of local environmental stressors will contribute to better performance and longevity, reducing the frequency of failures and the need for premature replacements. Furthermore, comparing various insulator materials across diverse environments will provide insights to help utilities choose insulators best suited to specific environmental conditions.

This research also intends to develop methodologies for estimating pollution severity and to create a pollution severity map that will support utilities in both operational and strategic planning. The map will facilitate assessments of insulator performance under varying pollution conditions and support decisions concerning new high-voltage installations like substations and transmission lines. Additionally, it will contribute to optimizing maintenance and replacement strategies for existing insulators, ensuring they are well-matched to the environmental challenges they face.

Beyond immediate operational benefits, the findings from this research also contribute to the improved selection of high-voltage insulators for polluted environments in both Ethiopia and internationally, especially in tropical regions. The insights gained will improve understanding of the performance and aging of non-ceramic insulators in such climates, positioning EEP as an informed purchaser of insulator products for present and future projects. Additionally, it encourages collaboration between academic institutions and power utility companies, creating a platform for addressing pollution-induced flashover challenges within Ethiopia's transmission and distribution systems.

By bridging knowledge gaps related to unexplained transmission line faults, this research introduces practical methodologies for estimating site pollution severity and mapping pollution levels. These tools are especially valuable in situations where direct pollution measurements are unavailable or where long-term field measurements are economically or technically challenging.

In conclusion, this research plays a crucial role in improving the reliability, efficiency, and safety of power transmission and distribution networks. By examining the root causes of unexplained faults and exploring solutions for pollution-related issues, it aims to enhance the reliability of Ethiopia's transmission lines, ultimately benefiting both utilities and their customers. The outcomes will not only contribute to academic understanding but also provide practical solutions for the power industry at large.

1.7 Methodology

The research methodology for this study is designed to systematically investigate the root causes of unexplained faults in transmission lines, with a particular focus on pollution-induced flashovers of insulators. Additionally, it aims to develop methods and tools to mitigate the impact of pollution on the reliability of the EEP transmission network. The methodology includes data collection, analysis, interpretation, and visualization. While specific methodologies for each section of the dissertation are detailed within their respective chapters, this section provides a general overview of the overall research methodology, including research design, data collection methods, data analysis, and the tools and software used in the study.

1.7.1 Research Design

This study adopts a mixed-methods approach, combining both quantitative and qualitative research methods to provide a comprehensive understanding of factors contributing to unexplained faults and unplanned outages in transmission lines.

The quantitative analysis includes:

- Statistical evaluation of historical operational and fault data.
- Examination of meteorological parameters and particulate matter density.
- Simulation and calculation of pollution severity parameters using IST software.
- GIS geospatial analysis and mapping.

The qualitative analysis includes:

- Assessment of climatic, environmental, and operational variables.
- Review of maintenance records.
- Expert interviews and field observations to validate findings.
- Analysis of existing documents, reports, and literature.

1.7.2 Data Collection and Preparation

Data collection involves gathering historical fault and operational data, environmental and climatic parameters, as well as insights from expert interviews and field observations. The collected data was processed, cleaned, and standardized to ensure consistency and reliability in the subsequent analysis.

1.7.2.1 Transmission Line Performance Data

Historical operational and fault data from the Ethiopian transmission network were collected for the period 2015 to 2022. The dataset includes information on the time (start date and time of faults),

location, duration, and original fault descriptions, assigned generic fault type, as well as line descriptions, line length, line design and operating voltages, and EEP transmission grid regions.

Given the inconsistency in fault recording, data cleaning is essential for reliable analysis. The fault data were organized, cleaned and standardized to ensure consistency and accuracy. This involves identifying and correcting errors in the collected data, including incorrect application of line naming conventions, changes in line configuration, and errors and vague descriptions by technical operators. Faults were first categorized based on their origin (internal system faults and external environmental faults) and by identifying unexplained faults among the total unplanned fault data and a dataset was prepared for root case analysis. The fault dataset was complemented with a geospatial information system (GIS) database, which includes geographic coordinates for each transmission line tower, used to locate towers (representing the actual location of in-service insulators) and to extract relevant climatic and environmental information for each tower, facilitating tower levels analyses.

Insulator performance data of different types of insulators installed in transmission lines and substations were collected. This includes information on insulators' physical dimensions (creepage distance, unified specific creepage distance, arcing distance and total length), material type and profile as well as flashover incidents and any preliminary diagnoses, line patrol and incident reports and maintenance records and environmental conditions.

1.7.2.2 Environmental and Climatic Data

Georeferenced environmental and climatic/meteorological data, including rainfall patterns, humidity levels, temperature, solar radiation, lightning activity, wind speed and direction, soil pH, and land cover and land use, were collected from multiple sources, including the Ethiopian Meteorological Agency, Climate Forecast System Reanalysis (CFSR), satellite data sources and other relevant sources. Moreover, pollution data including pollution sources and type across the country and ambient particulate matter (PM_{2.5}) levels derived from satellite estimates were gathered. This dataset facilitated the assessment of pollution levels across different regions and enabled correlation analyses between environmental conditions and unexplained faults in transmission lines.

1.7.2.3 Expert Interviews and Field Observations

Expert interviews and field observations were conducted to gain insights into practical challenges in transmission line operation and complement the quantitative analysis. The study involved:

- Interviews with EEP engineers and maintenance personnel to gather insights into operational challenges, common causes of unexplained faults, and the performance of insulators in-service.
- Field inspections of transmission lines and substations to visually assess insulator conditions and identify pollution-related flashover evidence.

- Review of operational reports from EEP, including historical maintenance records and performance evaluations.
- Questionnaire-based assessments, following IEC 60815-1:2008 recommendations, to obtain operational service experience of existing lines and substations and collect information on the behavior of in-service insulators across different grid regions.

These qualitative data sources provide context and support the findings from the quantitative analysis.

1.7.3 Data Analysis

1.7.3.1 Statistical Analysis

A statistical analysis was conducted on the collected fault data to identify patterns, trends, and their variability across different regions and environmental conditions. This analysis aimed to determine the root causes of unexplained line faults by examining correlations with environmental and operational variables. Additionally, the methods developed from this analysis helped in identifying high-risk periods and locations for transmission line faults.

The analysis focused on the following key variables:

1. Time of Day: Fault occurrences were analyzed based on the time of day to identify peak periods for unexplained faults.
2. Time of Year (Seasonal Trends): Fault data were examined to determine seasonal variations and trends in fault occurrences.
3. Rainfall Regimes: A correlation analysis was conducted between fault occurrences and rainfall patterns to assess the impact of climatic conditions on transmission line performance.
4. Geographic Location: Fault occurrences were analyzed across different grid regions to determine location-based variations in fault frequency. The performance of transmission lines was compared across various geographic areas to identify regions with higher fault incidences.
5. Voltage Levels: A correlation analysis was performed to evaluate fault occurrences at different voltage levels (132kV, 230kV, and 400kV). Transmission line performance was compared across these voltage levels to determine which had higher fault rates.

The fault data were analyzed to identify patterns in the occurrence of faults based on the time of day and time of year (season). This analysis helps in understanding the influence of diurnal and seasonal variations on fault occurrence. Fault frequency statistics (outage rates), which are expressed as the number of faults per 100 km of overhead line per year, were calculated for different rainfall regimes, voltage levels and grid regions. This metric is crucial for understanding the frequency and severity of

outages related to specific fault cause. The results from this analysis provided indicative values of fault performance of transmission lines at the respective voltage levels within the identified rainfall areas, offering valuable insights into the impact of climatic conditions on the frequency of unexplained faults.

1.7.3.2 Root Cause Analysis

A systematic approach was employed to identify the root causes of unexplained faults on transmission lines. The analysis was conducted through the following steps:

1. Literature review: An extensive literature survey was conducted to examine the major causes of unexplained faults on transmission lines. This helped in understanding the characteristic patterns associated with each fault cause, which provided a foundational basis for identifying the root causes.
2. Spatial and temporal distribution analysis: A detailed analysis of the spatial and temporal distribution of unexplained faults was conducted. The aim of this analysis was to determine the occurrence of faults across various grid regions, voltage levels, times of day, and times of year, providing insights into potential patterns and underlying causes of these faults.
3. Methodology Development: A methodology was developed to systematically identify the possible root causes of unexplained line faults, incorporating data and findings from the literature review and distribution analysis.
4. Validation: The findings were validated by cross-referencing line patrol reports, maintenance records, and case studies conducted on selected regions and transmission lines. This validation confirmed the robustness and applicability of the findings in real-world situations.

1.7.3.3 Assessment of Insulation Problems, Design Practices and Performance of In-service Insulators

Assessment was conducted to evaluate insulation problems, design practices, and the performance of in-service insulators. The evaluation involved the following key steps:

1. Field Investigations and Observations: Visual inspections of transmission lines and substations were performed to assess the condition and performance of insulators. These inspections aimed to identify common failure modes and their correlation with environmental factors, particularly pollution flashovers. Physical evidence of damage related to contamination was documented through on-site assessments conducted across various grid regions.
2. Review of Design Standards and Practices: The current design standards and practices for outdoor insulators used in the Ethiopian Electric Power (EEP) grid were reviewed to evaluate their effectiveness and suitability under prevailing environmental conditions.

3. Comparative Performance Analysis: The pollution performance of different types of insulators was analyzed under similar environmental conditions. This comparison helped determine the effectiveness of various insulation materials and designs in mitigating pollution-induced failures.

1.7.3.4 Analysis of Spatiotemporal Distribution of Fine Particulate Matter

A detailed analysis was conducted to examine the spatiotemporal distribution of fine particulate matter (PM_{2.5} and PM₁₀) and its potential impact on insulator performance. The assessment involved:

1. Data Acquisition: Long-term satellite data on fine particulate matter (PM_{2.5} and PM₁₀) were obtained from reliable sources such as the Atmospheric Composition Analysis Group (ACAG).
2. Spatial and Temporal Analysis: Geographic Information System (GIS) tools were utilized to integrate and analyze the satellite data. This analysis enabled the examination of the spatial distribution of particulate matter and the identification of temporal trends.
3. Pollution Impact Assessment: The study focused on identifying periods and locations of high pollution levels and assessing their potential effects on insulator performance. This helped establish correlations between pollution severity and intensity of pollution induced flashover.

1.7.3.5 Development of GIS-based Pollution Severity Map

A Geographic Information System (GIS)-based pollution severity map was developed to assess and visualize pollution levels affecting the Ethiopian power transmission network. The mapping process involved three key steps: data collection, pollution severity parameter evaluation, and GIS-based mapping.

(a) Data Collection

Relevant datasets were collected to support the development of the pollution severity map, including:

- Meteorological Data: Temperature, humidity, rainfall, wind speed and direction, solar radiation, and the number of dry days.
- Climatic and Environmental Data: Pollution sources, land use, topography, and PM_{2.5} distribution.
- Grid Data: Fault records, transmission line coordinates, and insulator performance data.

(b) Site Pollution Severity (SPS) Parameter Evaluation

Site Pollution Severity (SPS) parameters were evaluated using two estimation methods:

- Climatic and environmental condition analysis to assess natural and industrial pollution sources.
- Operational service experience analysis based on the historical performance of existing transmission lines.
- Field assessments were conducted at selected points along existing overhead transmission lines and substations to validate the estimations.

(c) Pollution Severity Mapping

The GIS-based pollution severity map was developed using geospatial analysis and mapping techniques:

- Georeferenced data processing and interpolation techniques were applied to generate a continuous GIS-based pollution severity map.
- Pixel-based mapping was utilized to incorporate the impact of localized pollution sources on the transmission network.
- The final GIS-based pollution severity map was developed in compliance with IEC 60815-1:2008 standards.

1.7.4 Tools and Software Used in This Research

The following tools and software were used for data processing, analysis, visualization and mapping in this study.

1. MATLAB: Used for processing, analyzing, and visualizing fault data.
2. ArcGIS: Utilized to manage and analyze georeferenced climatic and environmental data related to transmission lines. The collected environmental and operational data were integrated into a GIS platform, where spatial analysis tools were used to develop a comprehensive pollution severity map.
3. IST software: Used to calculate pollution severity parameters based on the principle of statistical dimensioning of insulators according to IEC 60815-1. This ensured accurate assessment of pollution-related risks affecting insulator performance.

1.8 Structure of the Dissertation

1.8.1 *Outline*

This dissertation is structured into seven chapters, each addressing different aspects of the research. Chapter 1 provides the foundation and the rationale for undertaking the research and defines the objectives, scope and significance of the study. The outline of the remainder of this dissertation is as follows:

Chapter 2 presents analyses of the characteristics and underlying causes of unexplained outages in the power grid of Ethiopia. Spatial and temporal distribution patterns of the faults are statistically analyzed and a method to identify root causes of unexplained faults is presented and mitigation measures for future fault prevention are proposed.

Chapter 3 assesses design practices adopted for outdoor insulator selection as well as describes meteorological and environmental conditions that affect the performance of outdoor insulators in Ethiopian transmission and distribution systems.

Chapter 4 investigates pollution-induced flashovers problems in Ethiopian power transmission network and evaluated the performance of in-service insulators.

Chapter 5 examines the spatial and temporal variation of long-term PM_{2.5} density across grid regions using satellite estimates. Additionally, it presents the trends and statistical characteristics of the mean annual PM_{2.5} density across Ethiopia.

Chapter 6 presents methods for estimating site pollution severity (SPS) and the process of creating a GIS-based pollution severity map for Ethiopia and Chapter 7 summarizes the main findings, conclusions, contributions, and broader implications of the research conducted in this PhD dissertation. It highlights the significance of the findings, points out the limitations, and proposes directions for future research. The dissertation concludes with a References section listing all cited sources and Appendices containing supplementary materials.

1.8.2 Contribution

This dissertation is based on the following publications, referenced throughout the text by their respective Roman numerals.

- I. Desta, B.Z.; Wogari, M.M.; Gubanski, S.M. Analyses of Unexplained Faults in Transmission Lines in the Power Grid of Ethiopia. *Electr. Power Syst. Res.* 2024, 231, 110293.
- II. Desta, B.Z.; Wogari, M.M. Assessment of external insulation problems related to pollution and climatic conditions in Ethiopia. *IEEE Electr. Insul. Mag.* 2020, 6, 36–46.
- III. Desta, B.Z.; Wogari, M.M.; Gubanski, S.M. Investigation on Pollution-Induced Flashovers of In-Service Insulators in Ethiopian Power Transmission Lines. *Energies* 2024, 17, 2007.

Berhanu Zelalem is the first author of Papers I-III and conducted all the data collection, formal analysis, investigation, and visualization of these papers. Professor Stanislaw M. Gubanski and Dr. Mengesha Mamo, who are supervisors, contributed with discussions, reviewing and editing of all the papers.

CHAPTER 2

2. Analyses of Unexplained Faults in Transmission Lines

2.1 Introduction

Overhead transmission lines are exposed to various environmental conditions that can affect their performance, including lightning, pollution, and others. If these factors are not adequately addressed through design and maintenance, they can lead to decreased reliability in the power system, which may incur significant costs (CIGRE Taskforce 33.04.01, 2000; Macey, Vosloo, & Turreil, 2004). Therefore, analyzing transmission line faults is crucial for identifying the primary causes of outages and developing preventative measures.

The Ethiopian national grid, operated by Ethiopian Electric Power (EEP), encompasses a total length of 19,305 km, with standard voltage levels: 6053 km of 132 kV lines, 7996 km of 230 kV lines, and 5256 km of 400 kV and 500 kV lines (EEP, 2022). These transmission lines, averaging 40 m in width, cover an area of approximately 772.2 km², excluding substation and power station areas. Prior to 2015, the management of line faults at EEP lacked organization, as there was no standard fault categorization or consistent reporting. Although improvements in fault record accessibility have occurred since 2015, a consistent method for describing fault origins is still absent, making it challenging to trace root causes. Presently, EEP focuses primarily on fault detection, location, and phase selection, with less emphasis on diagnosing faults induced by external factors, originating from environmental conditions or surrounding activities. As a result, many such faults are classified simply as generic Earth faults, leaving their root causes unaddressed.

For this research, power outage data obtained from the national load dispatch and control center (LDC), a unit of EEP responsible for monitoring, planning, and operating the national transmission grid—was utilized, alongside substation logbooks. From 2015 to 2022, a total of 8891 unplanned outages were recorded. The dataset contains information regarding the EEP grid region, transmission line name, line length, system voltage, outage and restoration dates, time of day for each fault, and their assigned causes. Additionally, a Geographic Information System (GIS) database was created to map the geographic locations of each transmission tower and to facilitate analysis.

The data were categorized into five primary fault types: (i) Earth faults, which arise from lightning strikes on towers or earth wires, insulator failures, environmental and bird caused pollution flashovers of insulators, fires, foreign object, animal interference, and external damage; (ii) Overload faults; (iii) Overvoltage faults, linked to internal system operational events such as transformer failures, line overloads, load fluctuations, and switching surges; (iv) Miscellaneous faults within the power system,

which include outages from grid disturbances like phase to phase short circuits, large motor starting, transformer energization, hardware failures, poor workmanship, mechanical failures, fires in equipment, protection and other malfunctions; and (v) Unknown/No signal faults, where root causes are indeterminate due to inadequate fault location data, minor flash marks, lack of post fault investigations or absence of relay signals.

The compiled fault data and the analysis results, as illustrated in Figure 1, reveal an overall system performance breakdown: 35% Earth faults, 22% Overload faults, 13% Overvoltage faults, 18% Miscellaneous faults, and 12% Unknown/No signal faults. This fault dataset serves as a vital historical line performance record, which can be analyzed alongside weather and climatic trends to determine primary causes and propose effective mitigation strategies.

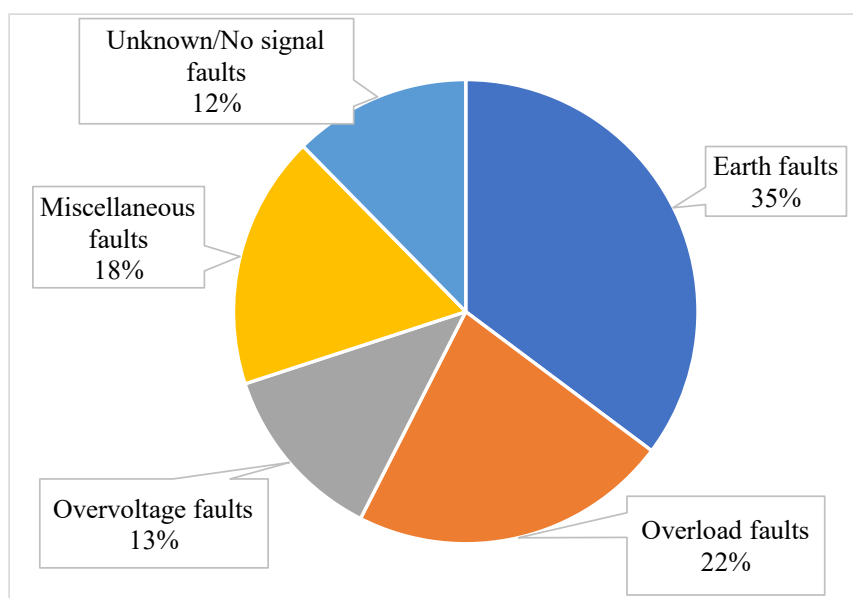


Figure 1: The relative occurrence of the major fault types on transmission line from 132 to 400 kV for the period between 2015 and 2022 (EEP, 2022).

In this study, Earth faults and Unknown/No signal faults were categorized as unexplained faults due to their unclear root causes. Collectively, these categories accounted for 47% of total faults, amounting to 4231 unexplained incidents. These faults are typically single-phase-to-ground types and exhibit a relatively high reclosing success rate, indicating that EEP's transmission network faces a significant challenge with excessive number of unexplained faults. This situation underscores the urgent need to identify the primary causes of these faults and implement corrective measures.

This chapter will focus on the statistical analysis of unexplained faults, aiming to elucidate their characteristics in relation to time of the day, seasonal occurrence across various grid regions (location), and rainfall regimes to identify their spatial and temporal distribution patterns. Understanding these factors will further inform the design, construction, and operation of Ethiopia's transmission system (Peter & Vajeth, 2005; Sandhu, 1988). Moreover, this analysis will support the development of

effective monitoring strategies, optimized maintenance procedures, and enhanced inspection techniques for existing transmission lines (CIGRE Working Group C4.303, 2008; Peter & Vajeth, 2005; Vosloo, 2009).

2.2 Identification Method of Unexplained Line Faults

To identify the root causes of unexplained faults, verification procedures were focused on looking for trends that may indicate or align with known characteristics of significant potential causes, including lightning, pollution, bird streamers, and fire. Relevant contextual fault information, such as time of the day, time of the year (season), geographic location, and the climatic and environmental conditions of the region where the faults occur, is crucial in determining their primary external causes (Bekker & Hoch, 2002; Macey, Vosloo, & Tourreil, 2004; Minnaar et al., 2016; Vosloo, 2009). Additionally, data concerning fault duration, voltage levels, and service experiences may also prove useful (Macey, Vosloo, & Tourreil, 2004; Minnaar et al., 2012; Minnaar et al., 2016; Vosloo, 2009).

Identifying line faults caused by environmental factors can be challenging. However, certain contextual characteristic patterns can assist in this identification process (Macey, Vosloo, & Tourreil, 2004; Minnaar et al., 2016; Peter & Vajeth, 2005; Sandhu, 1988). These patterns are described in greater detail below.

2.2.1 Time-of-Day of Faults Occurrence

For the fault data to align with lightning-induced events, incidents should predominantly occur in the late afternoon (13:00–19:00) during the rainy season (Bekker & Hoch, 2002; Burnham, 1995; He et al., 2015; Hu, 2007; Macey, Vosloo, & Tourreil, 2004). This pattern may vary slightly based on local rainfall conditions. Pollution flashovers caused by the wetting of pre-deposited contaminants are expected primarily between midnight and early morning (up to 8:00), coinciding with the formation of dew or mist (Bekker & Hoch, 2002; Burnham, 1995; Macey, Vosloo, & Tourreil, 2004; Major, 1993). As humidity increases during the night, pollution-induced outages become more frequent, peaking just before sunrise at around 06:00, with virtually no such faults occurring during the daytime (Bekker & Hoch, 2002; Kleinhans, 2005; Macey, Vosloo, & Tourreil, 2004; Major, 1993). Faults related to bird streamers tend to exhibit two peaks: one in the early evening around 22:00 and another in the morning around 06:00, linked to the birds' digestive cycles (Burnham, 1995; Macey, Vosloo, & Tourreil, 2004; Maehl, 1996). Studies in Florida and South Africa have revealed similar fault patterns (Burnham, 1995; Macey, Vosloo, & Tourreil, 2004; Sandhu, 1988). Figure 2 illustrates the typical daily distribution curves for the three main causes of flashovers, based on long-term analyses conducted in Florida, USA (Burnham, 1995; Sandhu, 1988) and South Africa (Macey, Vosloo, & Tourreil, 2004). In this analysis, pollution faults refer to all types of pollution flashover mechanisms,

including type A (pre-deposited pollution and wetting) and type B (instantaneous pollution) events as defined by (IEC/TS 60815-1 2008).

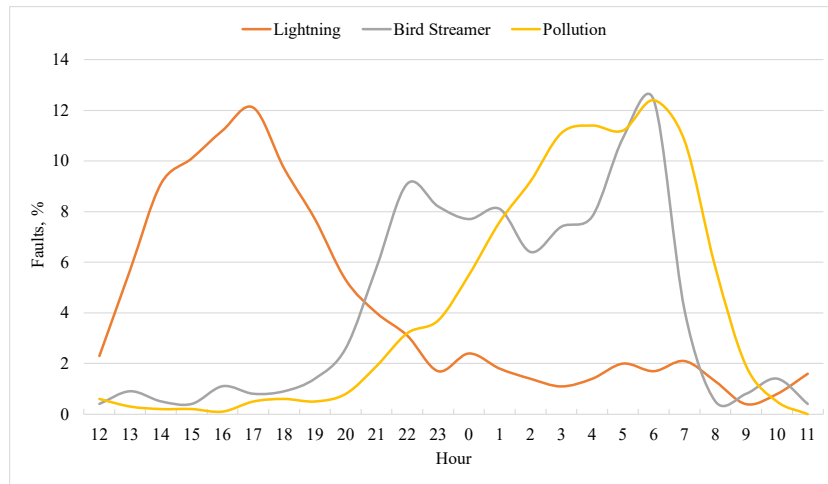


Figure 2: The typical time-of-day flashover occurrence characteristics of faults caused by lightning, pollution, and bird streamers in Florida, USA and South Africa (Burnham, 1995; Macey, Vosloo, & Tourreil, 2004).

Both pollution (from environmental factors and bird streamers) and lightning contribute significantly to the outages classified as unexplained. However, other factors such as tree contact, fire, and interference from foreign objects may also play a role (Chen, 2020; Vosloo, 2009). Fires and smoke occurring beneath transmission lines and its surroundings can bridge phase-to-phase and conductor-to-ground clearances, leading to flashovers. Most fire-induced flashovers typically happen midspan of the lines during hot midday periods (11:00 to 16:00) in dry months (Bekker & Hoch, 2002; Chen, 2020; Peter & Vajeth, 2005; Sukhnandan & Hoch, 2002; Vosloo, 2009). Similarly, tree contact faults occur when lines sag during hot, overloaded daytime conditions, especially around midday (Bekker & Hoch, 2002). Other unpredictable fault types include interference from foreign objects, external damage, theft, and vandalism, which generally lack a clear temporal pattern but are often associated with frequent human and animal activities and severe weather conditions (e.g., bird collisions or nesting, strong winds) and are more pronounced during daytime and early evening hours (Chen, 2020; Vosloo, 2009).

2.2.2 Seasonality of Faults Occurrence

When analyzing fault occurrences in relation to the time of the year, lightning-related faults typically align with specific rainy months (Macey, Vosloo, & Tourreil, 2004; Minnaar et al., 2012; Sandhu, 1988). Frequent heavy rainfall diminishes the likelihood of pollution accumulation on insulators; therefore, most pollution-induced outages are more prevalent during drier periods and seasonal transitions when fog and light rains occur after the dry season (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008; IEC/TS 60815-1, 2008; Major, 1993). Bird streamer faults

follow the seasonal pattern related to presence of birds or their feeding habits and tend to increase in frequency during spring (Burnham, 1995; Macey, Vosloo, & Tourreil, 2004; Maehl, 1996; Sandhu, 1988). Additionally, many fire-induced flashovers tend to occur during harvesting and the dry months of the year (Chen, 2020; Minnaar et al., 2012; Sukhnandan & Hoch, 2002; Vosloo, 2009).

2.2.3 Geographic Distribution of Line Faults

The spatial distribution of faults provides insight into their root causes (Minnaar et al., 2012; Peter & Vajeth, 2005; Vosloo, 2009). Lightning-induced faults are more likely to occur in areas with significant rainfall and higher elevations (He et al., 2015; Łoboda & Lenarczyk, 2014; Minnaar et al., 2012). Pollution-induced faults, which are heavily influenced by environmental conditions, are expected to occur near areas having sources of dust and pollution, such as industrial areas, intensive agricultural zones, busy roads, and coastal regions (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008; IEC/TS 60815-1, 2008; Kleinhans, 2005; Major, 1993). Furthermore, locations with abundant water and food resources for bird life are more susceptible to bird streamer faults (Burnham, 1995; Maehl, 1996; Montoya Tena et al., 2010; Moreira et al., 2023; Taklaja et al., 2013). Faults caused by fire are more likely to occur in lines traversing desert and semi-arid areas with high temperatures and abundant combustible materials such as grass and shrubs, bushes, and sugar cane farms (Sukhnandan & Hoch, 2002; Vosloo, 2009). Additionally, external interference-related faults are common in densely populated regions (Chen, 2020; Vosloo, 2009). Therefore, understanding the geographic location of a fault is crucial for identifying its cause and preventing future occurrences (CIGRE Taskforce 33.04.01, 2000; IEC/TS 60815-1, 2008; Macey, Vosloo, & Tourreil, 2004; Peter & Vajeth, 2005).

2.2.4 Climatic and Meteorological Conditions

Numerous studies have indicated that meteorological factors, including wind direction and speed, precipitation, relative humidity, and temperature, significantly influence fault occurrences on transmission lines. Thus, comprehending the climatic and meteorological conditions at the time of a fault is essential (CIGRE Taskforce 33.04.01, 2000; IEC/TS 60815-1, 2008; Macey, Vosloo, & Tourreil, 2004; Peter & Vajeth, 2005; Sandhu, 1988).

In this research, geographic coordinates for each transmission line tower in the network were determined. Meteorological parameters were then extracted for each tower's location using ArcGIS software, and an average was computed to represent the entire line's meteorological conditions.

2.2.5 System Voltage of the Line

The voltage level of a transmission line dictates its design specifications, including ground clearance, tower window size, and the necessary arcing and creepage distances as well as type of material of insulators (CIGRE Working Group C4.303, 2008; IEC/TS 60815-1, 2008; Vosloo, 2009). It also impacts the types of potential faults. Higher voltage lines, which have larger ground clearances and tower window sizes, tend to be less vulnerable to bird streamer faults. Typically, lightning impulse flashovers occur predominantly at system voltages below 300 kV (CIGRE Taskforce 33.04.01, 2000; He et al., 2015; Łoboda & Lenarczyk, 2014; Minnaar et al., 2012), while pollution flashovers are more frequent at higher system voltages (CIGRE Taskforce 33.04.01, 2000; IEC/TS 60815-1, 2008). Therefore, when the cause of a fault is uncertain, the voltage level of the affected transmission line can provide insights into its nature.

The entire dataset was carefully analyzed for consistency with the described fault characteristics. If sufficient trends emerged to suggest a particular fault type, the fault was categorized accordingly.

2.3 Statistics of Spatiotemporal Distribution of Unexplained Line Faults

2.3.1 Spatial Distribution of Unexplained Faults Across Grid Regions of EEP

The analysis includes the distribution of faults by region, time of day, and time of year, as well as their voltage levels. Figure 3 illustrates the distribution of grid disturbances across each operational region of EEP from 2015 to 2022. The Addis Ababa region reported the highest number of faults, totaling 905 (21.4%), while the South and North-West regions also recorded significant numbers of unexplained faults during this timeframe. Detailed results of frequency of unexplained faults per 100 km per year on 132, 230 and 400 kV lines across EEP grid regions can be found in Appendix B, Table A – 1, Table A - 2 and Table A - 3.

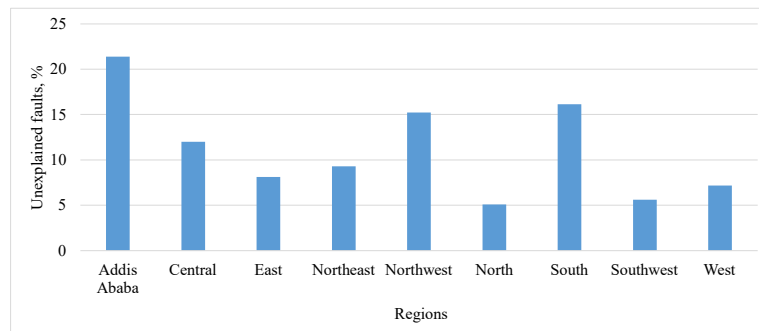


Figure 3: Distribution of unexplained faults across EEP regions during the years 2015–2022.

To facilitate comparisons and examine the spatial distribution of these unexplained faults, the centroids of each transmission line circuit were utilized to assign geographic locations to each event and estimate the prevalence of unexplained faults in terms of faults per unit length and time. The number of faults

per 100 km of transmission line per year was calculated for each circuit. This information was integrated into a Geographic Information System (GIS) database, allowing for the creation of a national-level map that displays spatial patterns using ArcGIS software. Figure 4 depicts the Ethiopian transmission grid (132–400 kV) as of 2022 (indicated by grey lines), along with the average number of unexplained faults recorded annually per 100 km of line for each circuit, represented through circles with proportionally varying radii.

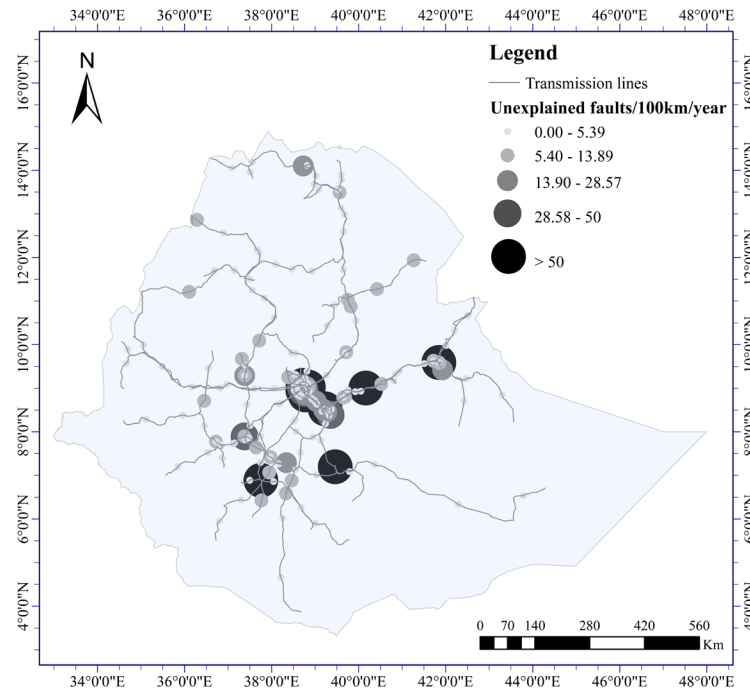


Figure 4: Spatial distribution of unexplained faults per 100 km per year across Ethiopia during the years 2015–2022.

In terms of spatial variations, unexplained faults were identified in 191 circuits, with frequencies ranging from 0.062 to 66.67 faults per 100 km per year, and an average of 9.96 faults. These circuits were predominantly located in the central, southern, and eastern regions of Ethiopia, as indicated in Figure 4. According to established standards, high-voltage transmission lines typically allow for the occurrence of 1–2 unexplained faults per 100 miles (equivalent to 0.62–1.24 unexplained faults per 100 km per year) (Maehl, 1996; Sandhu, 1988). The acceptable number of flashovers per kilometer of transmission line per year depends on the importance and location of the line. In many European countries, a rate of approximately one flashover per 150 km of line per year is generally considered acceptable (Taklaja et al., 2013). According to these benchmarks, the Ethiopian (132–400 kV) power grid has an alarmingly high incidence of unexplained faults related to line insulation flashovers. Table 1 presents examples of fault frequency for underperforming EEP’s 400, 230, and 132 kV transmission lines from 2015 to 2022. These lines experience unacceptably high rates of unexplained outages, significantly exceeding the anticipated design rates. Identifying the root causes of these issues is the first crucial step towards reducing these occurrences.

Table 1 Unexplained fault rates of selected EEP 400, 230, and 132 kV transmission lines during the period from 2015 to 2022.

Transmission Line Name	Region	Circuit Length (km)	In -service year (G.C.)	Voltage (kV)	Total Unexplained Fault	Number of faults per 100 km per year	Calculated Ground flash density per line
Bahir Dar II - Alamata	North-West & North-East	348.00	1998	230	150	5.39	21
Beles - GERD	North-West	241.00	2014	400	130	6.74	23
Combolcha 2 - Semera	North-East	174.80	2011	230	93	6.65	14
Shashemene - Alaba	South	63.23	2000	132	89	17.59	14
Combolcha 2 - Legetaffo	North-East & Addis Ababa	287.00	2012	230	88	3.83	20
Wolayita Soddo - Arba Minch	South	109.13	1986	132	83	9.51	5
Metema - Sudan Boarder	North-West	76.96	2008	230	81	13.16	42

A review of the fault data revealed that the yearly trend of unexplained faults varied from one year to another, peaking in 2021, as depicted in Figure 5. This trend may be attributed to variations in meteorological and environmental conditions, infrastructure aging, and maintenance practices. Further investigation is required to clarify the causes of this trend and to devise strategies for reducing the number of faults in the future.

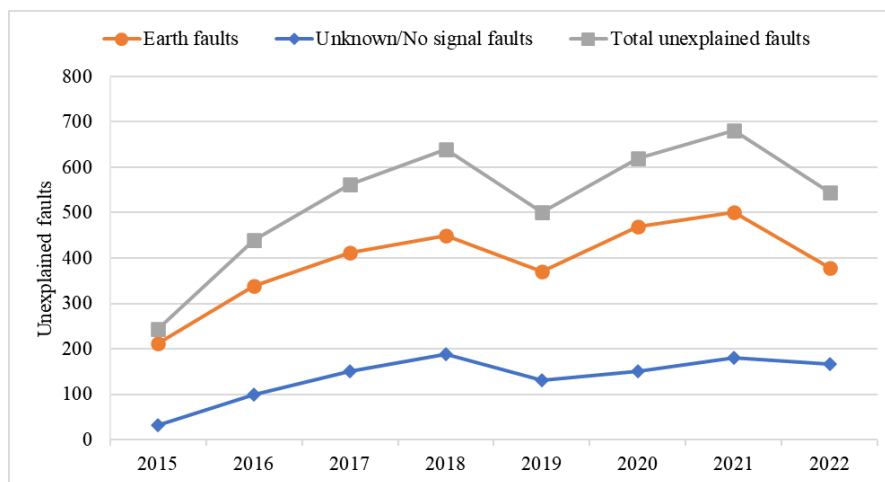


Figure 5: Yearly variation of unexplained faults in EEP network (EEP, 2022).

2.3.2 Temporal (time-of-day and seasonal) Analysis of Unexplained Faults

This section presents the daily and annual trends of unexplained faults. The daily occurrence of unexplained faults, shown in Figure 6, displays a pattern with three peaks: the first occurs around midnight, the second peaks at approximately 06:00, likely due to pollution flashovers occurring in the early morning, and the third peak appears in the afternoon around 14:00–15:00. The afternoon peak may result from a combination of lightning-induced faults during the summer rainy season and other

factors such as tree contact, mechanical failures due to aging components, vandalism, and fires during the dry season. The time-of-day trend of unexplained faults for 132, 230 and 400 kV networks are shown in Figures A – 1, A – 2, A – 3 in Appendix B.

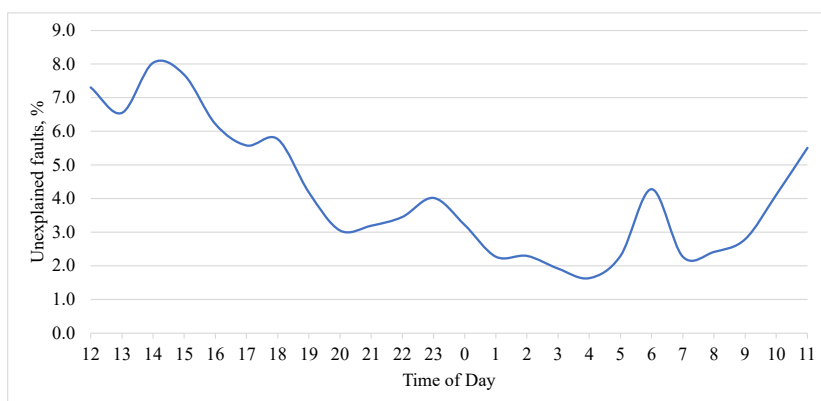


Figure 6: The time-of-day trend of unexplained faults in EEP network.

Figure 7 illustrates the seasonal trend of fault occurrences, showing a maximum of 510 faults in August and a minimum of 229 faults in January. A total of 1838 faults were recorded from June to September, coinciding with the rainy summer season in Ethiopia. These faults can primarily be attributed to external object interference and lightning induced faults occurring in the late afternoons. Faults occurring during other times of the year are likely caused by pollution, bird streamers, fires, and other unidentified reasons. Annual trend of unexplained faults for 132, 230 and 400 kV networks are shown in Figures A – 4, A – 5, A – 6 in Appendix B.

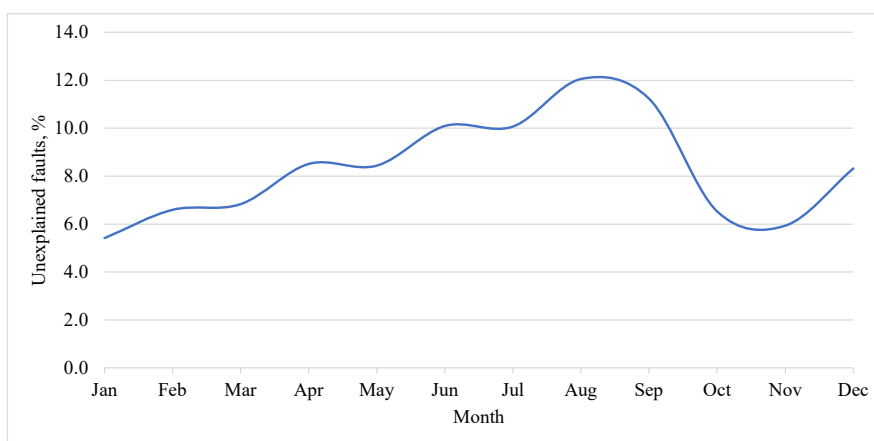


Figure 7: Annual trend of unexplained faults in EEP network.

Annual trends of unexplained faults per 100 km of lines from 2015 to 2022 across the EEP grid management regions, for all the voltages levels, are presented in Figure 8. The results indicate that the Addis Ababa, North-East, North-West, and South grid regions experience a significantly higher frequency of outages than expected, attributed to unclear root causes.

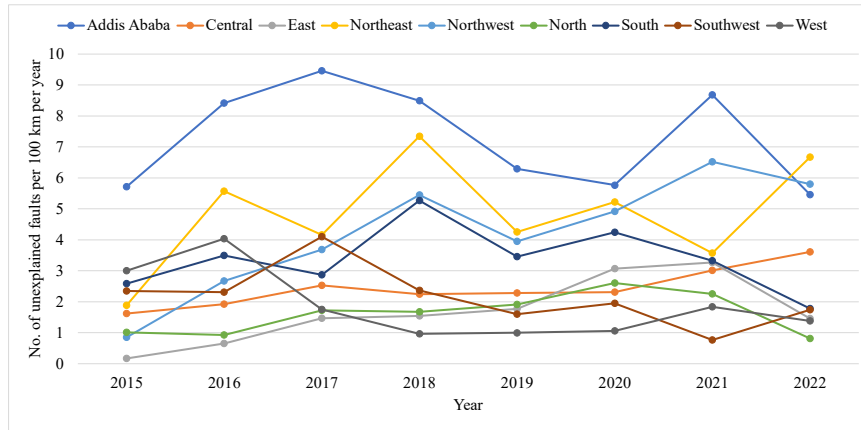


Figure 8: Reginal distribution of unexplained faults per 100 km of lines during the period 2015–2022 in EEP grid management regions.

These findings reflect poor performance of the transmission lines. The reasons can be different, depending on the environmental and climatic conditions in each region. For instance, the Addis Ababa region experiences high lightning flash density, coupled with significant air pollution from industrial emissions, vehicle exhaust, and household activities. In contrast, the North-East region has a desert environment with heavy accumulation of salty sand and dust, making pollution a likely cause. The South, South-West, and North-West regions also exhibit a higher frequency of unexplained outages, attributed to high rainfall and intense agricultural activities. Therefore, the poor performance of transmission lines in these areas may originate from lightning, pollution, fires, and crop burning.

The unexplained fault frequency statistics for major voltage levels per 100 km per year are depicted in Figure 9. The 132 kV lines exhibit the highest fault frequency at 4.9 faults/100 km/year, which is twice the amount suffered by 230 kV lines (2.6 faults/100 km/year). This indicates the underperformance of these lines. The 400 kV lines show a lower fault frequency of 1.13 faults/100 km/year. Most of the 132 and 230 kV lines were constructed before 2005, and their poor performance is attributed to aging infrastructure as well as environmental factors.

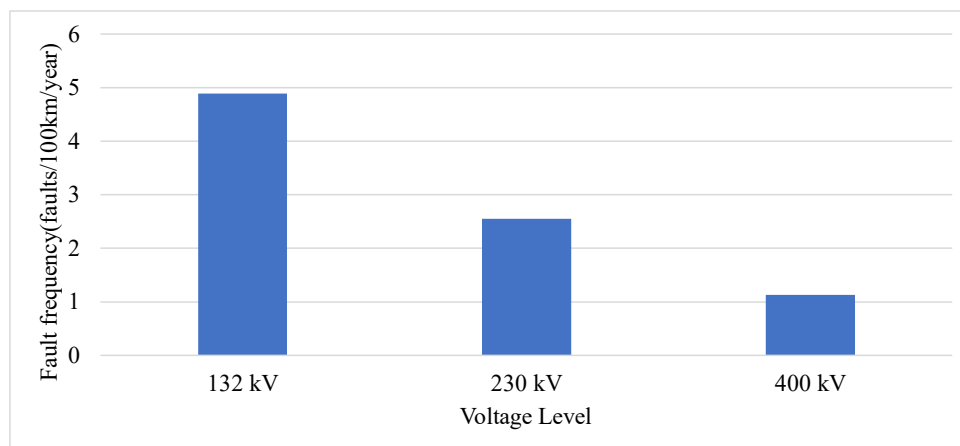


Figure 9: Unexplained fault frequency per 100 km per year for 132, 230 and 400 kV transmission lines.

2.4 The climatic and Meteorological Conditions of Ethiopia

One objective of this study was to investigate how unexplained faults vary with wet and dry climatic cycles. This section discusses Ethiopia's climatic and meteorological conditions, which help classify the country into distinct rainfall regimes that characterize their seasonal distribution in specific locations, thereby providing a framework for analyzing unexplained fault with respect to climatic conditions.

2.4.1 *Rainfall Regimes in Ethiopia*

Ethiopia generally experiences a tropical climate with distinct wet and dry seasons, characterized by varying precipitation and temperature patterns (Abebe, 2010; NMSA, 1996). The country has three distinct seasons, known locally as "Bega", "Belg", and "Kiremt". Bega is the dry season, which occurs from October to January, characterized by hot, dry days and cool nights. It is chilly in the early mornings and occasionally there is frost in highland areas. Kiremt represents the main rainy season, occurring from June to September, marked by frequent rains and consistent temperatures. The rainfall typically occurs in the afternoons and evenings. Belg is the light rainy season, occurring from February to May, featuring significantly less rainfall, which varies greatly in both time and location, alongside high maximum temperatures (McSweeney et al., 2012; NMSA, 1996; Seleshi & Zanke, 2004). These unimodal and bimodal rainfall patterns in Ethiopia form the basis for categorizing the country into three rainfall regimes (Abebe, 2010), which are commonly referred to as Regime A, Regime B, and Regime C.

Figure 10 illustrates that Regime A encompasses the central and eastern parts of the country, characterized by a bimodal rainfall system comprising the long rainy season (June-September) and the short rainy season (March-May). Regime B covers the western region, stretching from southwest to northwest, exhibiting a unimodal rainfall pattern from February to November, although the timing of the rainy season varies from southwest to northwest. Regime C includes the southern and southeastern regions, featuring two distinct wet and dry seasons, with the main rainy season occurring from February to May and short rains from October to November. The dry periods extend from June to September and December to February (Abebe, 2010; NMSA, 1996; Seleshi & Zanke, 2004). Most transmission lines are subjected to varying rainfall levels throughout the year, impacting their performance (Desta & Wogari, 2020).

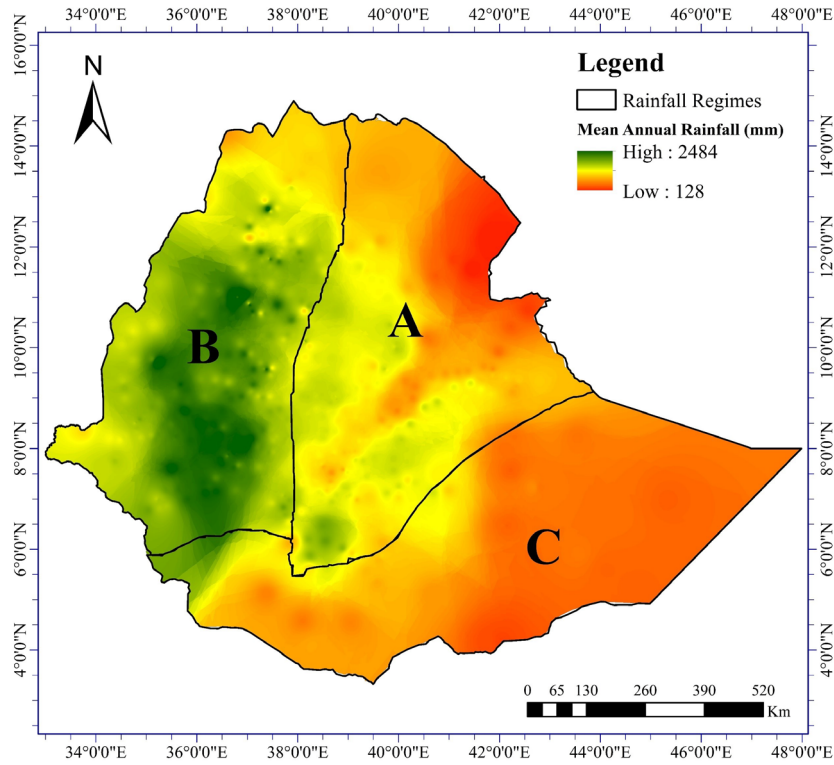


Figure 10: Annual average rainfall map of Ethiopia showing the three rainfall regimes (Abebe, 2010; NMSA, 1996).

2.4.2 Lightning Density in Ethiopia

Faults in overhead transmission lines due to lightning can arise from three mechanisms, depending on where the lightning strikes: back-flashover from a tower top or shielding wire to a phase, shielding failure that allows lightning to terminate on the phase conductor (direct flashover), and induced surges from lightning strikes to the ground near the line. The likelihood of shield failure and back-flashover is primarily influenced by the design and installation of the transmission line, which is typically specific to the line's voltage. These factors can be aggregated and adjusted according to the lightning ground flash density (N_g) (He et al., 2015; Minnaar et al., 2012). Figure 11 presents a map illustrating the spatial distribution of ground flash density (N_g) throughout Ethiopia alongside transmission line routes. It depicts average N_g values for 10 km² blocks, assigning each transmission line tower within a square the corresponding N_g value. The flash density per line is determined by averaging N_g across all line towers (Łoboda & Lenarczyk, 2014; Minnaar et al., 2012).

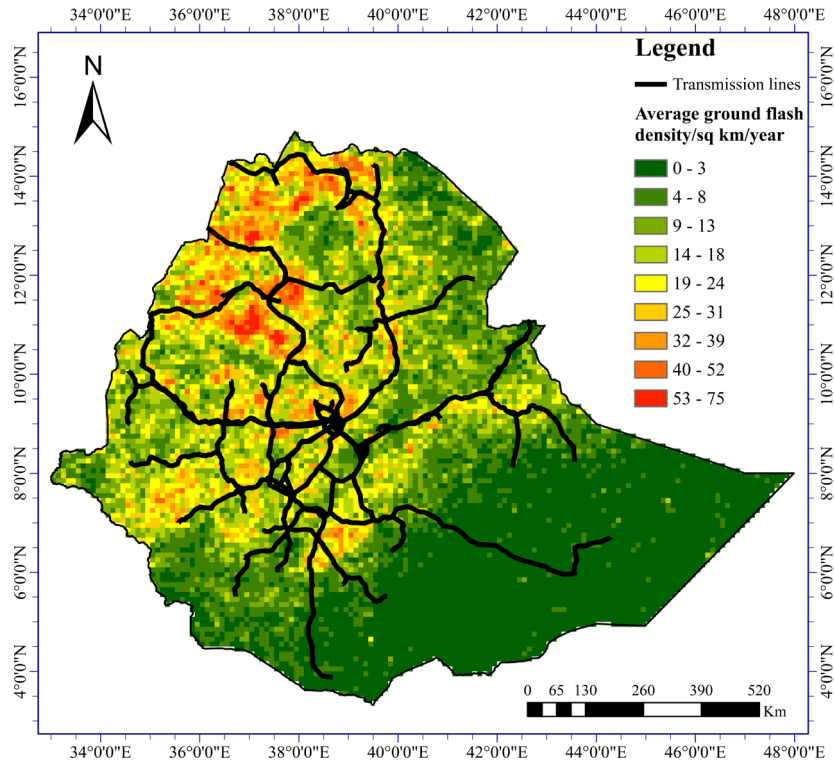


Figure 11: Map of average ground flash density (Ng) in Ethiopia with power transmission line routes for the period 2006–2010 (NMA, 2010).

Annual lightning incidence in Ethiopia varies widely, with rates of less than 3 flashes/km²/year in the East and Southeast regions, compared to more than 75 flashes/km²/year in the North, Northwest, and West regions. Most of the identified problematic lines are situated in high lightning incidence areas, with lightning events predominantly occurring from late afternoon to midnight during the rainy months from June to September. Table 2 outlines the average ground flash density for each EEP grid region based on the data collected between 2016 and 2022 by Vaisala’s Global Lightning Detection Network (GLD360) (Vaisala's National Lightning Detection Network NLDN & Global Lightning Detection Network GLD360, 2022).

Table 2 The average ground flash density for transmission lines of EEP grid management regions, from 2016 to 2022 (Vaisala's National Lightning Detection Network NLDN & Global Lightning Detection Network GLD360, 2022).

Grid Region	Average ground flash density from 2016 to 2022 (flashes/km ² /year)
Addis Ababa	15.3
Central	6.9
East	2.3
North-East	12
North-West	17.7
North	23.5
South	6.9
South-West	7.1
West	16.9

2.5 Analysis of Unexplained Faults in Relation to Climatic Condition, Time-of-Day and Time-of-Year

This section analyzes the correlation between the frequency of unexplained faults and local climatic conditions, focusing on time-of-day and seasonal variations (Herman & Gaunt, 2010; Minnaar et al., 2012; Taklaja et al., 2013). The analysis consists of three primary steps. The first step involves preparing a fault dataset for examination. The second step associates each transmission line with a specific grid region (as a geographic indicator) and a rainfall regime (as a climatic representation). This classification aids in identifying regions more prone to unexplained faults due to environmental and climatic factors. Finally, the faults are categorized according to time-of-day and season, allowing for the identification of any seasonal or daily patterns. This comprehensive analysis connects fault frequency to local climate, highlighting their spatiotemporal patterns.

The EEP grid management regions are classified according to rainfall regimes. The Addis Ababa, Central, North, North-East, and East grid regions fall under Regime A, while the North-West, West, and South-West regions belong to Regime B, and the South region is categorized as Regime C, as detailed in Table 3. Results indicate clear variations in fault frequency across the different rainfall regimes. Transmission lines situated in rainfall Regime C exhibit higher fault frequencies compared to those in Regimes A and B. Regime A experiences 19–75 ground flashes/km²/year (see Fig. 11),

with the increased fault frequency likely attributable to lightning-induced events that typically occur during the afternoons and nights of the rainy season. Notably, approximately 51% of the total line length falls within rainfall Regime A.

Table 3 Yearly average frequency of unexplained faults in the rainfall regimes of Ethiopia.

Rainfall Regime	Grid Region	Total length of lines (km)	Fault frequency (faults/100 km/year)	Std. Dev.
Regime A	North	9868	3.17	0.58
	North-East			
	Central			
	Addis Ababa			
Regime B	East	6516	2.53	0.42
	West			
	North-West			
Regime C	South-West	2921	3.38	0.98
	South			
Total		19305	2.98	0.47

The relationship between unexplained fault frequency and transmission line voltage levels is illustrated in Figure 12. Fault occurrences on 132 kV lines are most frequent in rainfall Regime A. The considerable variation in fault frequency between rainfall regimes suggests that these lines are more influenced by climatic conditions than those of other voltage levels. The frequency of faults on 230 kV lines is slightly lower in Regime A compared to Regimes B and C, but the difference is minimal. Meanwhile, 400 kV lines demonstrate even lower fault frequencies, showing a tendency for increased occurrences in Regime B. This pattern indicates that most faults may be linked to high rainfall intensity in the area. This also provides an indication of which the unexplained faults are less influenced by local climate for 400 kV lines. Details of the fault frequency per 100 km per year in different rainfall regimes evaluated for 132, 230 and 400 kV lines are shown in Table A - 4 in Appendix B.

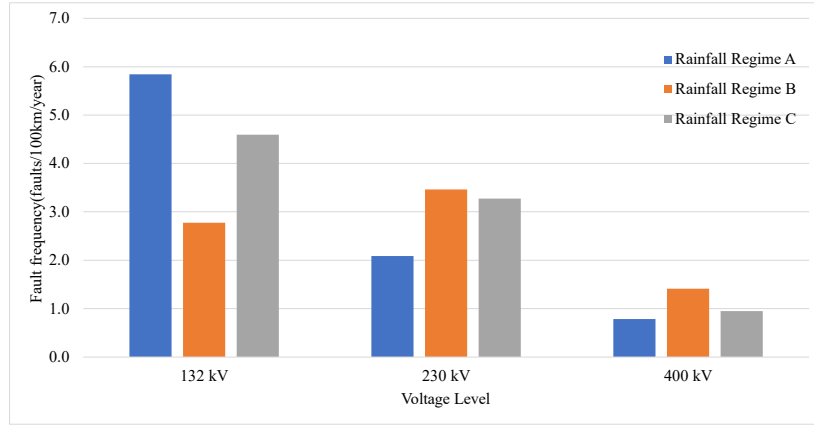


Figure 12: Fault frequency per 100 km per year in different rainfall regimes.

The time-of-day distribution of unexplained faults is presented in Figure 13. Across all voltage levels, 40% of unexplained faults occurred during the daytime, specifically from 13:00 to 19:00. These occurrences are likely attributed to lightning, fire, theft, vandalism, tree contact, or other operational issues. In contrast, faults occurring during the night and early morning hours (19:00 to 08:00) account for 38% of the total, potentially due to bird streamers and pollution. The simultaneous impact of time-of-day and time-of-year on fault occurrence can be analyzed, as suggested in prior studies (Herman & Gaunt, 2010; Minnaar et al., 2012).

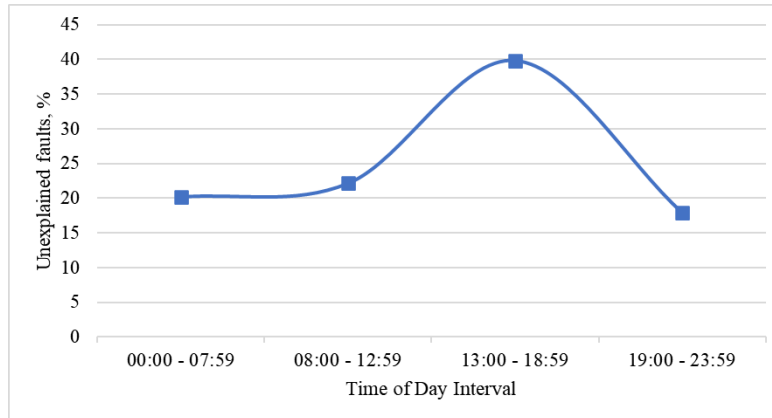


Figure 13: Time-of-day distribution of unexplained faults on 132, 230, 400 kV lines based on data from 2015–2022.

Of the total 4231 unexplained faults recorded in the EEP network from 2015 to 2022, 2250 (53%) occurred on 132 kV lines, 1597 (38%) on 230 kV lines, and 384 (9%) on 400 kV lines. When fault frequency is independently assessed for each voltage level, the 400 kV network shows its highest fault frequency (0.23 faults/100 km/year) during the Bega season, primarily between 13:00 and 19:00. For 230 kV lines, fault frequency peaked at 0.46 faults/100 km/year during the Kiremt season, also in the afternoon hours. Similarly, 132 kV lines experienced a peak of 0.89 faults/100 km/year during Kiremt afternoons. Figure 14 illustrates the time-season dependent characterization of unexplained fault frequency (per 100 km/year) across the entire EEP network. The results reveal that the highest fault

frequency occurs from 13:00 to 18:59 during the Kiremt rainy season. Season and time dependent characterization of the unexplained fault frequency evaluated for 132, 230 and 400kV lines is shown in Table A - 5 in Appendix B.

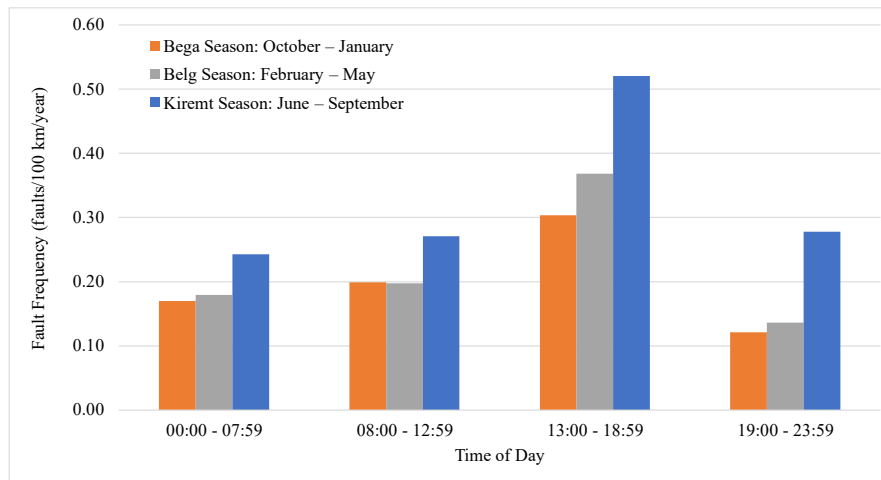


Figure 14: Season and time dependent characterization of the unexplained fault frequency for the entire EEP network.

2.6 Classification of Unexplained Faults According to Their Root Cause and Possible Mitigation Measures

2.6.1 Criteria for Unexplained Faults Root Cause Classification

As indicated in previous studies (Jian et al., 2021; Minnaar et al., 2016), effective classification of transmission line fault root causes can be achieved by focusing on contextual fault features such as time-of-day, month, location (grid region), and climatic and environmental conditions. By applying the characteristic criteria associated with the most probable root causes, as discussed in Section 2.2, a classification procedure was developed to connect available line fault information with the climatic and environmental contexts represented by rainfall regimes across different grid regions (see Sections 2.4 and 2.5). Table 4 outlines the criteria used for this classification.

Table 4 Classification criteria to identify the most probable causes of unexplained faults.

Major causes of unexplained faults	Classification criteria		
	Time of the day	Time of the year	Rainfall Regime
Pollution	0:00 – 8:00	January – December	All Regimes
	21:00 – 23:00	October – February	Regime A
	21:00 – 23:00	October – May	Regime B
	21:00 – 23:00	June – September	Regime C
	21:00 – 23:00	December – February	Regime C
Lightning	17:00 – 23:00	June – September	Regime A and B
	17:00 – 23:00	March – May	Regime A and C
	17:00 – 23:00	October – November	Regime C
Fire	13:00 – 16:00	October – February	Regime A
	13:00 – 16:00	October – May	Regime B
	13:00 – 16:00	June – September	Regime C
External interferences	9:00 – 20:00	January – December	All Regimes

The application of these criteria is illustrated by the flowchart in Figure 15. Each fault dataset was thoroughly analyzed for consistency with these criteria; if a fault met the conditions for a particular probable cause, it was categorized accordingly. Faults that did not meet the criteria for pollution, lightning, or fire-induced events were classified under external interference.

Among the 4231 unexplained faults, lightning events accounted for 787 (19%), pollution-induced faults for 1135 (27%), fire-related faults for 479 (11%), and external interferences for 1830 (43%). It is important to note that the external interference category includes lightning and pollution events occurring outside their typical trend areas. This highlights that lightning, pollution, and fire-induced flashovers are significant contributors to unexplained outages within the EEP transmission system, with each cause associated with environmental and natural climatic phenomena (Macey, Vosloo, & Tourreil, 2004; Peter & Vajeth, 2005; Vosloo, 2009).

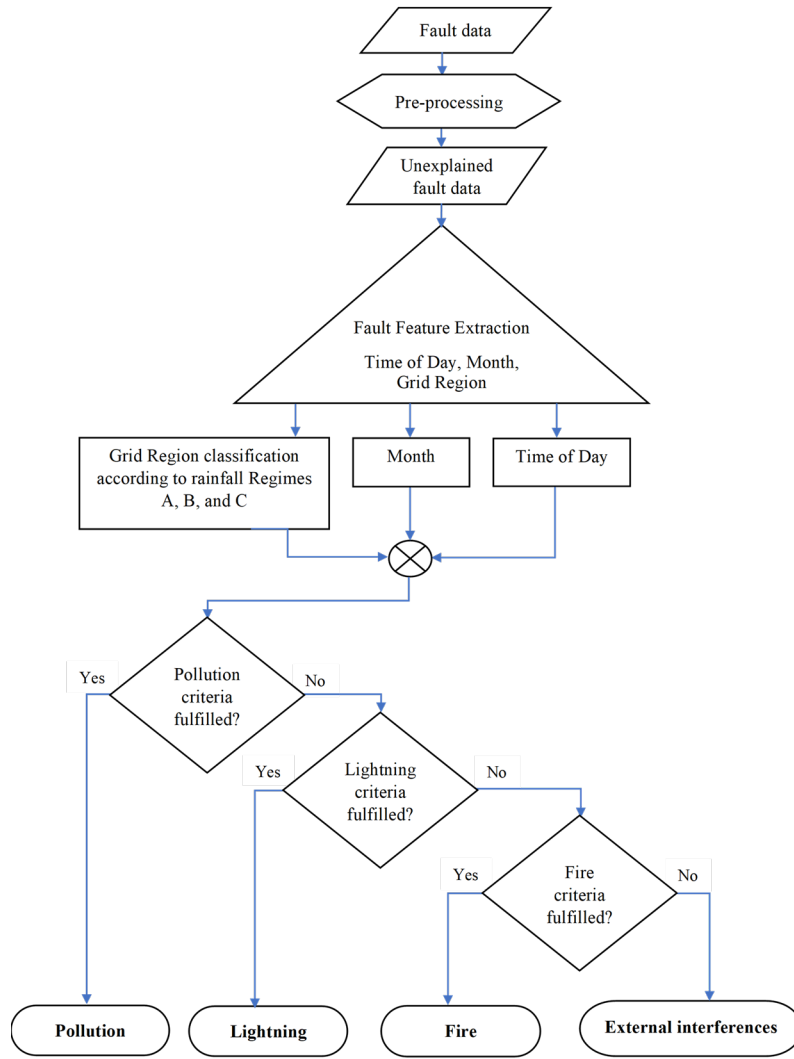


Figure 15: Flowchart of the procedure used for classification of unexplained faults root causes.

2.6.2 Possible Mitigation Measures to Minimize Unexplained Faults Occurrence

Several improvements and preventive measures can be implemented to minimize the occurrence of unexplained outages. These strategies were often not adequately considered in older line designs but should be prioritized in the planning and design phases of new transmission lines.

To reduce lightning-related flashovers, it is crucial to enhance protective measures by considering local lightning flash density, which may include improving tower footing resistance. Installing line surge arresters can serve as an alternative solution when improving tower footing resistance is uneconomical or ineffective due to soil type or rocky conditions encountered in mountainous terrains. When adopting this solution, for efficient functioning of line surge arresters, at least one or two towers having adequate grounding and adjacent to the line sections with poor grounding also need to be equipped with line surge arresters. During the design phase, utilizing tower types that have lower surge impedance is advantageous in mitigating lightning-related flashovers. For instance, the cross-rope tower design

offers lower tower surge impedance compared to self-supporting designs (Chen, 2020; He et al., 2015; Hu, 2007; Peter & Vajeth, 2005; Vosloo, 2009).

To address all types of pollution related flashovers on insulators, various techniques can be employed, including washing substation or line insulators, applying silicone grease to ceramic substations insulators, increasing the creepage distance of insulators, and replacing hydrophilic insulators with hydrophobic alternatives, depending on the economic and technical feasibility of each measure. Implementing bird guards and increasing clearances can help mitigate issues related to bird streamers and pollution resulting from bird excrement, which can contribute to pollution-related flashovers (Chen, 2020; CIGRE Taskforce 33.04.01, 2000; Hu, 2007; Macey, Vosloo, & Turreil, 2004; Moreira et al., 2023; Peter & Vajeth, 2005).

To minimize fire-induced flashovers on transmission lines, effective vegetation management and servitude practices must be established. Combustible materials such as dry trees, grass, bushes, and shrubs in line corridors should be regularly cleared. Special attention is required during harvesting seasons in agricultural areas that produce an abundance of fine fuels for fire, particularly during sugarcane harvesting, which involves burning excess plant material. Additionally, developing an early warning system for fire detection, location, and monitoring, in conjunction with satellite remote sensing technology, can help mitigate fire-induced outages on transmission lines (Chen, 2020; Hu, 2007; Peter & Vajeth, 2005; Sukhnandan & Hoch, 2002; Vosloo, 2009).

Finally, to reduce faults caused by external interferences, it is essential to strengthen line inspection efforts. All foreign and other floating objects that may collide with transmission lines and cause short-circuit events should be cleared from their corridors. EEP should also enhance its communication network, collaborate with relevant stakeholders, and implement technical measures to minimize damage from vehicle collisions, tree contact, and illegal construction activities near power lines. Furthermore, addressing theft and vandalism of line components, such as the stealing of tower members and damaging insulators, which contributes to a fair percentage of faults and has intensified greatly in recent years, is essential. EEP should therefore strengthen security measures and patrol the most vulnerable lines while taking preventative actions against criminal activities targeting power transmission infrastructure (Chen, 2020; Hu, 2007; Vosloo, 2009).

2.7 Study Cases: Analyses of Poorly Performing Transmission Lines

This section offers a detailed examination of probable fault causes for two transmission lines that experienced significantly high rates of unexplained outages from 2015 to 2022. The analysis utilizes time-of-day and seasonal data to scrutinize the fault records for each line and establish the most likely

reasons for flashovers. Local meteorological and climatic information, through which the lines run, alongside actual field experiences, are incorporated into the analysis.

2.7.1 Bahir Dar II–Alamata 230 kV Line

The Bahir Dar II - Alamata 230 kV line, constructed in 1998, stretches 348 km northeast from Bahir Dar to Alamata and continues an additional 141 km north to the Ashegoda wind farm. This line serves as a crucial link among the North-West, North, and North-East grid regions of the EEP system. It traverses the tropical savanna and semi-arid climates prevalent in these regions of Ethiopia. The line's glass insulator strings are particularly vulnerable to dew formation. Between 2015 and 2022, it experienced 150 unexplained faults, averaging 18.8 faults annually. Figure 16 presents the average monthly meteorological parameters along the line's entire route, indicating exposure to high rainfall, exceeding 200 mm in July and August, alongside high relative humidity (~80%). Light rains of approximately 50 mm also occur in March and April, while the hot and dry season lasts from October to February.

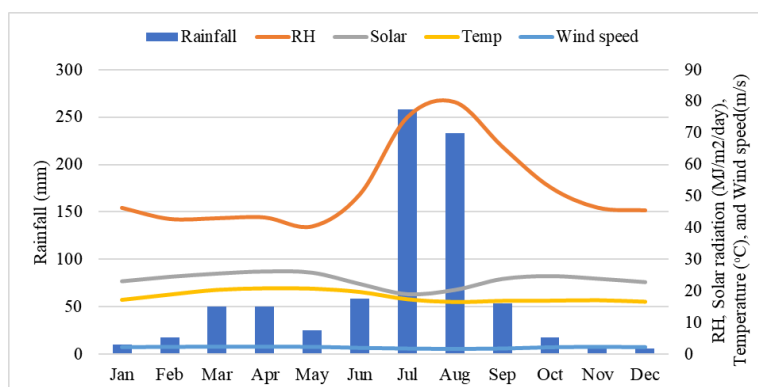


Figure 16: Average monthly meteorological parameters along the entire route of Bahir Dar II–Alamata 230 kV line (CFSR, 2019).

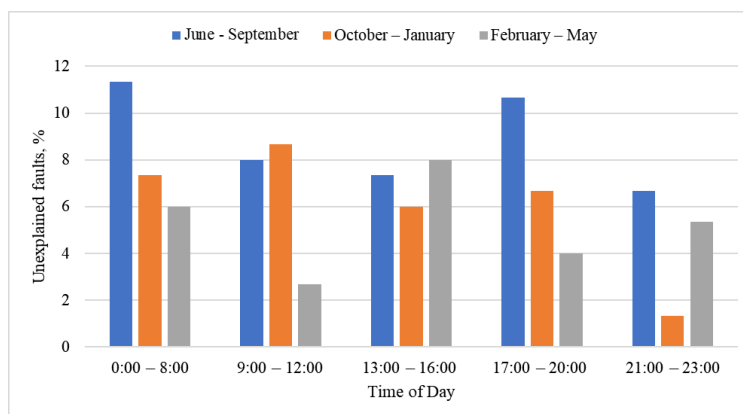


Figure 17: Time-of-day and month (seasonal) appearance of unexplained faults on Bahir Dar II–Alamata 230 kV line.

As shown in Figure 17, this line suffered a high number of unexplained faults, with 29% occurring during the late afternoon to early evening (17:00–20:00) and from midnight to early morning (21:00–

8:00), particularly from June to September when rainfall is highest. In terms of time of the day, the highest outage frequency (25%) is recorded from 0:00–8:00, and with respect to time of the year 44% of all faults happen during the June to September period. Lightning, which has an incidence of about 21 flashes/km²/year, primarily strikes during late afternoon to midnight (17:00–23:00) in these months, making it a likely cause of these faults.

The line passes through areas affected by a mixture of desert, agricultural, and light industrial pollutants. A strong correlation exists between fault records and characteristic patterns of various pollution flashovers, particularly from October to January and February to May, occurring near midnight (21:00–23:00) and during the early morning (0:00–8:00). Additionally, bird streamer-induced faults are suspected during the June to September period, especially from 0:00–8:00. It is therefore assumed that pollution flashovers account for many unexplained faults in the evening and at sunrise. During the October to May period, from 13:00 to 16:00, fire induced flashovers probably also cause unexplained faults. All other faults occurring from 9:00–12:00 throughout the year as well as those registered between 13:00–16:00 and 17:00–20:00 in seasons that are not typical for the major causes can be attributed to external interferences. Thus, lightning-induced faults are predominant for this line, followed by pollution-induced faults.

2.7.2 Shashemene–Alaba 132 kV Line

The Shashemene - Alaba 132 kV line is 63 km long and operates in the tropical savanna and subtropical highland climate of Ethiopia's Southern region. Since commencing operations in 2000, the line has recorded 89 unexplained faults between 2015 and 2022, averaging 11 faults annually. Figure 18 displays the monthly meteorological parameters along the line, revealing rainfall intensities of approximately 90 mm and relative humidity exceeding 60%, which increases from June to September. Light rainfall of less than 60 mm is also recorded from February to May, resulting in frequent wetting of the insulators and increased susceptibility to pollution flashovers.

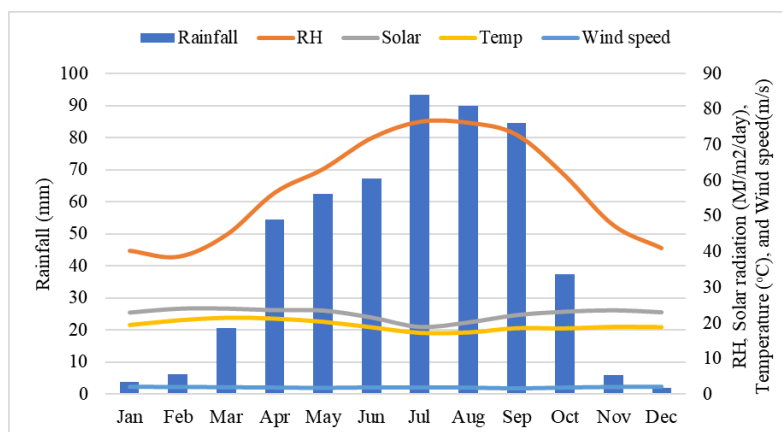


Figure 18: Average monthly meteorological parameters along the entire route of the Shashemene–Alaba 132 kV line 32(CFSR, 2019).

As shown in Figure 19, 58% of unexplained faults occur from the afternoon (13:00–16:00) to early evening (17:00–20:00), with a consistent distribution throughout the year. A further 18% of the total faults happened occur from midnight to early morning (0:00–8:00), peaking at 11% from February to May, when 37% of the total unexplained faults occur.

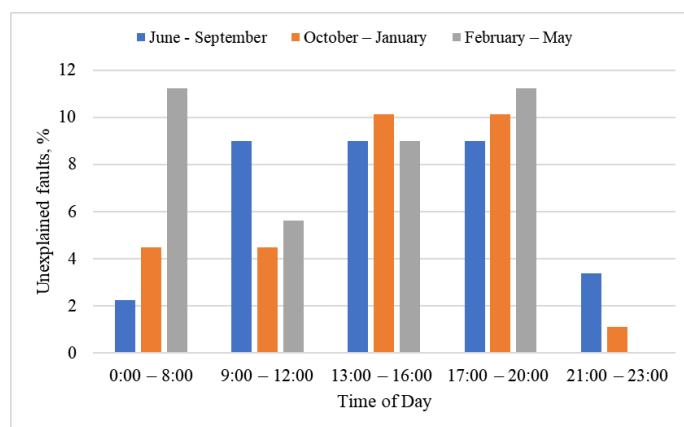


Figure 19: Time-of-day and month (seasonal) characterization of the unexplained fault on the Shashemene–Alaba 132 kV line.

This line runs through agricultural areas, where insulator pollutants primarily originate from ploughing, crop spraying, and soil fertilization. The unexplained faults occurring from October to January, especially from early evening up to early mornings hours, during the periods of increased humidity and dew formation, are likely due to pollution flashovers. Furthermore, the unexplained faults from February to May occurring from 0:00–8:00 are also likely attributed to pollution flashovers and bird streamers.

The local lightning intensity is about 14 flashes/km²/year, suggesting that lightning is the probable cause of unexplained line faults occurring between 17:00 and 23:00 during the rainy season from June to September, as well as in the late afternoons of April and May. During the harvesting and driest periods from October to January, unexplained faults peaking from 13:00–16:00 are likely due to fire-induced flashovers. External interferences are typically responsible for unexplained faults occurring from 9:00–12:00 throughout the year, as well as during 13:00–16:00 and 17:00–20:00 in months not typically associated with pollution, lightning, or fire caused outages. Thus, pollution-related faults are the most prevalent for this line, followed by those caused by lightning and fire.

CHAPTER 3

3. Assessment of Outdoor Insulation Problems Related to Pollution and Climatic Conditions

3.1 Introduction

At present, the primary transmission lines in Ethiopia operate at voltages of 500 kV, 400 kV, 230 kV, and 132 kV, with a 500 kV DC line recently started operation for connection with Kenya. The national grid is divided into nine operational regions: Addis Ababa, Central, North, North-West, North-East, East, South, South-West, and West (Parsons Brinckerhoff & EEP, 2014). Figure 20 illustrates the existing and planned transmission network across Ethiopia.

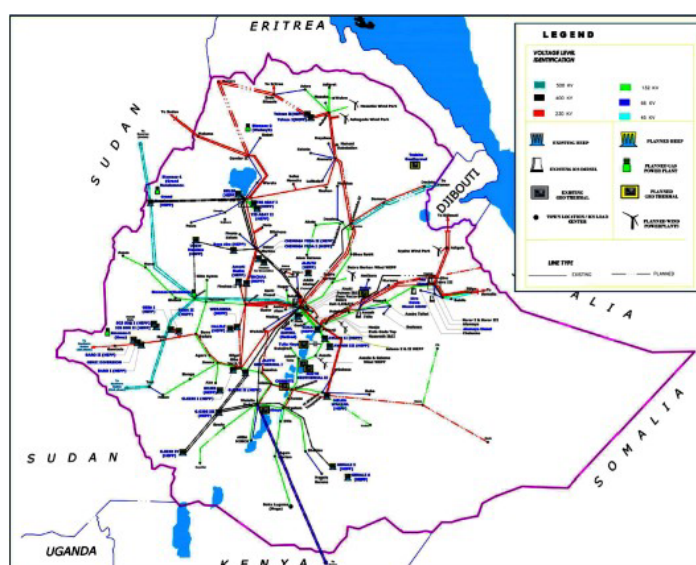


Figure 20: The existing and planned transmission network of Ethiopia (source: (Parsons Brinckerhoff & EEP, 2014)).

Pollution-related flashovers of high voltage insulators remain a significant challenge for the Ethiopian power system, necessitating comprehensive research to evaluate both general and localized environmental pollution conditions, along with meteorological data. Accurate assessment of site pollution severity levels is essential for selecting appropriate insulators that meet the required performance standards against pollution flashovers. This effort aims to develop a pollution severity map for the country, which is vital for conducting in-depth statistical analyses of various pollution scenarios and assessing flashover risks.

This chapter outlines the initial phase of the work undertaken to assess environmental and climatic conditions, as well as the policies governing insulator selection for both existing and planned transmission and substation projects. Additionally, it evaluates the current maintenance strategies and plans, while estimating and classifying regions based on pollution type and severity levels. This

baseline assessment has been conducted in close collaboration with the Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU) companies to identify candidate test sites characterized by heightened pollution risks, thereby focusing future research initiatives on areas designated for new power network installations (both AC and DC).

3.2 Climatic and Meteorological Conditions in Ethiopia

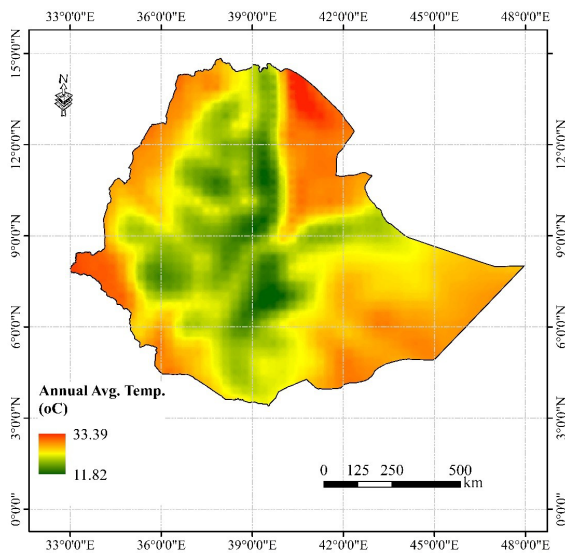
To effectively characterize the insulator environment in Ethiopia, it is crucial to gather information on various environmental conditions, such as pollution sources, deposition rates of soluble and insoluble contaminants, and relevant meteorological parameters. These factors exhibit considerable variation across the country. In the northern, northwestern, central, and southern regions, particularly within the Ethiopian highlands and Semien Mountains, altitudes can reach 4,500 meters above sea level. These areas are densely populated with agricultural activities and exhibit higher levels of industrialization, resulting in substantial carbon emissions and smoke from vehicles and households. In contrast, the northeastern and parts of the eastern regions lie within the Afar Depression, a 1,200 km² area characterized by alkaline soil and salt deposits. This region, part of the Greater Rift Valley, features its lowest point at 162 meters below sea level. The Danakil Desert, located in the northeastern region, is home to several saline lakes and is known for its prevalent salt mining activities. The northwestern, western, southwestern, and southern regions are primarily covered with vegetation, shrubs, and forests, where intensive agricultural and mining activities lead to significant fertilizer and chemical usage. The eastern and southeastern regions are largely desert, dominated by grasslands with limited rainfall, frequent sandstorms, and salt fog from the Red Sea and Arabian Sea.

Due to its proximity to the equator, Ethiopia generally experiences a tropical climate, characterized by distinct wet and dry seasons. The country has hot, dry desert regions around Semera and Ogaden, where rainfall is scarce. Although cold weather is uncommon, nighttime temperatures can drop sharply. The northeastern, eastern, and southeastern parts of Ethiopia exhibit tropical or semi-desert steppe climates with short rainy seasons, during which rainfall is unpredictable and varies significantly by location. To provide insight into Ethiopia's general climatic conditions, Figure 21 (a) to (d) presents meteorological parameter maps. The data shown are long-term annual averages (30 years), sourced from the Climate Forecast System Reanalysis (CFSR), which integrates observations from ground stations alongside estimates from various satellites, balloons, and aircraft. The dataset has a spatial resolution of approximately 38 km and has been available since 1979 (CFSR, 2019).

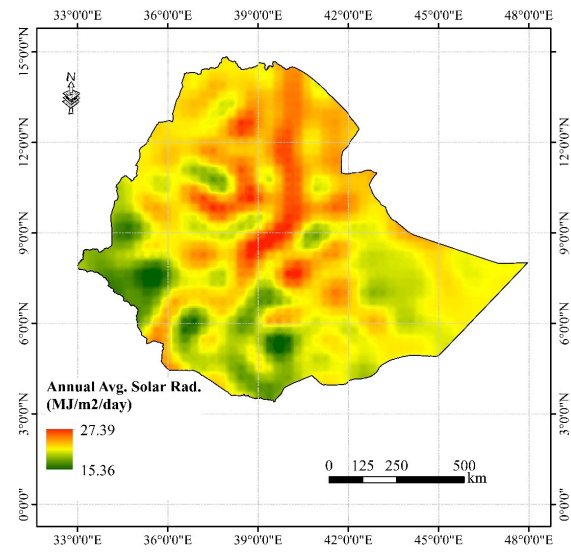
The altitude at which insulators are installed and population density both significantly influence insulator performance and the types and sources of pollutants present. Figures 21 (e) and (f) illustrate the altitude and population density across the country. The altitude data is derived from a 30 m

resolution Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (<https://earthexplorer.usgs.gov/>) (USGS & EROS, 2019a), while population density figures are collected from the Global Gridded Population Database maintained by the Center for International Earth Science Information Network (CIESIN) at Columbia University and the International Center for Tropical Agriculture (CIAT) (CIESIN & CIAT, 2019).

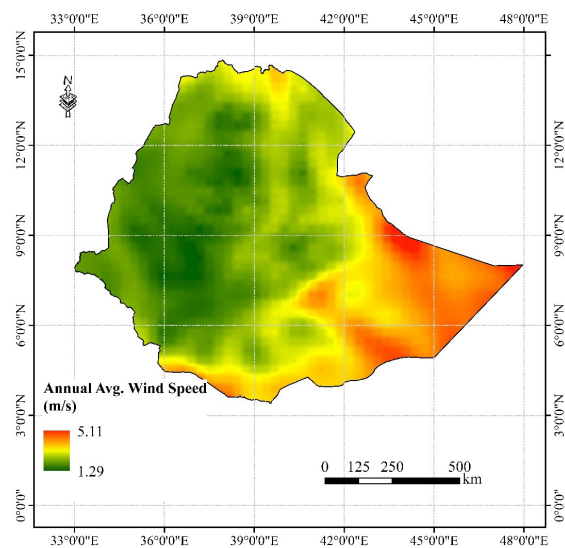
As shown in Figure 21 (a), the annual average temperature in the northwestern, central, and parts of the southwestern regions of the Ethiopian highlands and plateau can be as low as 12 °C. Conversely, temperatures can soar up to 34 °C in the lowlands of the northeastern region (Semera) and eastern regions (Adama, Dire Dawa, and Somali). Gambella, located in the western part of the country, records the highest average monthly maximum temperatures exceeding 30 °C in February, March, April, and June, with lower temperatures observed in other months.



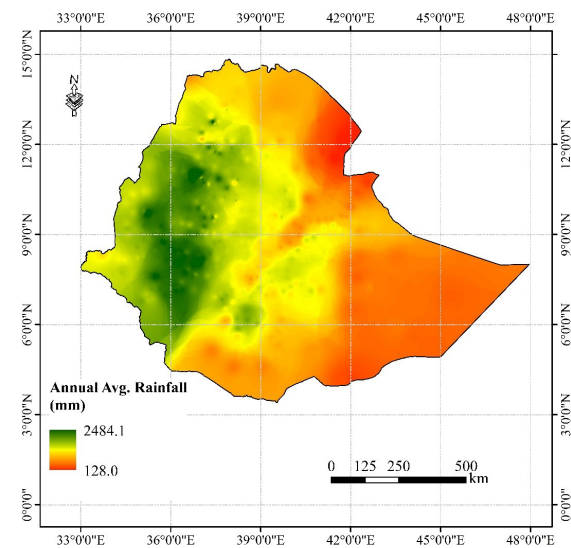
(a) Annual average temperature (°C)



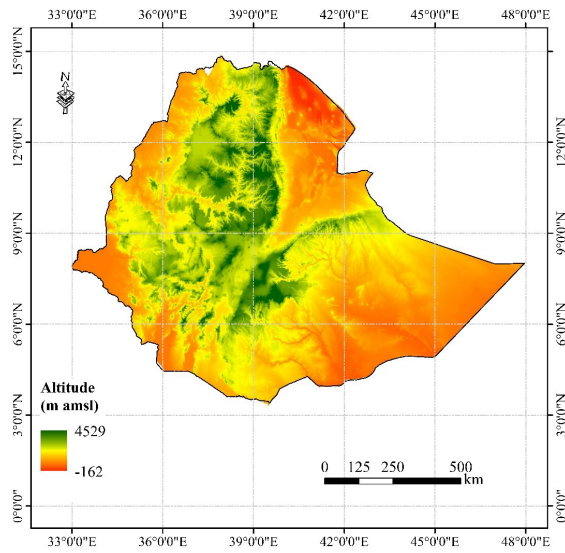
(b) Annual average solar radiation (MJ/m²/day)



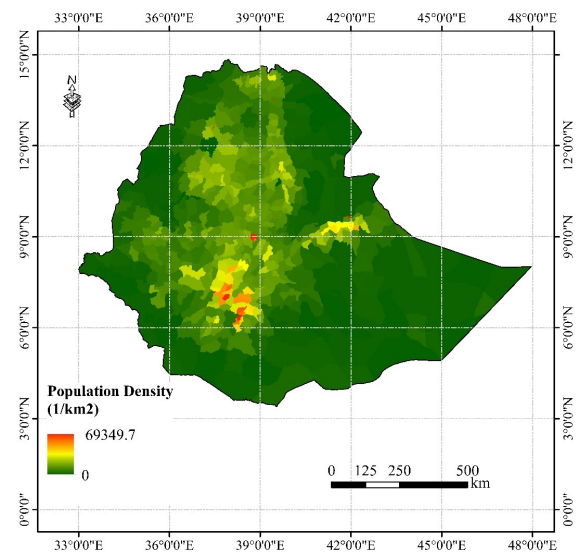
(c) Annual average wind speed (m/s)



(d) Annual average rainfall (mm)



(e) Altitude (m)



(f) Population density (1/km²)

Figure 21: The general meteorological condition, altitude and population density in Ethiopia (CFSR, 2019; CIESIN & CIAT, 2019; USGS & EROS, 2019a). (a) Annual average temperature (°C). (b) Annual average solar radiation (MJ/m²/day). (c) Annual average wind speed (m/s). (d) Annual average rainfall (mm). (e) Altitude (m). (f) Population density (1/km²).

The maximum annual average solar radiation varies between 27.4 MJ/m²/day and 15.4 MJ/m²/day, as depicted in Figure 21 (b). The central and northeastern regions of the Rift Valley register the highest monthly average solar radiation during March, April, and May, while the western and southern regions experience comparatively lower solar radiation.

Annual average wind speeds are typically lower in the northern, northwestern, western, and southwestern regions, with a minimum value of 1.3 m/s. Higher wind speeds, reaching an annual average of 5.1 m/s, are recorded in the eastern region (Dire Dawa and Somali). Figure 21 (c) indicates that, according to long-term studies, the dominant wind direction is from the east, flowing from the coastal areas of the Red Sea and the Gulf of Aden toward the western part of the country. The highest monthly maximum average wind speed, recorded in Dire Dawa, exceeds 3 m/s during June, July, and August, significantly influencing pollution accumulation on insulators in that area.

Annual average rainfall ranges from approximately 128 mm in the arid regions of northeastern (Danakil Desert) and southeastern (Ogaden) Ethiopia to nearly 2,500 mm in parts of the northwestern region (Bahir Dar), western region (Assossa), and southwestern region (Gambella). Other regions experience relatively lower annual rainfall, with some areas facing drought conditions due to insufficient rainfall in certain years. Most rainy periods typically commence in early June and last until the end of September, suggesting that natural washing of insulators is likely during these months.

Ethiopia's climate predominantly varies with altitude, exhibiting temperate conditions on the plateau and highlands, while lowland areas remain hot and arid. As illustrated in Figure 21 (e), Ethiopia's

lowest altitude is found in the northeastern part, specifically at 162 meters below sea level in the Danakil Depression. The Ogaden area in the Somali region and Gambella in the southwestern region also features low altitudes. In contrast, the northern and parts of the northwestern region, where the Ethiopian highlands and mountains are situated, have relatively high elevations, peaking at 4,500 meters above sea level at Ras Dashen.

With only about 20% of the population residing in urban areas, the majority of Ethiopians live in dispersed rural communities. Figure 21 (f) shows that the highest population density is found in the highlands of the north, northwestern, southern, and central regions, particularly surrounding the capital city of Addis Ababa. In contrast, the northeastern, far eastern, and southeastern regions are sparsely populated.

To further pollution-related research, nine cities have been selected to represent the diverse climatic conditions across each operational region of the Ethiopian power grid. This selection considers the presence of transmission lines and substations of commercial and strategic importance, the number and significance of customers, the connected load, voltage levels, and prevailing climatic conditions. At this stage, it is assumed that other locations within each region experience similar meteorological conditions. Figure 22 depicts the locations of the test sites within the nine operational regions of the Ethiopian national power grid.

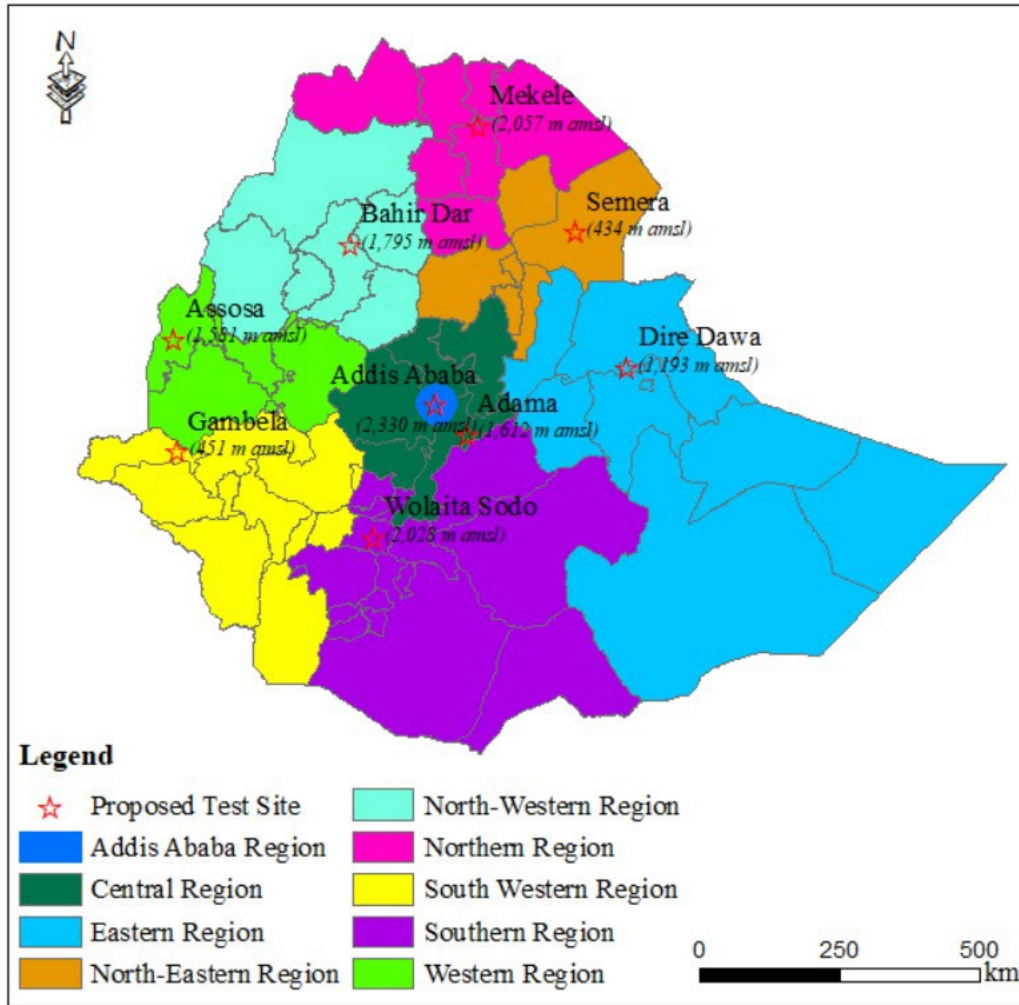
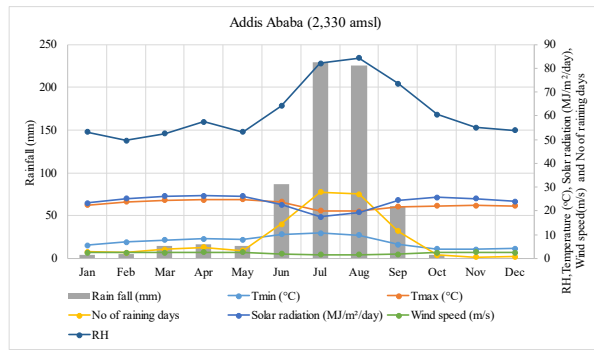


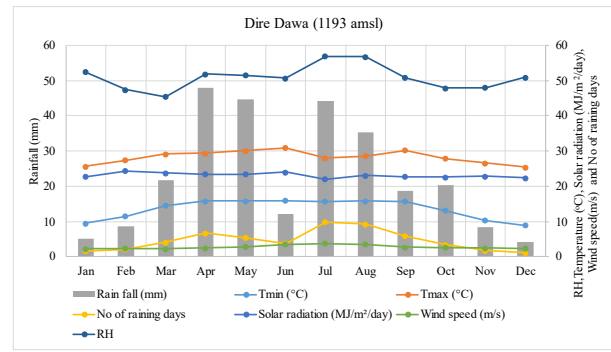
Figure 22: Locations of pollution test sites in Ethiopia.

Figure 23 illustrates variations in specific meteorological conditions for Addis Ababa, Bahir Dar, Dire Dawa, and Assosa, which serve as typical examples among the selected test sites to represent climatic conditions along transmission lines and at substations. The presented parameters include monthly average wind speed, rainfall, temperature (minimum and maximum), altitude, average number of rainy days, relative humidity, and solar radiation intensity.

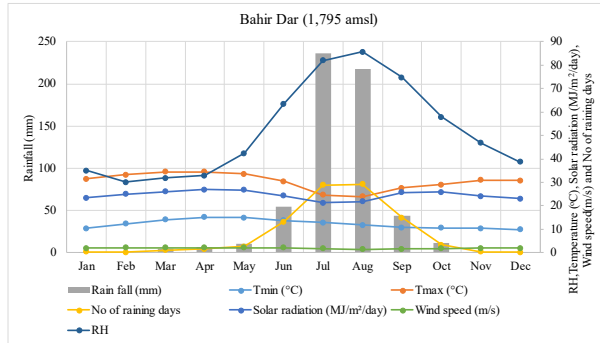
In recent years, significant fluctuations in climatic conditions, coupled with the development of large industrial and transport networks (including cement, sugar, fertilizer, and steel factories), increased mining activities, and agricultural advancements, have led to increased pollution levels and the emergence of various pollution mixtures that adversely affect the performance of existing outdoor insulators. If these issues are not addressed promptly and carefully, their impact may escalate over time, potentially affecting newly planned projects as well. It is also crucial to recognize that many of the existing transmission lines linking the various regions of the country traverse areas with different climatic and pollution conditions, necessitating varying levels of insulator performance.



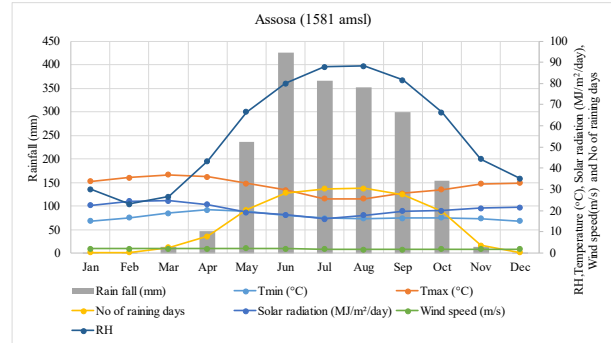
(a) Meteorological conditions in Addis Ababa



(c) Meteorological conditions in Dire Dawa



(b) Meteorological conditions in Bahir Dar



(d) Meteorological conditions in Assosa

Figure 23: Examples of yearly variations (based on 30 years data) of meteorological parameters for the selected four test sites in Ethiopia. (source: Climate Forecast System Reanalysis (CFSR)) (CFSR, 2019). (a) Meteorological conditions in Addis Ababa. (b) Meteorological conditions in Bahir Dar. (c) Meteorological conditions in Dire Dawa. (d) Meteorological conditions in Assosa.

Table 5 presents the classification of the operational regions of the Ethiopian transmission network based on general environmental types and pollution sources. This classification is achieved by estimating the site pollution severity (SPS) class according to (IEC/TS 60815-1, 2008).

The assessment of pollution severity levels has been conducted using environmental and meteorological data in conjunction with operational flashover incident records from insulators on or near service lines and substations, considering qualitative indicators for typical environments as defined in (IEC/TS 60815-1, 2008).

Table 5 Types of environments and pollution in Ethiopian grid regions.

Region (represent ative site in the region)	General types of environments and types of pollution	Description of the environment/ region	Estimated site pollution severity (SPS) class
Addis Ababa (Addis Ababa)	Industrial, Type A (carbon, cement, gypsum, metallurgical, chemical substances and wastes, smoke from cars and households)	400 kV and 230 kV transmission lines (TL) and substations are in close proximity to an extended industrially developed area, typically with numerous man-made pollution sources producing carbon leftovers. It is the most densely populated region in Ethiopia. Since almost all TLs are connected to this region, it has very high strategic importance. Pollution, originating from transport infrastructure and households, is very high.	Heavy
Central (Adama)	Mixture of agricultural and industrial pollutants, Type A (carbon, sand, dust, cement, smoke from cars and households)	230 kV and 132 kV TLs and substations are in this region. It is in the Great Rift Valley region with many agricultural activities thus subjected to pollution from ploughing and crop spraying of fertilizers, products of burning and salts present in the soil; limited industrial pollution and regular rain washing. Sand and dust storms are common.	Medium
Northern (Mekelle)	Mixture of desert, agriculture, mining and light industrial pollutants, Type A (carbon, cement, gypsum, salty dust, chemical waste, smoke from cars and households)	230 kV and 132 kV TLs pass through and are near some industries and mining activities, which are sources of pollution. Mostly extended periods of dry conditions and desert area with salty and sandy soil. Dust storms are common. Subject to wind-borne salt particles from Afar depression region and Red Sea. Close to desert and open dry land and subjected for a long period (several weeks or months) of dry pollution accumulation.	Heavy
North- Western (Bahir Dar)	Mixture of agricultural and light industrial pollutants, Type A (ploughing, crop spraying, fertilizers, smoke from cars and households)	Double circuit 400 kV TL from Beles to Addis Ababa and double circuit 230 kV line to Sudan with very high commercial and strategic importance passes through the region. Substations are located in close proximity to many agricultural activities, thus subject to pollution from ploughing, crop spraying by chemicals and fertilizers, products of burning and bird droppings. Limited industrial pollutions from cement factories around Debre Markos and Dejen. Most of the lines are located close to highways with records of some vandalism activities.	Medium

Region (representative site in the region)	General types of environments and types of pollution	Description of the environment/ region	Estimated site pollution severity (SPS) class
North-Eastern (Semera)	Mixture of pollutants from desert, coastal, mining, and agricultural sources, combining both Type A and Type B pollution, (saline lakes, sandy soils and salty dust storms, direct salt sprays)	230 kV TLs and planned 500 kV TL to Yemen with very high strategic importance. Substations are in proximity to salt mining and agricultural activities. Sugar factory (light desert-industrial mixture). Subject to wind-borne salt particles and sandy soils with extended periods of dry conditions. Also directly subjected to salt sprays from the Red Sea and Gulf of Aden and dense saline fog and salted dew formation on insulator surfaces.	Very heavy
Eastern (Dire Dawa)	Mixture of desert, coastal and light industrial pollutants, Combination of Type A and Type B (sandy soils and salty dust storms, direct salt sprays)	230 kV TL to Djibouti. Substations are located in close proximity to cement factories. Very high economic and strategic importance, with the Ethiopia-Djibouti railway connection passing through. Heavy sandstorms and salted dews are common. Desert areas with fast accumulation of sand and salt, with regular moisture condensation and extended periods of dry conditions. May also be exposed to direct salt sprays from Red Sea, Gulf of Aden and Indian Ocean. High possibility of salted dew formation on insulator surfaces. Directly subjected to highly conductive contaminants or cement type dust of high density and frequent wetting by fog or drizzle.	Very heavy
Southern (Wolaita Sodo)	Agricultural and mining, Type A (chemical wastes, fertilizers, ploughing)	500 kV HVDC converter station and TL to Kenya, 400 kV TL to Addis Ababa and 230 kV TL and substations are in this region with very high strategic importance. Most of the land is covered with forest and shrubs with regular monthly rain washing. Many agricultural and mining activities. Subjected to pollution from chemical waste, ploughing or crop spraying.	Medium
South-Western (Gambela)	Agricultural and mining, Type A (chemical wastes, fertilizers, ploughing, crop spraying)	Planned 500 kV TL extending from Dedessa substation to South Sudan and existing 230 kV TL and substation are in this region. Most of the land is covered with natural forest and shrubs. Many large farmlands and agricultural activities with regular rain washing. Subject to pollution due to ploughing, crop spraying with chemicals and fertilizers, products of burning, and bird droppings.	Medium
Western (Assosa)	Agricultural and mining, Type A (chemical wastes, fertilizers, ploughing, crop spraying)	This is the region where the Grand Ethiopian Renaissance Dam (GERD) hydropower plant is situated with the capacity of 6000 MW and a planned 500 kV double circuit line to Sudan will pass. 400 kV TL to Bahir Dar and 132 kV TL and substations are in the region. Very high economic and strategic importance to the country with many agricultural and mining activities. Most of the land is covered with forest and shrubs, with regular monthly rain washing. Subjected to contamination from chemical wastes, ploughing or crop spraying. Prevailing wind is not directly from these pollution sources.	Light

Measurements of parameters such as equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD) or any other site assessment have yet to be performed, and their absence affects the accuracy of the estimates presented, which will require further validation through an extensive measurement program in the future.

Based on the evaluation of general environmental types and climatic conditions, five regions with distinct pollution types have been identified: agricultural pollution, industrial pollution, a mixture of desert and coastal pollution, a combination of agricultural and industrial pollution, and a mixture of desert and industrial pollution. The map illustrating the estimated site pollution severity (SPS) classes for the grid regions is displayed in Figure 24.

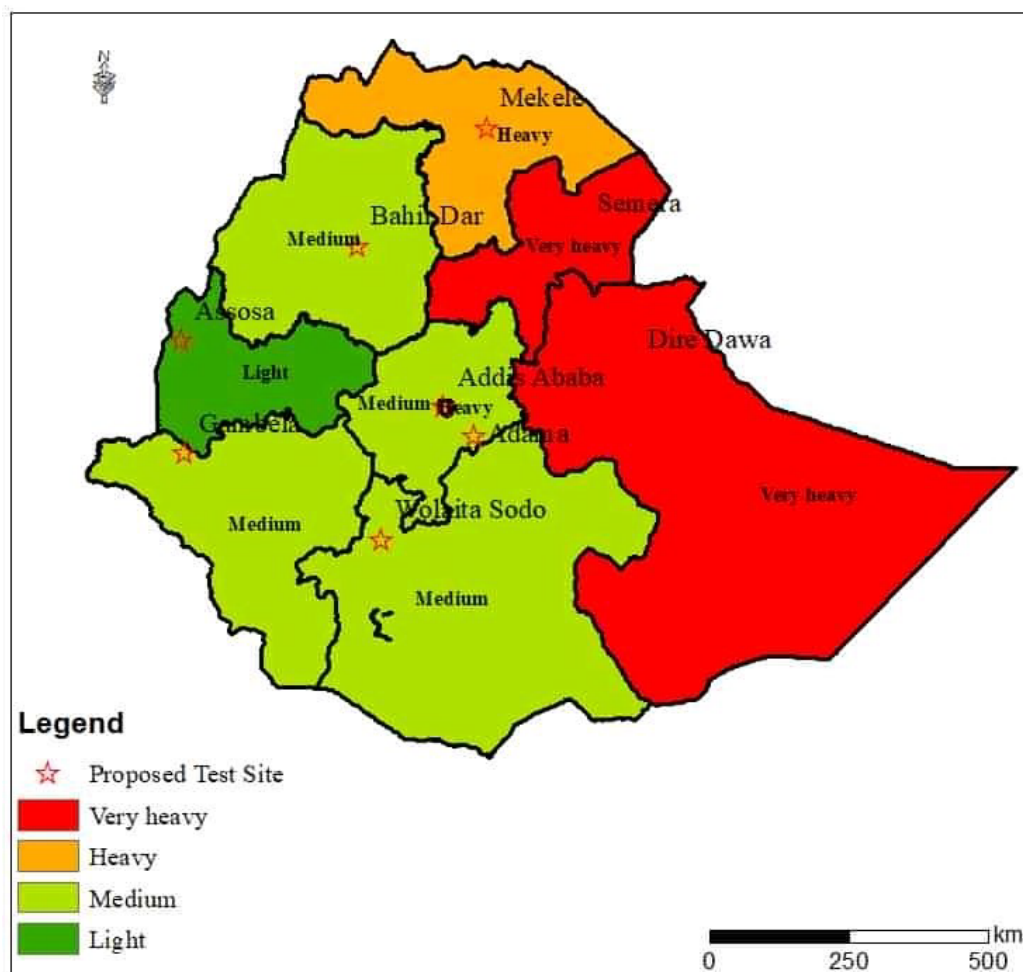


Figure 24: Estimated distribution of site pollution severity (SPS) classes of Ethiopian grid regions.

3.3 Policies and Practices of Power Companies Regarding Present and Future Insulator Selection

The selection of insulator types and materials is heavily influenced by national and power company policies, as well as the prevailing economic conditions. This choice directly impacts the insulator profile, primarily determined by the environmental context. Environmental and system constraints also play a crucial role in determining the type of material used (CIGRE Working Group C4.303, 2008). The Ethiopian Electric Power (EEP), the sole government-owned power company, is tasked with the design, specification, construction, and supervision of all transmission lines and substations in Ethiopia. This section evaluates EEP's practices and approach to selecting and dimensioning outdoor insulators, focusing on the environmental conditions considered during the selection process and assessing the monitoring and maintenance procedures for insulators.

The analysis indicates that most existing transmission lines and substations in Ethiopia utilize glass and porcelain insulators, while composite insulators have been introduced more recently, with their usage steadily increasing. Glass insulators are the most commonly used and are associated with the majority of observed faults.

A significant limitation in the design approach identified in this assessment is the absence of consistent guidelines that take into account specific application requirements and environmental conditions in which the insulators will be deployed. For many new projects, insulator selection and dimensioning have been conducted without a comprehensive review of service experiences from existing lines and substations. Additionally, field measurements to ascertain site pollution severity at test stations in comparable geographical areas or similar environmental conditions are rarely performed, and only estimated pollution severity values are utilized. Consequently, system requirements and economic considerations often dominate the selection of insulator materials and types.

When economic factors primarily drive the selection process without adequately considering environmental conditions and service experiences, a balance between initial investment, maintenance costs, and replacement expenses is seldom achieved. While this approach may seem straightforward and cost-effective, it can lead to over- or under-dimensioned solutions. Documentation for projects generally lacks clearly defined test methods and acceptance criteria for evaluating insulator suitability. There are typically no reports on service experiences or field measurements aimed at estimating site pollution severity. The prevailing practice is to assume the site pollution severity class as a worst-case scenario (either heavy or very heavy) and to apply the corresponding minimum Unified Specific Creepage Distance (USCD) requirements from international standards (IEC/TS 60815-1, 2008; IEC/TS 60815-2, 2008; IEC/TS 60815-3, 2008). This can lead to unnecessarily costly over-design of

insulators. Constraints related to cost and time often prevent thorough site assessments, forcing the company to accept designs based on limited information, even though with sound assumptions. Such a situation should be avoided, as it can result in increased maintenance costs and is neither economical nor reliable in the long term (CIGRE Taskforce 33.04.01, 2000).

Additionally, many EEP projects tend to use identical insulator types and sizes along the entire transmission line route, even when it traverses diverse geographical and environmental conditions. The lack of necessary corrections, particularly for altitude, has been identified as a key reason for the poor performance of external insulators in various regions of the country. This issue is especially pronounced where lines cross the Ethiopian highlands and plateaus, where elevations exceed 2,000 meters above sea level.

Another limitation within the operational practices of the power company is the inability to implement well-defined insulator pollution monitoring techniques. This poses a significant risk to the reliability of power system operations. Moreover, EEP lacks a scheduled maintenance plan and proactive mitigation practices to ensure that insulators perform adequately throughout their expected lifespan. Therefore, EEP should develop measures to prevent premature failures of outdoor insulators, informed by comprehensive studies of environmental conditions, as well as economic and logistical considerations.

3.4 Insulation Problems Met in Practice and Fault Performance Records

According to insights from technical experts within the EEP, insulator flashovers are a major cause of observed failures, primarily attributed to incorrect dimensioning and failure to account for the complex and dynamic interactions with the environment. A range of data from service experience or laboratory tests can be utilized for insulator selection. While service experience is valuable, it may reflect the performance of lines with over-designed insulation (CIGRE Working Group C4.303, 2008). One challenge encountered in this study was the lack of organized data and detailed fault records. Typically, earth faults and transient faults are logged in substation records without specifying the actual causes, making it difficult to determine whether they are due to pollution flashovers or other factors, such as lightning strikes.

In an attempt to identify patterns in the monthly records of transient earth faults relative to meteorological and environmental variations, Figure 25 summarizes fault data from the 400 kV, 230 kV, and 132 kV transmission lines of the Ethiopian power grid from July 2018 to January 2020 (EEP, 2020).

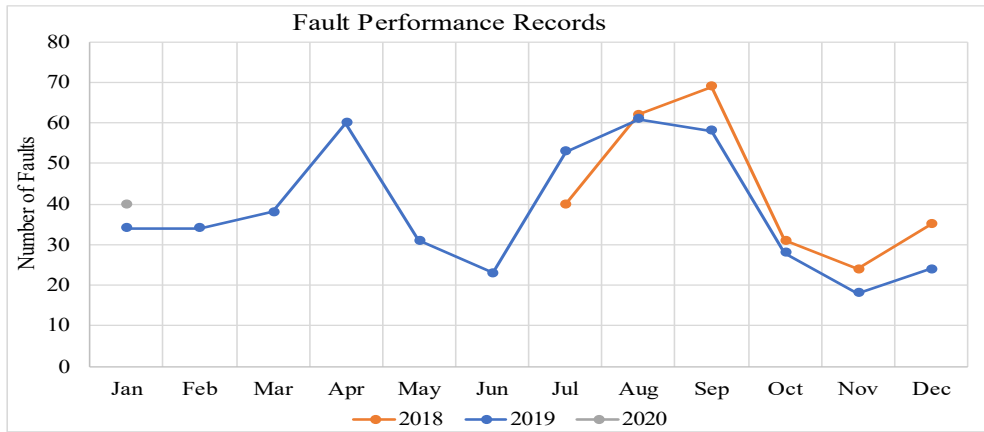


Figure 25: Earth fault/transient earth faults records on HV transmission lines in Ethiopian power grid.

Analysis of the monthly transient earth faults shows that their occurrence aligns with seasonal changes in meteorological parameters. Transient earth faults predominantly occurred during dry periods and seasonal winds characterized by salt spray and dust storms (approximately from October 2018 to May 2019), suggesting that pollution-induced flashovers are likely responsible for these faults, accounting for around 58% of the total earth faults recorded annually. Therefore, it is estimated that the high voltage transmission system experiences approximately 270 faults annually due to pollution-induced flashovers. However, this estimate requires further validation through research employing fault cause identification methods.

The primary reason for unexpected and recurring insulator failures is inadequate insulator selection that fails to match local conditions and the consistent use of identical types and sizes of insulators along the entire transmission line route, which often crosses various climatic and environmental conditions. This issue affects nearly all critical lines in the Ethiopian grid. A substantial number of failures also occur due to the evolving climatic and meteorological conditions and the increasing prevalence of large industrial, mining and agricultural projects, contributes to the emergence of new pollution types and accumulation patterns. Problems escalate further when timely monitoring and maintenance measures are neglected.

Notable examples include the failures of glass and porcelain suspension insulators in northern and northeastern desert areas, such as Mekelle and Semera, where insulators are exposed to a mixture of industrial and desert-derived pollutants. The accumulation of salt particles carried by winds from saline lakes in the Danakil Desert may also contribute to recurring insulator failures in these regions. Similar issues are reported in the eastern region around Dire Dawa and Jijiga, where dust storms and direct salt sprays from the Red Sea, Indian Ocean, and Gulf of Aden are common. Extended dry periods with little to no rainfall, and hence with very low probability for natural cleaning, result in rapid pollution

buildup on insulator surfaces in these areas. Figure 26 depicts the impact of a significant dust storm that swept from Djibouti into Dire Dawa and Jijiga on May 18, 2019. Dust storms from the Sahara Desert typically reach Ethiopia during March and April, particularly in the northern and northwestern regions, including Gondor and Bahir Dar. Additional examples include incidents affecting glass-insulated lines, such as the 132 kV line from Adama to Awash, the 230 kV line around Gehedo and Semera, and the 400 kV lines from Debre Markos to Sululta (particularly near tower number 342 in Muketuri) and from Bahir Dar to the Grand Ethiopian Renaissance Dam (GERD).



Figure 26: Effect of dust storms in Dire Dawa (a and b) and Jijiga (c), May 2019.

Pollution-related challenges extend beyond transmission lines and substations; failures have also been noted in distribution-level insulators, up to 33 kV, which are predominantly linked to local contamination sources, altitude variations, poor quality of insulator materials and manufacturing processes, particularly those produced domestically.

Figure 27 shows examples of insulators (132 kV cap and pin porcelain and 230 kV long rod composite) damaged by pollution flashovers at Adama and Hurso substations in the central and eastern regions of the Ethiopian power grid.



Figure 27: Examples of insulators damaged by pollution flashover events.

3.5 Summary and Conclusion

This chapter summarizes information on the climatic and environmental conditions in Ethiopia, categorizing them into five distinct types based on pollution sources and types by estimating the site pollution severity class for the nine operational regions of the Ethiopian power grid. This classification serves as a foundation for selecting candidate test sites for further research aimed at developing a more accurate pollution severity map for the entire country.

Additionally, the chapter critically evaluates the Ethiopian grid operator's (EEP) strategies for selecting and sizing insulators for high voltage (HV) transmission lines and substations. To date, the company has not systematically employed practices based on the service experience of existing

insulators, nor has it utilized site pollution level measurements or laboratory tests. Documentation for new projects lacks evidence of such practices, instead relying on worst-case scenario estimates for insulation design.

It is clear that EEP has not applied consistent and standardized approaches to the selection and sizing of HV insulators across its previous, ongoing, and upcoming projects. The increasing frequency of faults and unplanned outages resulting from unpredictable, frequent, and early insulator failures reflect poor design and selection trends in insulation practices. This situation poses serious financial implications due to the tendency for over-dimensioning of insulation and towers, coupled with rising maintenance costs. Although the current number of outages may seem manageable, this assessment indicates that pollution-related flashovers are likely to rise in the coming years, potentially impacting the overall operation of the Ethiopian power system and, consequently, the country's growth and economy.

To address the challenges related to the pollution performance of outdoor insulation, EEP should promptly begin initiatives to develop a precise pollution severity map for Ethiopia to mitigate future issues. Detailed assessment of the pollution levels across various regions is critical for understanding the pollution performance of in-service insulators and for the development of effective maintenance strategies. Additionally, pollution severity mapping can guide the selection of suitable insulators for different environmental conditions, supporting EEP's efforts to enhance network resilience and reduce outage frequency.

CHAPTER 4

4. Investigation into Pollution-Induced Flashovers of In-Service Insulators

4.1 Introduction

Analysis in chapter two revealed that, out of 8,891 unplanned outages between 2015 and 2022, 4,231 (47%) were of unknown origin (Desta et al., 2024a). This high rate of unexplained faults undermines the system's reliability, as each incident prompts circuit breakers to operate repeatedly, triggering transients in the network that wear out components prematurely, interrupt power supply, and incur financial costs (Herman & Gaunt, 2010; Maehl, 1996; Major, 1993; Taklaja et al., 2013). Addressing these challenges requires identifying fault origins and establishing appropriate remedial actions. Based on the findings from the previous chapters, this chapter focuses specifically on the pollution-induced flashover of insulators, identified as a key factor contributing to unexplained outages in the Ethiopian power transmission network.

To further investigate the issue, this chapter concentrates on detailed examination of unexplained faults, using refined and detailed methodology specifically designed to identify pollution-induced flashovers (PFO) and assess their spatial and temporal distribution within Ethiopia's power grid. The analysis aims to identify regions prone to these failures and the specific lines that are most impacted. It also evaluates the performance of different insulator types based on their trip-out frequency. These insights will guide EEP in selecting and sizing insulators for future transmission projects and in establishing suitable maintenance and monitoring procedures for existing lines (CIGRE Working Group C4.303, 2008; Peter & Vajeth, 2005; Sandhu, 1988; Vosloo, 2009).

4.2 Method for Identifying Pollution Induced Line Faults

Determining whether pollution flashovers are responsible for line faults can be challenging. However, certain patterns can assist in their identification (Jian et al., 2021; Macey, Vosloo, & Turreil, 2004; Minnaar et al., 2016; Peter & Vajeth, 2005; Sandhu, 1988). To distinguish pollution-related faults from unexplained ones, this study examined fault patterns that align with known characteristics of pollution-induced failures. The analysis considered factors such as time, season, and location of faults, as well as the climate and environmental conditions in affected regions (Bekker & Hoch, 2002; Jian et al., 2021; Macey, Vosloo, & Turreil, 2004; Minnaar et al., 2016; Vosloo, 2009). Additionally, voltage and current data during faults, fault duration, reclosure success, and operational history, provided valuable insights (Jian et al., 2021; Macey, Vosloo, & Turreil, 2004; Minnaar et al., 2012; Minnaar et al., 2016; Vosloo, 2009).

4.2.1 Characteristic Patterns and Conditions of Pollution Flashovers

4.2.1.1 Time-of-Day of Fault Occurrence

To identify faults likely due to pre-deposited pollution and moisture-triggered flashovers (type A pollution flashover process) (IEC/TS 60815-1, 2008), incidents should predominantly occur between midnight and early morning, up to around 08:00, which correlates with periods of dew, mist, or light rain (Bekker & Hoch, 2002; Burnham, 1995; Macey, Vosloo, & Tourreil, 2004; Major, 1993). Humidity increases overnight, with flashover incidents peaking around sunrise, approximately 06:00, and rarely happening during daytime (Bekker & Hoch, 2002; Kleinhans, 2005; Macey, Vosloo, & Tourreil, 2004; Major, 1993). Bird streamer-related flashovers, classified as Type B or instantaneous pollution flashover, typically show two occurrence peaks, in the evening at around 22:00 and another in the morning at 06:00, aligning with bird's feeding and digestive patterns (Burnham, 1995; Macey, Vosloo, & Tourreil, 2004; Maehl, 1996). Similar patterns have been observed in studies from Florida, Estonia, and South Africa (Burnham, 1995; Macey, Vosloo, & Tourreil, 2004; Sandhu, 1988; Taklaja et al., 2013).

4.2.1.2 Seasonal Patterns of Fault Occurrence

Pollution-induced faults are more frequent during hot and dry seasons, where nighttime cooling facilitates condensation and moisture accumulation on insulators. Additionally, seasonal changes marked by fog and light rains following hot and dry periods are conducive to pollution-induced outages (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008; IEC/TS 60815-1, 2008; Major, 1993). Bird streamer faults also show a seasonal trend influenced by bird presence and feeding cycles, with an increase typically seen in spring (Burnham, 1995; Macey, Vosloo, & Tourreil, 2004; Maehl, 1996; Sandhu, 1988).

4.2.1.3 Geographical Location of Faults

Geographic location is another indicator of fault causes (Minnaar et al., 2012; Peter & Vajeth, 2005; Vosloo, 2009). Pollution-related faults tend to occur in areas exposed to industrial and agricultural pollution, and proximity to deserts, high traffic, or coastal environments (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008; IEC/TS 60815-1, 2008; Kleinhans, 2005; Major, 1993). Bird streamer faults are common in areas supporting significant bird populations and near water sources (Burnham, 1995; Maehl, 1996; Montoya Tena et al., 2010; Moreira et al., 2023; Taklaja et al., 2013). Therefore, identifying a fault's location is critical in determining its cause (CIGRE Taskforce 33.04.01, 2000; IEC/TS 60815-1, 2008; Macey, Vosloo, & Tourreil, 2004; Peter & Vajeth, 2005).

4.2.1.4 Climatic and Meteorological Conditions

Studies highlight that weather factors like temperature, rainfall, wind speed and direction, and relative humidity can influence the build-up and wetting of pollutants on insulator surfaces and subsequent flashovers (CIGRE Taskforce 33.04.01, 2000; IEC/TS 60815-1, 2008; Macey, Vosloo, & Turreil, 2004; Peter & Vajeth, 2005; Sandhu, 1988). Heavy rain washes away pollutants, lowering flashover risks, whereas lighter rainfall contributes to pollution wetting and potential flashovers. In this context, the primary rainy or wet seasons are characterized by most days within a month experiencing significant precipitation, specifically when daily rainfall exceeds 10 mm. In contrast, periods with rainfall ranging from 1 mm to 10 mm are categorized as light rain/less-wet seasons. During prolonged dry spells, more than 5–10 consecutive days without rain, pollutant accumulation is more pronounced (CIGRE Taskforce 33.04.01, 2000; Major, 1993; Sandhu, 1988; Wesley & Garcia, 2022). Pollution deposition tends to be higher in warm conditions above 5 °C. Strong winds can unevenly spread pollutants on insulators, and high humidity or morning dew combined with sea winds accelerates pollutant deposition and increases flashover risk (CIGRE Taskforce 33.04.01, 2000; Major, 1993; Sandhu, 1988; Wesley & Garcia, 2022).

This study included mapping the geographic positions of each transmission line tower in Ethiopia and, using ArcGIS 10.5, analyzing meteorological parameters to estimate average conditions along the network. The averages were calculated along each line or between substations for longer segments.

4.2.1.5 Contextual Characteristics of Line Faults

Analyzing the fault voltage and current magnitudes, the affected phases, fault duration, reclosure success, and other protection data provides insights into possible causes behind faults (Jian et al., 2021; Maehl, 1996; Minnaar et al., 2016; Sklenicka, 2023; Taklaja et al., 2013). The features derived from fault voltage and current waveforms, however, are highly sensitive to the system's pre-fault operating state and lack a direct correlation with external causes. In contrast, contextual fault characteristics such as time stamps (season, day/night, month, hour), geographic location, environmental and meteorological data, and information related to service experience are more directly linked to external fault triggers like lightning, pollution, fire, or wind (Jian et al., 2021; Minnaar et al., 2016).

Typically, pollution flashovers manifest as transient, single-phase-to-ground faults with high reclosure success rates and occur under stable operating conditions, with steady-state voltages and currents unaffected by preceding lightning, switching surges, or significant changes in voltage or current. During such faults, the faulted phase voltage does not immediately drop to zero, and the fault current remains low due to the typically high fault resistance, which differs from a solid or metallic short-circuit fault (Maehl, 1996; Sklenicka, 2023; Taklaja et al., 2013).

These distinctive fault patterns and contextual factors provide a foundational framework for classifying grid regions and creating criteria for attributing unexplained faults to pollution-induced flashovers.

4.2.2 Classification of Grid Regions

Ethiopia's diverse meteorological and environmental characteristics, specifically those influencing pollution build-up, wetting patterns, and natural cleaning processes, serve as a foundation for classifying its grid regions. This classification relies on identifying specific seasonal trends in each grid region where pollution accumulation on insulators intensifies, conditions are optimal for critical wetting and encourage natural cleaning to reduce pollution over time. By categorizing the national territory this way, distinct groups of grid regions are established, allowing for more structured analysis of unexplained faults. The Ethiopian Electric Power (EEP) grid management regions are thus grouped as follows: the North, North-West, Addis Ababa, and Central regions form Group 1 (G1); the West and South-West regions comprise Group 2 (G2); the South region is designated as Group 3 (G3); and the East and North-East regions are grouped into Group 4 (G4). Figure 28 shows these grid regions' geographic layout along with average annual rainfall.

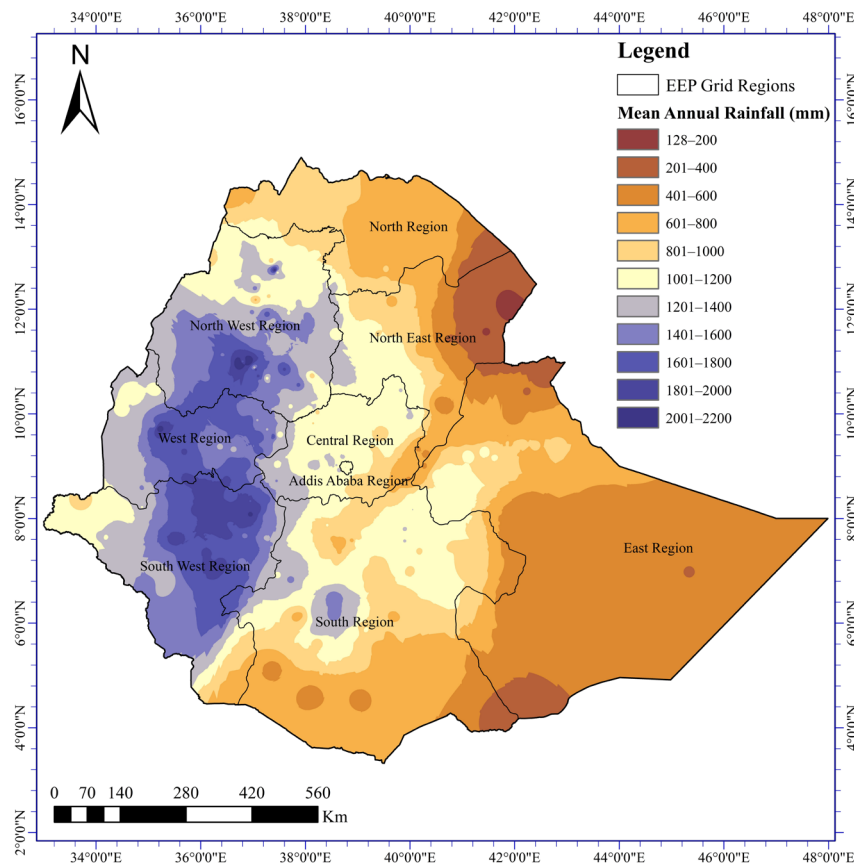


Figure 28: Map of annual average rainfall of Ethiopia showing the grid regions of EEP.

While climatic and meteorological data do not directly indicate pollution severity, they do provide insight into conditions that favor pollutant build-up and wetting on insulator strings (CIGRE Taskforce

33.04.01, 2000; Sandhu, 1988). Ethiopia's tropical climate creates distinct wet and dry seasons with varying rainfall and temperature patterns (Abebe, 2010; McSweeney et al., 2012; Seleshi & Zanke, 2004). To characterize the meteorological conditions relevant to each group, four representative sites are used: Addis Ababa for Group 1, Assosa for Group 2, Gode for Group 3, and Semera for Group 4. It is assumed that other areas within each group experience similar or comparable regional climate conditions as their representative sites (CIGRE Taskforce 33.04.01, 2000). Figure 29 illustrates the meteorological variations for each group. Chapters two and three provide further details on Ethiopia's climate and pollution conditions for each grid region, including site pollution severity classifications (Desta & Wogari, 2020; Desta et al., 2024a).

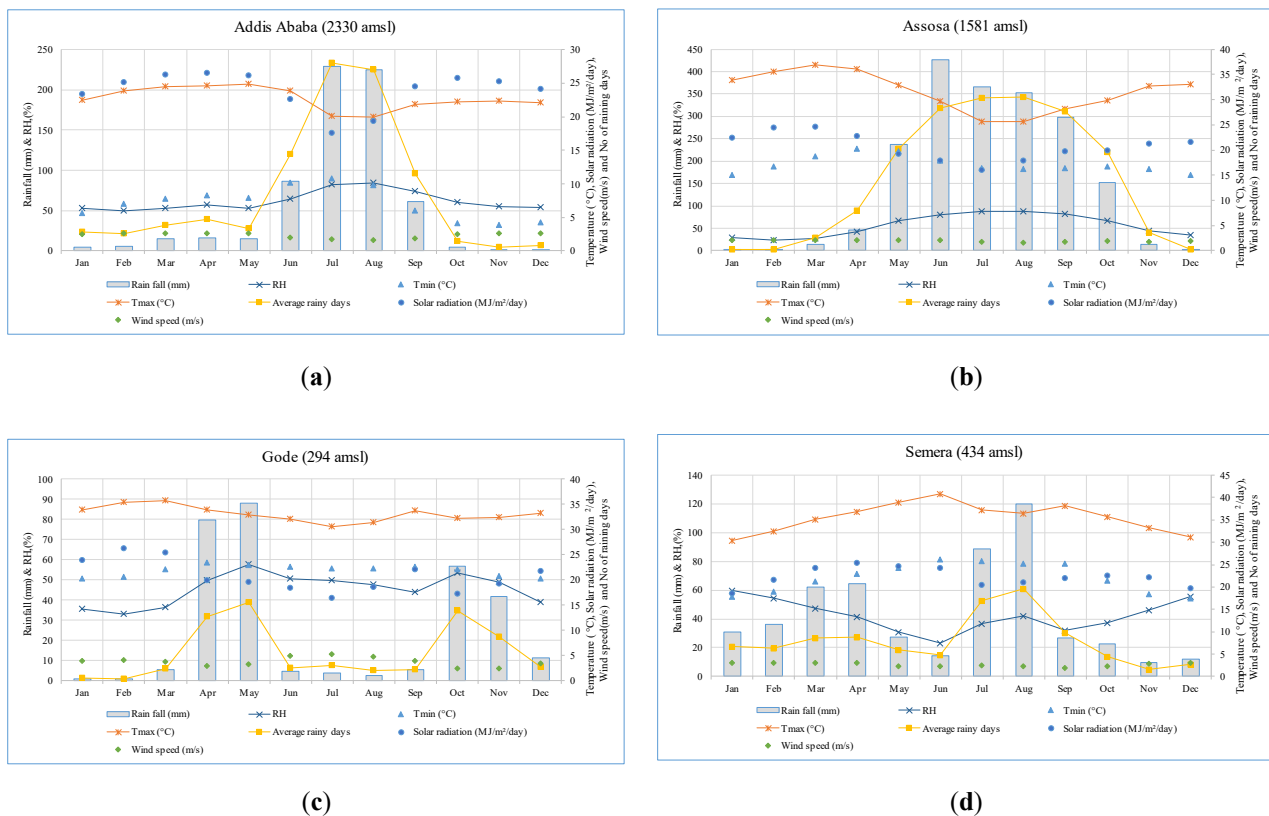


Figure 29: Illustrations of annual variations in meteorological parameters (derived from 30 years of data (CFSR, 2019)) for four representative sites in Ethiopia. (a) Addis Ababa; (b) Assosa; (c) Gode; (d) Semera.

The environmental and meteorological conditions for each group are described as follows:

Group 1 includes the North, North-West, Addis Ababa, and Central grid regions of the EEP, areas that experience pollution from highways, construction sites, transportation, natural dust and both industrial and agricultural activities. Characterized by a mix of desert, industrial, and agricultural environments, this group primarily has type A pollution, with an estimated SPS classification of medium to heavy (Desta & Wogari, 2020; IEC/TS 60815-1, 2008). According to Figure 29a, Group 1 regions experience a dry period from October to February, with a short rainy season from March to

May, during which monthly rainfall averages about 6.4 mm. Pollution accumulation on insulators is the highest during these periods. Seasons marked by rainfall below 20 mm typically start in late March and extend through to the end of May. Meanwhile, drier periods with rainfall levels under 10 mm usually commence in late September and persist until the end of March in the following year. The main rainy season from June to September, averaging 170 mm per month, provides natural cleaning. This period averages 20 rainy days, with relative humidity staying above 55% year-round, peaking at 77% in July and August. Average temperatures vary from 27°C during the hot, low-rain season to 24°C in other months, with prevailing eastern winds at speeds between 1.7 and 2.7 m/s. As a result, pollution accumulation and wetting are more likely from October to February and again from March to May, increasing the risk of flashovers during these months.

Group 2 covers EEP's South-West and West grid regions, where pollution stems mainly from agriculture and mining, classified as type A with a light to medium SPS class (Desta & Wogari, 2020; IEC/TS 60815-1, 2008). Figure 29b shows that October to February is mainly dry, with an average monthly rainfall of 6.7 mm. Rainfall less than 20 mm typically occurs in March and November, while levels below 10 mm are seen from December to February. March to September marks the main rainy season, averaging 200 mm of rainfall monthly, which helps clean the insulator surfaces naturally. Relative humidity in this region stays above 65% from May to October, and maximum temperatures reach up to 34°C in dry seasons, dropping to 31°C during other periods. Winds mainly blow from the southeast, with speeds between 1.8 and 2.3 m/s. This seasonal pattern raises flashover risks significantly from October to February, when pollution accumulation and wetting are most pronounced.

Group 3 encompasses the South grid region of EEP, including southern and southeastern Ethiopia, with pollution sources ranging from dust in semi-arid areas, highways, construction, mining, industrial, and agriculture. The region is characterized as having a mix of agricultural and industrial types of environments (Desta & Wogari, 2020), with type A pollution accumulation, estimated at a medium to heavy SPS class (IEC/TS 60815-1, 2008). As Figure 29c indicates, Group 3's dry seasons occur from June to September and December to February, with brief rainfall in October and November. Monthly rainfall averages 17 mm during these dry months, dropping below 10 mm in some months. March to May brings the main rainy season, with an average ten days a month and 44 mm in total, facilitating insulator cleaning. Relative humidity exceeds 50% between April and October, aiding moisture accumulation on polluted insulators. Average maximum temperatures reach around 31°C in dry months and increase to 33.5°C in the wet season, with prevailing southeast winds averaging 2 to 3.5 m/s. Consequently, flashover risks are highest from June to September and again from October to February.

Group 4 includes the East and North-East regions, where rainfall is scarce year-round (Abebe, 2010; Seleshi & Zanke, 2004; Sklenicka, 2023). Pollution sources here include highway traffic, salty soil, dust storms from the desert, salt sprays from coastal areas, agriculture, and mining. These regions feature a combination of desert, coastal, and agricultural types of environments, with both type A and B pollutions, and an estimated heavy to very heavy SPS class (IEC/TS 60815-1, 2008; Desta & Wogari, 2020). As depicted in Figure 29d, the main dry seasons extend from October to February of the next year and from March to May, with monthly rainfall around 27 mm. Additionally, periods with rainfall under 20 mm are observed in January and June, while those with rainfall less than 10 mm generally occur in November and December. From June to September, which represents the primary rainy season, the climate remains humid, though precipitation levels tend to be mild. Rainfall during these months is often characterized by continuous drizzle or intermittent showers, resulting in an average monthly rainfall of about 45 mm. Thus, the cleaning effect of the rainfall is quite limited during this season.

Relative Humidity remains low year-round, averaging 46% but slightly higher and exceeds 50% in December and January. The maximum temperature is around 31°C in dry months, rising to 34°C during other seasons. Prevailing winds from the east reach speeds of 2.2 to 3.5 m/s. The climatic and meteorological conditions, for this group, favor continuous pollution build-up and wetting, creating high flashover risks throughout the year. Coastal proximity in some areas introduces saline moisture, originating from the Red Sea and the Gulf of Aden, accelerating pollution accumulation and flashover potential.

4.2.3 Criteria for Evaluating Unexplained Fault Data

Previous studies (Jian et al., 2021; Minnaar et al., 2016) indicate that accurately identifying the causes of transmission line faults requires analyzing contextual fault characteristics. Data on fault characteristics, time, date, and location of occurrence, along with relevant meteorological or environmental conditions (linked to grid region groups), form the basis for establishing the criteria to classify fault origins. Table 6 outlines these criteria, deemed sufficient for identifying pollution-induced flashover faults, with the step-by-step evaluation illustrated in Figure 30.

Table 6 Criteria used to identify pollution caused unexplained faults.

Conditions	Time of the Day	Month of the Year	Grid Region Classification (Groups)
Condition 1	19:00–8:00	October–February	Group 1, Group 2, Group 3, Group 4
Condition 2	19:00–8:00	March–May	Group 1, Group 4
Condition 3	19:00–8:00	June–September	Group 3, Group 4

This flowchart provides a systematic approach for assessing unexplained faults, beginning with a preliminary check to see if fault characteristics meet the criteria in Section 4.2.1.5. If the fault does not meet these criteria, then it is deemed unrelated to pollution and marked as “Not Consistent with PFO.” If it does meet the criteria, the process continues, and information on the fault location (Grid Region), month, and time of day are extracted and considered in subsequent steps. The decision-making process then applies the conditions outlined in Sections 4.2.1 and 4.2.2 and Table 6.

In subsequent steps, the fault is assigned to the appropriate grid region group and checked for consistency with the time-of-day and month criteria. Faults that meet all these conditions are classified as “Consistent with PFO.” If only one criterion is met, the fault’s origin remains “Inconclusive,” as other environmental factors could produce similar fault characteristics, necessitating further investigation. If neither condition is satisfied, the fault is classified as “Not Consistent with PFO,” suggesting it is not pollution-induced.

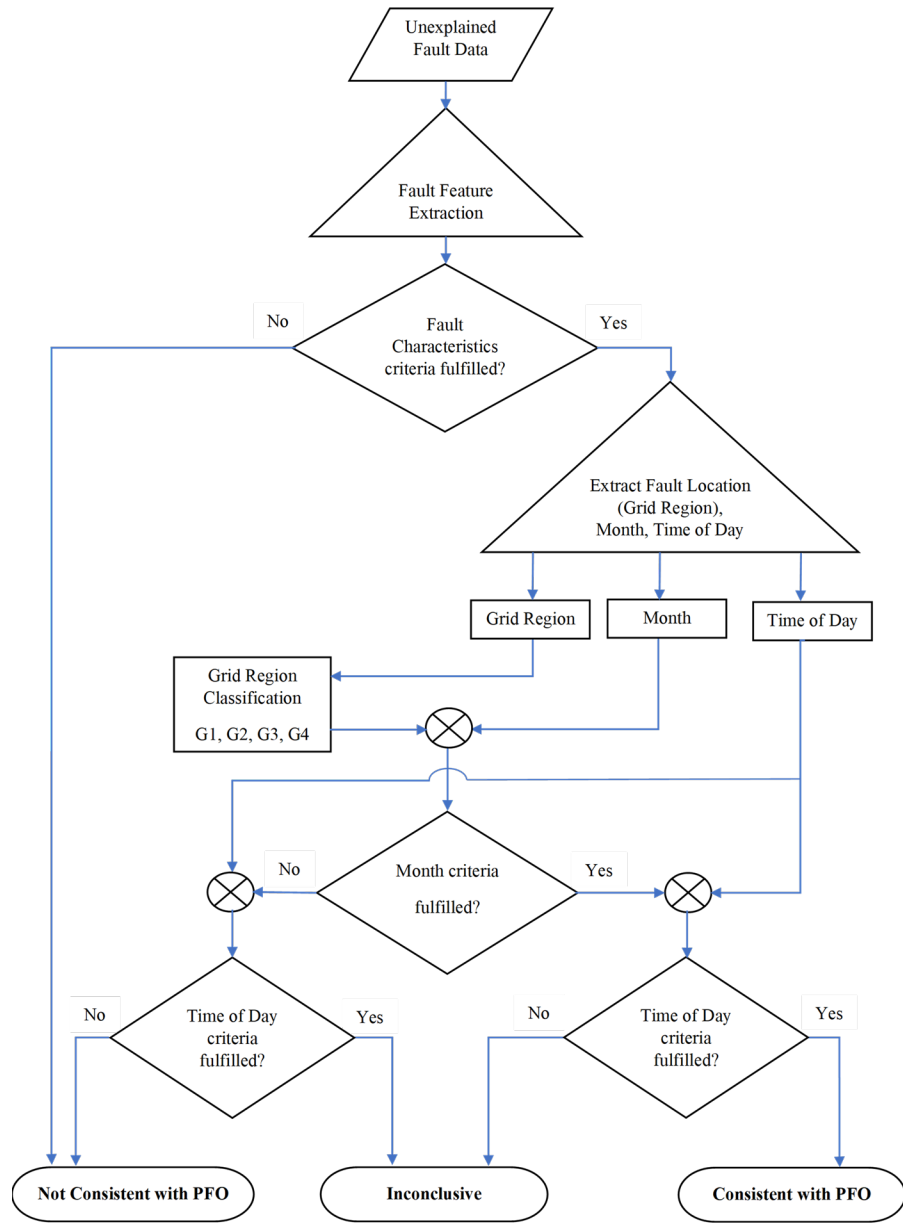


Figure 30: Procedure for application of criteria for identifying pollution flashover-induced faults.

4.3 Statistics of Spatiotemporal Distribution of Pollution-Induced Flashover Faults

In assessing all unexplained outages within the dataset against the criteria outlined in Section 4.2.3, a total of 4,231 cases were reviewed. Among these, 1,045 (24.7%) faults were classified as Consistent with Pollution-Induced Flashover (PFO), while 2,222 cases (52.5%) were marked Inconclusive. Within the Inconclusive cases, 1,649 (39%) did not align with the time-of-the-day criteria, and 573 (13.5%) did not meet the seasonal (month) criterion specified. The remaining 964 faults (22.8%) were found Not Consistent with PFO, typically linked to other causes occurring in the daytime and early evening hours (Bekker & Hoch, 2002; Chen, 2020). However, the Inconclusive category may still contain PFO instances that deviated from their typical characteristic trends (Burnham, 1995; Hu, 2007; Macey, Vosloo, & Turreil, 2004).

These findings highlight that pollution-induced flashovers play a significant role in unexplained service interruptions within the EEP transmission network. A deeper statistical analysis was conducted to explore the temporal and spatial patterns of these flashovers over the years, seasons, times of day, and across grid regions and voltage levels. The rate of faults on individual transmission lines was also calculated to assess performance, with detailed results presented in the following subsections.

4.3.1 Geographical Distribution of Pollution-Induced Flashovers Across EEP Grid Regions

Figure 31 provides a breakdown of pollution-induced faults across EEP’s grid regions from 2015 to 2022. The North-East region experienced the most interruptions, with 290 faults (27.8%) at a rate of 3.1 faults per 100 km per year. The North-West followed, with 155 faults (14.8%) at 1.1 faults per 100 km per year. Additional high-incident regions, including Addis Ababa, East, Central, and South, each recorded over 100 faults with each region observing rates above 0.55 faults per 100 km per year. In contrast, the South-West region encountered the fewest incidents, with 23 faults (2.2%) at a rate of 0.2 faults per 100 km per year. Detailed results of frequency pollution-induced flashovers per 100 km per year on 132, 230 and 400 kV lines across EEP grid regions can be found in Appendix C, Table A – 6, Table A - 7 and Table A - 8.

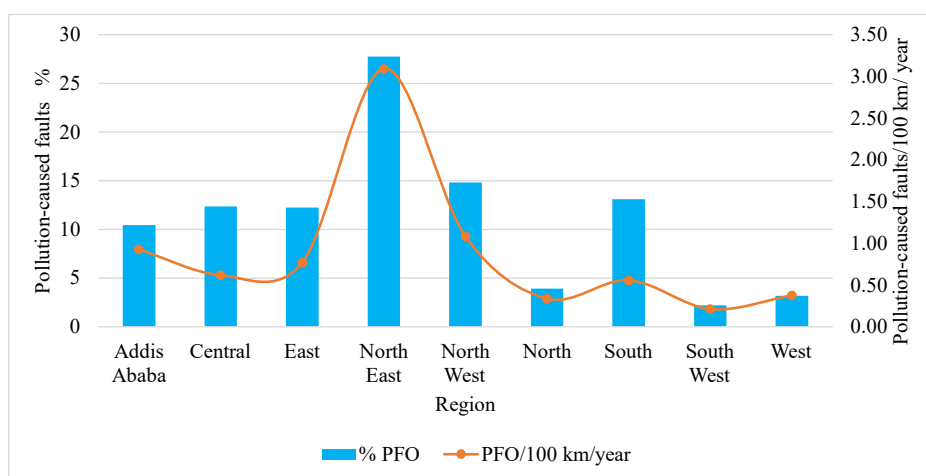


Figure 31: Distribution of pollution-induced flashover faults across EEP grid regions from 2015–2022.

To facilitate comparison and examine the geographical distribution of these faults, incident locations were mapped using transmission line circuit centroids, allowing the estimation of PFO prevalence in terms of faults per unit length and time. For each circuit, the fault rate was computed per 100 km of transmission line per year. These values were integrated into a GIS database, where ArcGIS software determined circuit centroids to create a national map displaying spatial trends, as shown in Figure 32. This figure illustrates Ethiopia’s 132–400 kV transmission grid as of 2022, with grey lines marking

grid routes and circles with varying radii indicating pollution-induced fault averages per 100 km per year for each circuit (Desta et al., 2024a).

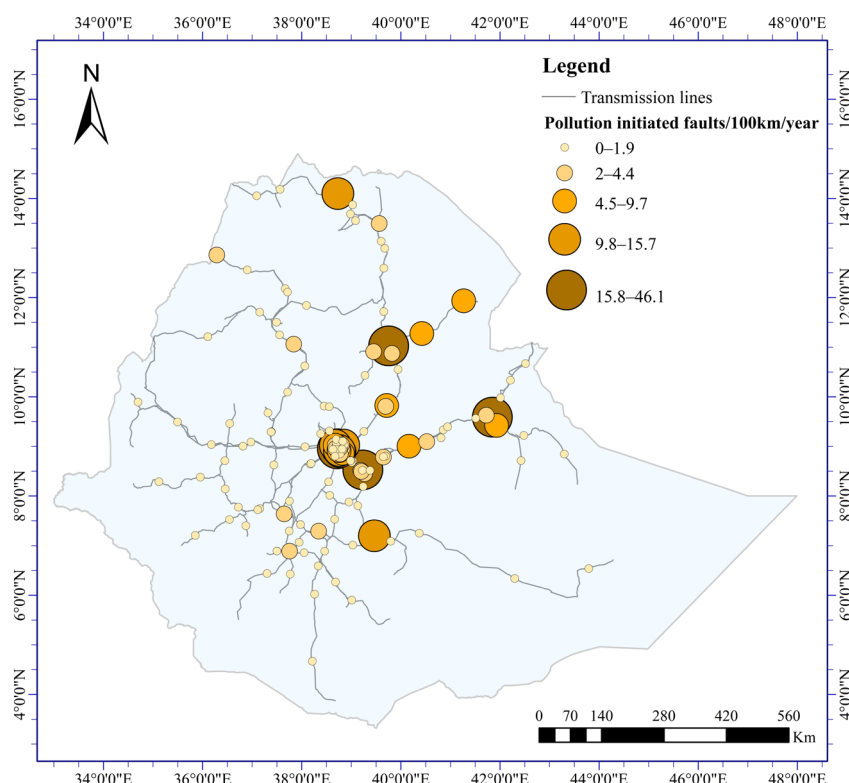


Figure 32: Geographical distribution of pollution induced faults across Ethiopia from 2015–2022.

A total of 152 circuits recorded pollution-induced faults, averaging 3.0 faults per 100 km per year. The North-East, East, and Central regions had the highest concentration of affected circuits, as displayed in Figure 32. Distribution of pollution-induced flashover fault frequency across grid region classification groups is shown in Figure A –7 in Appendix C. Generally, transmission line standards in high-voltage systems accept up to 1–2 unexplained faults per 100 miles annually (equivalent to 0.62–1.24 faults per 100 km per year) (Maehl, 1996; Sandhu, 1988), although the acceptable rate varies depending on a line's importance and location. In Europe, for example, a rate of one flashover per 150 km annually (equivalent to 0.67 faults per 100 km per year) is often considered reasonable (Taklaja et al., 2013). In comparison, the Ethiopian power grid's 132–400 kV transmission lines exhibit a high incidence of pollution-related flashovers, averaging over 130 faults annually between 2015 and 2022, corresponding to a rate of 0.81 faults per 100 km per year. This is an unacceptably high rate, suggesting pollution-induced issues may be more prevalent within the EEP network than anticipated. Table 7 details the frequency of faults for underperforming lines in the EEP's 132, 230, and 400 kV network for this period.

Table 7 Pollution-induced fault frequencies of specific EEP 132, 230, and 400 kV lines between 2015 and 2022.

Transmission Lines	Grid Region	Line Length (km)	Number of Towers	In-Service Year	System Voltage (kV)	Type of Insulator Material	Number of Insulator Strings	Total Pollu Induced F.
Combolcha II—Semera	North East	174.8	391	2011	230	Polymeric composite	1275	78
Combolcha II—Legetaffo	North East and Addis Ababa	276.3	608	2012	230	Polymeric composite	2106	53
Bahir Dar II—Debre Markos	North West	193.8	427	2011	400	Glass	2562	46
Bahir Dar II—Alamata	North West and North East	344.5	792	1998	230	Glass	2544	33
Combolcha I—Akista	North East	82.0	191	2006	132	Polymeric composite	669	28
Semera—Dicheto	North East	65.9	131	2017	230	Polymeric composite	414	27
Debere Berhan—Showarobit	North East	57.5	206	1985	132	Porcelain	636	27
Debre Markos—Sululta	Central and North West	432.0	464	2011	400	Glass	5568	26
Alamata—Combolcha II	North East	170.5	362	2010	230	Polymeric composite	1200	25

The frequency of pollution-induced faults at different primary voltage levels is illustrated in Figure 33. Among these, fault rates were highest on 132 kV lines, with 0.98 faults per 100 km per year, while 230 kV lines experienced 0.75 faults per 100 km per year. These findings are consistent with EEP’s service reports, which attribute the underperformance of many 132 and 230 kV lines, constructed prior to 2005, partly to aging infrastructure, alongside environmental and climatic stressors. In comparison, 400 kV lines exhibited a lower fault rate, at approximately 0.57 faults per 100 km per year. Frequency pollution flashover faults according to grid region classification Group and voltage levels is shown in Appendix C, Figure A – 8.

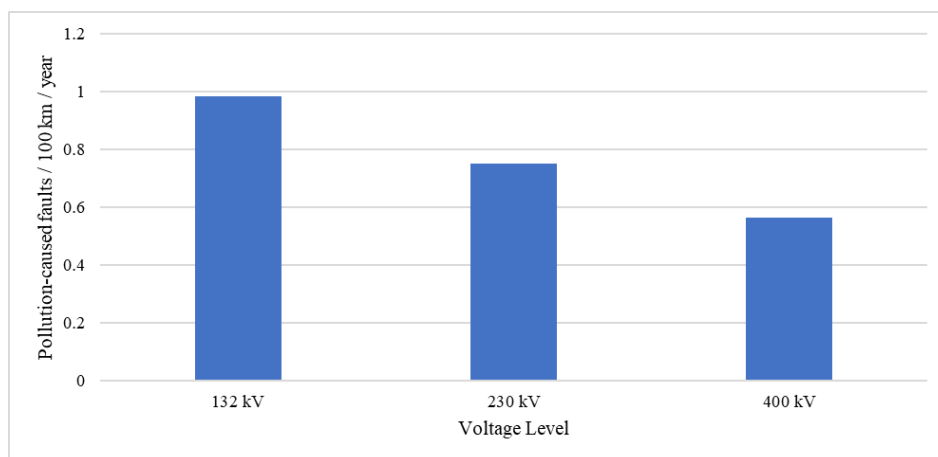


Figure 33: Frequency of pollution-induced faults for 132 kV, 230 kV, and 400 kV lines.

4.3.2 Time-of-Day and Seasonal Examination of Pollution-Induced Faults

An examination of yearly trends in pollution-induced faults revealed variability, with a general increase that peaked in 2018, as shown in Figure 34. Fault rates stabilized after 2019, likely due to pollution saturation, an apparent balance between pollution deposition and natural cleaning mechanisms (CIGRE Taskforce 33.04.01, 2000). Potential causes for the rising trend before 2019 may include environmental changes, insulator selection and dimensioning issues, infrastructure aging, and ineffective maintenance. Further research is needed to understand these factors more deeply and devise

effective fault mitigation strategies. Annual distribution of PFO faults per 100 km of lines during the period 2015-2022 in EEP grid management regions is shown in Figure A – 9 in Appendix C.

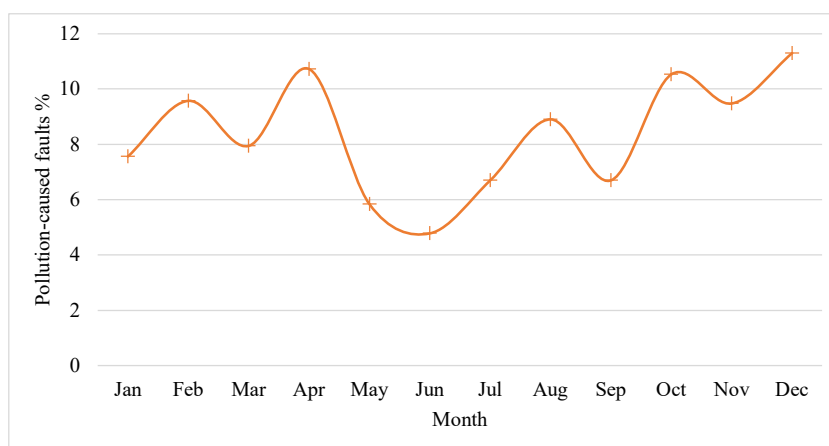


Figure 34: Annual variation in pollution-induced faults in Ethiopian power grid.

The time-of-day analysis in Figure 35 reveals a distinct pattern, with three peaks in pollution-induced faults. The fault rate rises sharply after sunset, reaching a peak between 19:00–20:00, decreases briefly, then increases again around midnight, likely due to pollution wetting from light precipitation, dew, or moisture absorption at night. A further peak occurs around 06:00, possibly due to combined effects of pollution wetting and bird streamers, which are common in spring season in regions populated by large birds. After this early morning peak, fault incidents drop and remain minimal throughout the day. This daily pattern closely correlates with patterns observed in bird streamer and pollution-induced faults in regions like Florida and South Africa, as shown in Figure 35.

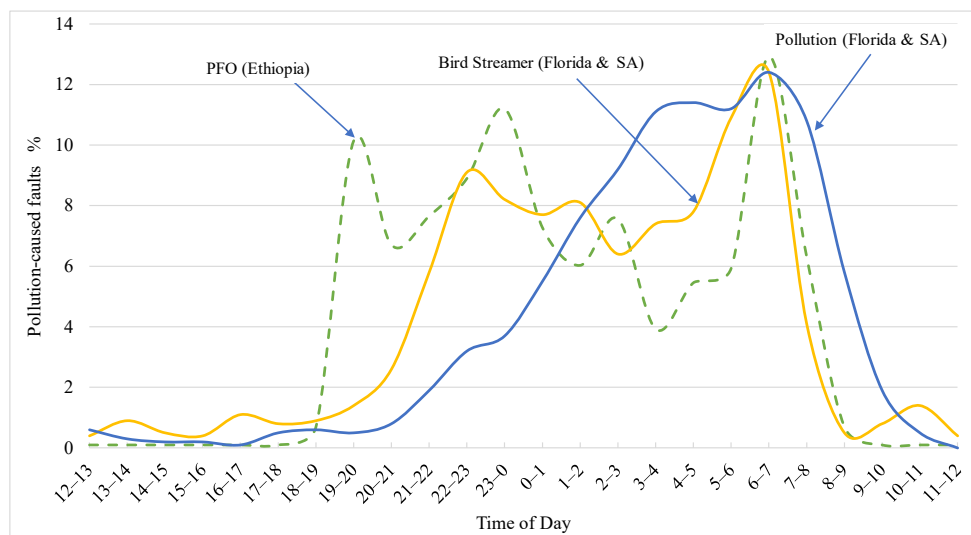


Figure 35: Pollution-induced faults within the Ethiopian network, in comparison with the typical time-of-day fault profiles attributed to pollution and bird streamers observed in Florida, USA, and South Africa (Burnham, 1995; Macey, Vosloo, & Tourreil, 2004).

Figure 36 illustrates the seasonal pattern of fault incidence, showing peaks during the dry months from October to February and March to May, with the highest frequencies occurring in December and April.

Fault occurrences are relatively lower from May to September, apart from a minor increase in August, which coincides with Ethiopia's primary rainy season. This seasonal trend in fault rates corresponds closely with regional rainfall patterns. Seasonal trend of pollution-induced flashover faults in the Ethiopian power network for all voltage levels is shown in Figure A – 10 in Appendix C.

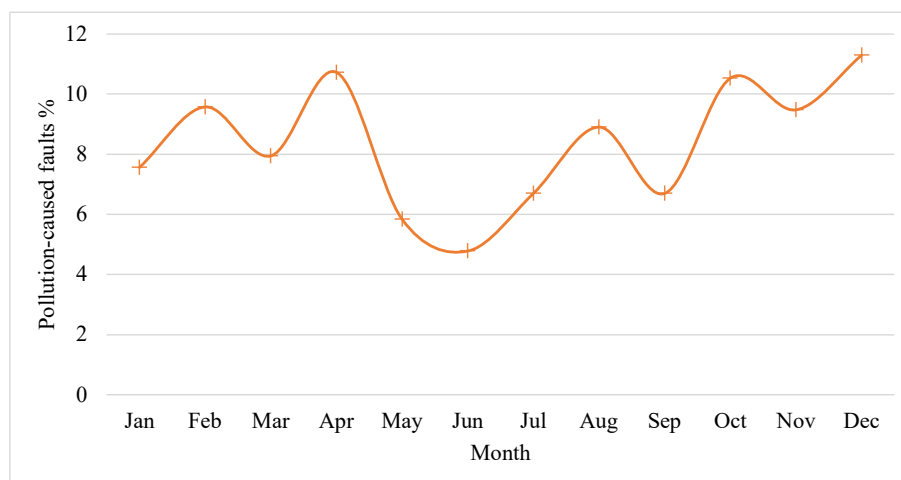


Figure 36: Seasonal trend of pollution-induced flashover faults in the Ethiopian power network.

4.4 Analysis of Pollution-Induced Flashover Faults by Type of In-Service Insulator

Evaluating the flashover performance of insulators under pollution conditions reveals notable patterns based on the insulator's design (such as cap-and-pin or long rod configurations), energization type (AC or DC), and material composition (glass, porcelain, or polymeric) (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008; IEC/TS 60815-1, 2008). This section delves into the relationship between insulator material type and the prevalence of pollution-induced flashover (PFO) incidents. For this analysis, faults were categorized by the insulator type used on each line. The study examined pollution flashover intensity, specifically the frequency of pollution flashovers assigned to each insulator type (porcelain and glass cap-and-pin strings, or silicone rubber polymeric composite long rods), calculated per 1000 units over a designated period and system voltage (Sklenicka, 2023). Findings reveal that out of 1045 pollution-related events, 77 incidents (7.3%) involved porcelain strings, 542 (51.9%) were associated with glass insulators, and 426 (40.8%) affected polymeric composite long rods. Glass and polymeric insulators experienced the majority of these incidents, making up 61% and 34% of the total insulators installed in the system, respectively, while porcelain insulators comprised just 5%. Figure 37 shows the intensity of flashovers by voltage and insulator type over the 2015–2022 period.

On 132 kV lines, porcelain insulators experienced the most pollution-induced flashovers at 1.79 faults/year per 1000 units, followed by glass insulators at 1.10 faults/year per 1000 units, and polymeric long rods with the fewest incidents, under 0.93 faults/year per 1000 units. At the 230 kV

level, polymeric composite insulators exhibited the highest fault intensity (1.36 faults/year per 1000 units), with glass insulators at 0.93 faults/year per 1000 units, and porcelain insulators at only 0.26 faults/year per 1000 units. In the 400 kV lines, exclusively glass insulators are used, showing a fault intensity of 0.47 faults/year per 1000 units.

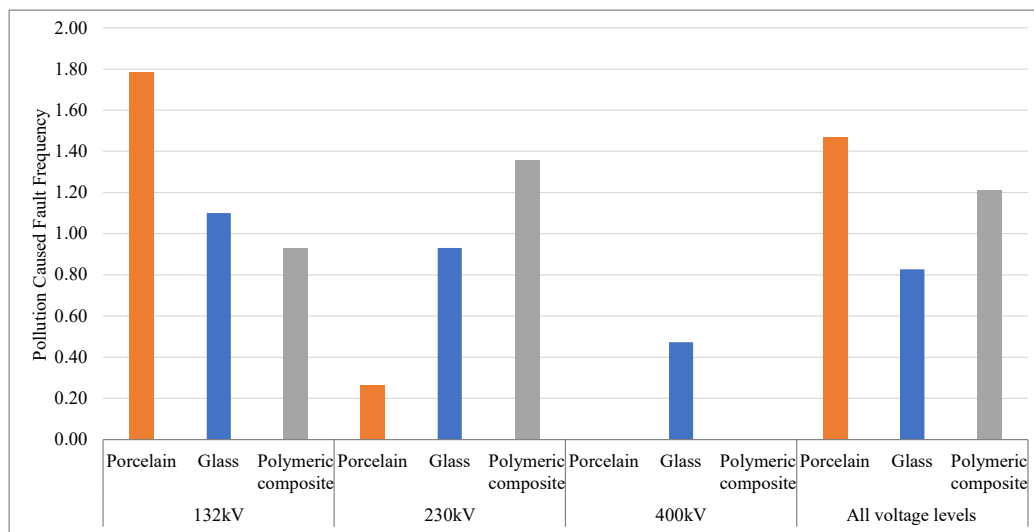


Figure 37: Distribution of PFO intensity by type of insulator (2015 to 2022).

Across these three voltage levels, porcelain strings have the highest average fault intensity at 1.47 faults/year per 1000 units, followed by polymeric composite insulators at 1.21 faults/year per 1000 units, with glass insulators showing the lowest average fault rate at 0.83 faults/year per 1000 units. The percentage distributions of individual insulator types, along with a comparison of the intensities of pollution-induced flashovers for all voltage levels are presented in Figure A – 11 in Appendix C and summarized in Table 8.

Table 8 Distribution of PFO intensity by type of insulator for 132 kV, 230 kV, and 400 kV system voltage (2015 to 2022).

Voltage Level	Type of Insulator					
	Porcelain		Glass		Polymeric Composite	
	Percent of Insulator Strings	Pollution Flashover Intensity (%)	Percent of Insulator Strings	Pollution Flashover Intensity (%)	Percent of Insulator Long Rods	Pollution Flashover Intensity (%)
132 kV	10	46.8	59.2	28.8	30.8	24.4
230 kV	2.7	10.3	38.6	36.5	58.7	53.2
400 kV	0	0	100	100	0	0
All voltage levels	4.9	41.9	61.2	23.6	33.9	34.5

The highest flashover intensity occurred on ceramic (porcelain and glass) insulators, mainly due to their hydrophilic surfaces, which retain moisture and pollutants more readily. The poor pollution performance of these insulators is also related to aging; lines using these insulators were typically installed 30 to 40 years ago and have since experienced material degradation. Extended exposure to extreme environmental stresses has led to the deterioration of end fittings and surfaces, accelerated by factors such as temperature fluctuations during dry spells and acts of vandalism. Service reports support these observations.

High-temperature-vulcanized (HTV) silicone rubber (SR) polymeric insulators installed on 132 and 230 kV lines have also encountered a substantial number of pollution-induced flashovers, despite their relatively recent installation. Although these composite insulators were expected to outperform traditional ones due to their hydrophobic properties, their performance in Ethiopia's unique climatic and environmental conditions has been less satisfactory than anticipated. Polymeric composite insulators were integrated into the EEP network starting in 2008, initially deployed on 132 and 230 kV lines. To evaluate their effectiveness in preventing pollution flashovers, fault data were compared between older lines insulated with glass or porcelain and newer lines insulated with silicone composites. Between 2015 and 2022, 869 pollution-induced flashovers were recorded on 132 and 230 kV lines, with 426 faults occurred on lines using silicone composite insulators and 443 on glass or porcelain-insulated lines. These results indicate that the addition of SR polymeric insulators has not significantly enhanced network performance. This raises concerns about their potential deterioration in performance as they age, particularly when approaching a service lifespan of 30 to 40 years, similar to the issues seen in glass or porcelain insulators.

Several factors could contribute to the relatively poor performance of SR polymeric insulators. Improper planning in the initial line design and failure to account accurately for site-specific pollution levels may lead to inappropriate insulator choice and sizing. The environmental and climatic stresses that insulators will encounter in actual operation are often overlooked or incorrectly estimated. This is particularly true when it comes to considering or accurately determining site pollution severity (SPS) levels for specific line locations. Over time, pollution levels at various sites may have changed significantly (usually increased) since the initial assessments. This change complicates the process of selecting and sizing the optimal insulator type to suit local environmental conditions, often resulting in a mismatch between insulator capabilities and actual environmental demands (Desta & Wogari, 2020). Another factor may be prolonged exposure to high UV radiation and extreme temperatures from October to May, leading to the formation of micro-cracks and surface degradation of the rubber, which reduces hydrophobicity and promotes pollutant accumulation. Furthermore, polymeric insulators are susceptible to biological growth in Ethiopia's humid highland climate, which further diminishes their

hydrophobicity. The changes in the housing material's properties, caused by service conditions, undermine its hydrophobicity and resistance to tracking. This deterioration significantly impairs its performance against pollution flashover and increases the risk of premature failure (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008; IEC/TS 60815-1, 2008).

Additionally, material quality and manufacturing processes significantly impact insulator performance and should be carefully considered (CIGRE Taskforce 33.04.01, 2000). This factor may partly explain the poor performance of polymeric insulators in Ethiopia's power network. In the process of constructing new lines or maintaining existing ones, laboratory tests are conducted on candidate insulators to assess their electrical properties; however, pollution flashover tests are often omitted. Even if pollution flashover tests were performed, Ethiopia lacks pollution monitoring activities or a pollution severity map to establish reference parameters, such as Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD), that are essential for creating a relevant testing environment. Documentation for these projects does not provide clear testing methods or acceptance criteria for evaluating the suitability of insulators. Moreover, it lacks service experience records and field measurements necessary for estimating the level of site pollution severity (Desta & Wogari, 2020). As a result, insulators that are either under or over dimensioned and of lower quality are often used, leading to operational inefficiencies that are costly for EEP and negatively impact the insulators' performance.

Currently, there is a notable shift toward replacing porcelain and glass insulators with polymeric composites on transmission lines experiencing high outage rates, often attributed to unexplained outages (likely due to PFO). However, these replacements are commonly implemented without a thorough investigation into the underlying causes or a proper evaluation of the pollution severity specific to the environment. Instead, there is a tendency to apply the same insulator types and specifications used in other projects, despite differing environmental conditions and pollution levels. This approach involves considerable financial investments, which may ultimately fail to address the problem and lead to substantial financial losses.

Overall, the poor performance of in-service insulators seems to stem from the policies and practices that EEP employs in selecting and sizing both current and future outdoor insulators. These processes often lack well-defined, consistent guidelines that properly account for the specific application requirements and environmental conditions in which the insulators will operate. Improving the network's performance in this regard calls for the EEP to enhance its approach to selecting and sizing outdoor insulators by establishing clear guidelines for monitoring, maintenance, and inspection procedures for both new and existing lines. A key challenge in selecting outdoor insulators lies in accurately assessing the pollution severity levels at installation sites. To address this, it is crucial to

conduct field monitoring of pollution levels at critical locations along transmission lines and set up test stations to gather detailed data. Developing a nationwide pollution severity map would provide invaluable insights, enabling more informed and effective insulator selection. In addition, pollution performance tests and acceptance criteria should be incorporated into the purchase specifications for outdoor insulators.

Furthermore, EEP should establish regular maintenance schedules and deploy corrective measures to address design limitations, which would help reduce operational expenses and prevent premature failure of outdoor insulators. These efforts should be based on thorough evaluations of environmental factors, while also taking into account technical and logistical constraints, and cost-effectiveness. Possible maintenance and preventive approaches include regular cleaning substation and line insulators, installing creepage extenders, replacing hydrophilic insulators with hydrophobic ones, and applying RTV silicone coatings. The decision to implement these strategies should be based on a careful evaluation of their technical effectiveness and economic viability (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008; Macey, Vosloo, & Tourreil, 2004; Peter & Vajeth, 2005).

4.5 Case Studies: Analyses of Underperforming Lines

This section examines two transmission lines with significant pollution-related outage rates between 2015 and 2022, serving as validation for the previously discussed assessment methodology. By analyzing localized climate and meteorological conditions alongside historical service experience, this assessment aims to evaluate the alignment of these findings with the typical conditions that favor pollution-induced flashovers.

4.5.1 Combolcha II—Semera—Dicheto 230 kV Line

The Combolcha II—Semera—Dicheto line spans 241 km, connecting the Combolcha II substation with Semera and extending to the Dicheto substation in northeastern Ethiopia, a region characterized by desert and semi-arid conditions with minimal rainfall. Located near the Danakil Desert and the Red Sea, this area experiences exposure to direct salt spray, salty dust, and salty fog carried by strong winds, as well as mining contaminants from the desert and saline lakes. Thus, the area is subject to both type A and type B pollutants. Equipped with long-rod HTV silicone rubber composite insulators, this line has shown poor operational reliability based on service records. A total of 105 pollution flashover incidents were identified on this line from 2015 to 2022, an average of 13.1 faults per year. Figure 38 illustrates the monthly average meteorological parameters along the line's route, with rainfall seldom exceeding 48 mm from March through August. Average yearly conditions include relative humidity above 42%, temperatures exceeding 27°C, and wind speeds around 2.5 m/s, all of which are conducive to pollution buildup and wetting.

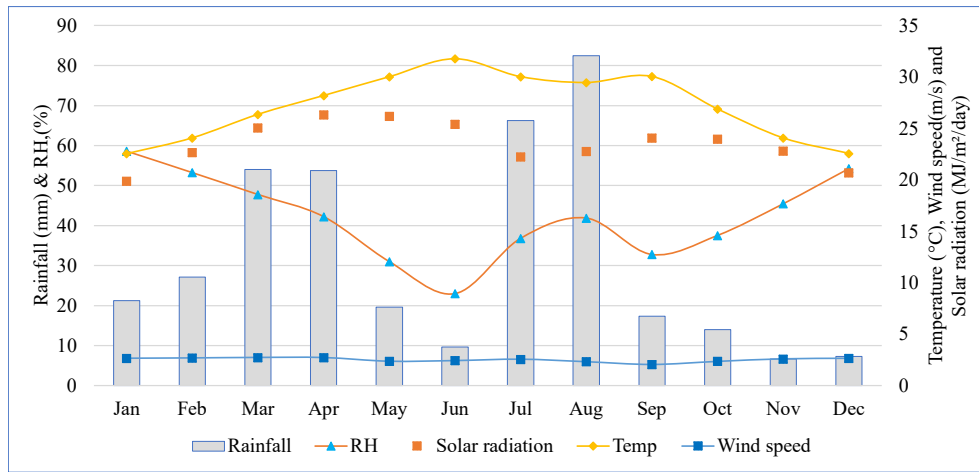


Figure 38: Monthly average meteorological parameters across the entire length of the Combolcha II—Semera—Dicheto 230 kV line (CFSR, 2019).

Figures 39 and 40 illustrate that most of these pollution-related faults occurred during nighttime, specifically from 19:00 to early morning (from 5:00 to 6:00), peaking around midnight (from 23:00 to 1:00), particularly in April and August. This coincides with the rainy season in the region, characterized by relatively low rainfall, when insulator surfaces are wetted by light precipitation during the evenings and by dew formation at sunrise, triggering flashover conditions.

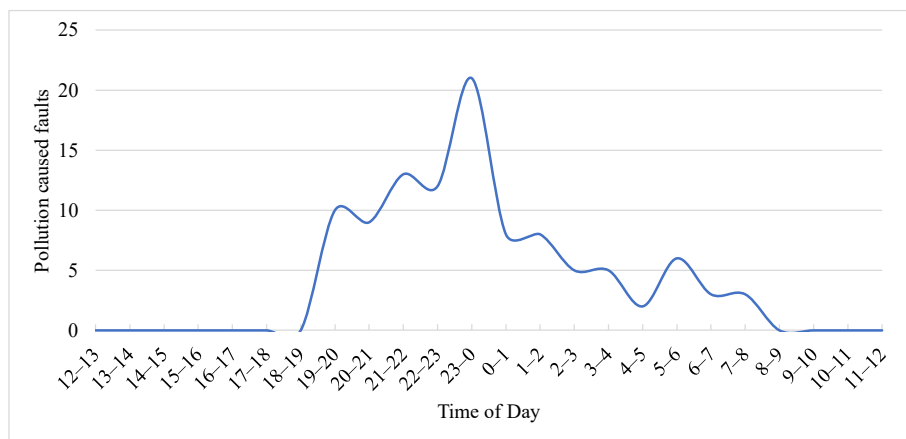


Figure 39: Daily distribution of pollution-induced faults of the Combolcha II—Semera—Dicheto 230 kV line.

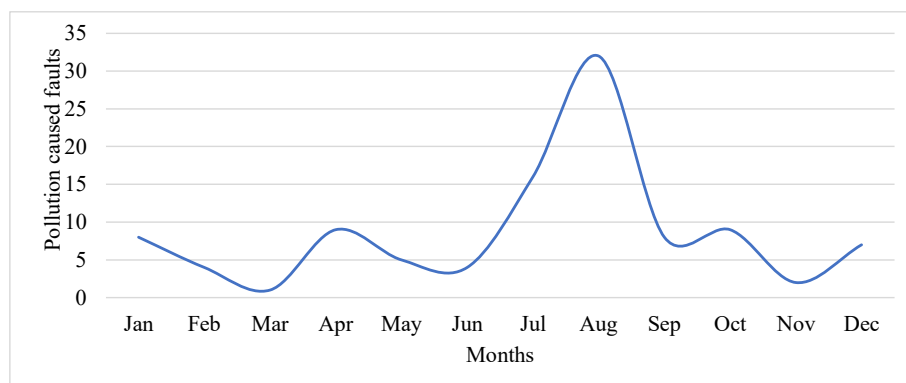


Figure 40: Monthly distribution of pollution-induced faults of the Combolcha II—Semera—Dicheto 230 kV line.

Both type A and type B pollution flashover mechanisms are highly likely to occur on this line, given the conditions. However, the region is not conducive to large bird populations, making bird streamer-caused faults unlikely. Observed data supports a strong correlation between the temporal distribution of identified pollution-induced faults and prevailing weather patterns. Additionally, the significantly degraded pollution performance of silicone rubber composite insulators installed on this line can be attributed to their prolonged exposure to sandstorms (as local desert sand contains calcium and sodium salts) as well as intense UV radiation and high temperatures, which contribute to the formation of surface micro-cracks and a loss of hydrophobicity on the insulators.

4.5.2 Bahir Dar II—Debre Markos—Sululta 400 kV Line

The Bahir Dar II—Debre Markos—Sululta line extends 410 km, traversing from Ethiopia's northwestern highlands to Addis Ababa, crossing both subtropical highland and tropical savanna regions. Environmental pollution sources along this route are diverse, including desert dust, industrial emissions, and agricultural pollutants. Specific contaminants come from transportation, construction activities, quarry sites, natural soil dust, cement factories, and agricultural practices like ploughing, fertilization, crop spraying, and harvesting. Glass-cap and pin strings are used to insulate this line, which has experienced frequent unexplained outages. From 2015 to 2022, the analysis identified 72 pollution-related flashovers, averaging 9 incidents per year. Figure 41 presents the monthly average meteorological conditions along the line, with an annual rainfall of about 270 mm from June through September and an overall average relative humidity above 58%, temperatures above 17°C, and wind speeds of 1.8 m/s.

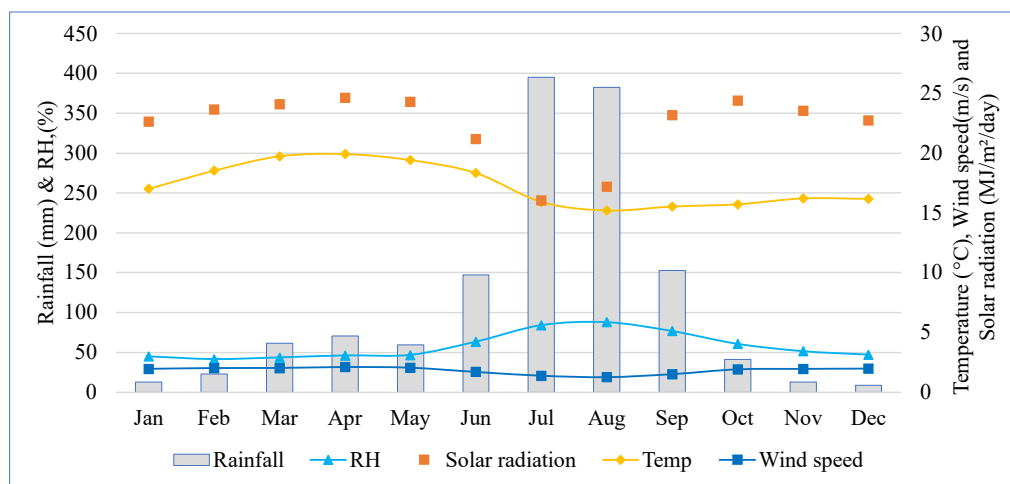


Figure 41: Monthly average meteorological parameters across the entire length of the Bahir Dar II—Debre Markos—Sululta 400 kV line (CFSR, 2019).

As shown in Figure 42, most of the faults occurred around midnight (from 22:00 to 23:00) and early morning (from 6:00 to 7:00). As Figure 43 highlights, outages were concentrated from November to February (due to dew formation on glass insulators) and March to May (due to light rain), during dry

and light rainfall seasons in the area. The majority of faults were concentrated around key agricultural activities, specifically during spring ploughing, winter crop harvesting, and the subsequent burning of crop residues. These periods appear to significantly contribute to fault occurrences, highlighting the impact of seasonal farming practices on system reliability. Bird streamer incidents may contribute to faults observed in October and November, coinciding with the autumn season. The conditions described, associated with these faults, are consistent with the characteristics of both type A and type B pollution-flashover mechanisms.

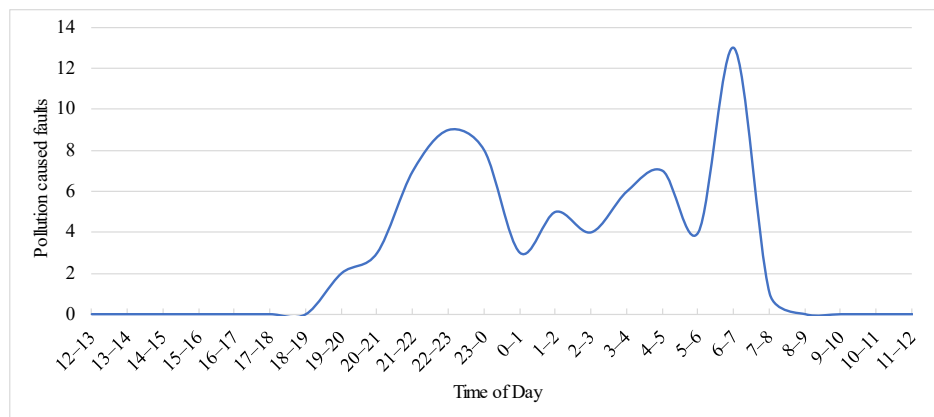


Figure 42: Daily distribution of pollution-induced faults of the Bahir Dar II—Debre Markos—Sululta 400 kV line.

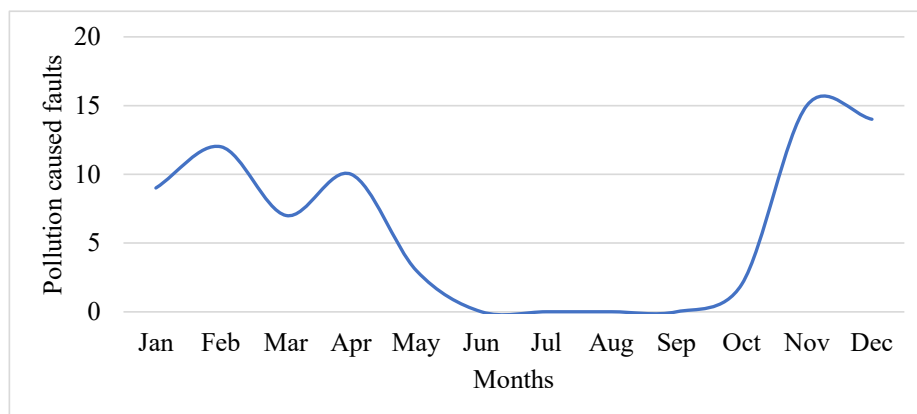


Figure 43: Monthly distribution of pollution-induced faults of the Bahir Dar II—Debre Markos—Sululta 400 kV line.

Additionally, a reduction in flashover voltage by more than 10%, due to the decreased air density at the line's high altitude (approximately 2000 meters) and the relatively stable temperature across the route, may also be a factor in the higher outage rates as suggested by CIGRE Taskforce 33.04.01 (2000). Thus, the region's meteorological conditions, environmental factors, and operational reports consistently correlate with observed pollution flashover incidents.

CHAPTER 5

5. Assessment of Fine Particulate Matter Pollution Variability in Ethiopia

5.1 Background

Studies show that ambient particulate matter (PM_{2.5} or PM₁₀) can significantly contribute to pollution-induced insulator flashovers. Hence, assessing PM level for a particular site is an important part of the pollution severity evaluation process. Moreover, monitoring PM density helps in creating a pollution severity map that will aid selecting and sizing outdoor insulators as well as ease the maintenance of railway insulators, photovoltaic (PV) plants and other infrastructures sensitive to pollution (Chisholm, 2019a; Gutman et al., 2023; Nigris, 2023; Pons & Jeanmaire, 2022; Volpov & Kishcha, 2017).

Information about PM density can be obtained from long-term ground-based measurements and satellite observations, or from both methods depending on the availability of resources. These methods typically complement each other. Ambient air pollution monitoring and measurement stations help to evaluate the concentration of various pollutants in the troposphere, including carbon monoxide, tropospheric ozone, nitrogen oxides, sulfur oxides, and particulate matter. There has also been considerable progress in the assessment of pollution mapping using satellites, which can provide estimates of the density of conductive substances, such as nitrates, sulfates and sea born salt. Additionally, they also can independently estimate the density of nonconducting particulate matter (PM) (Chisholm, 2019a).

In Ethiopia, the availability of PM_{2.5} or PM₁₀ monitoring stations, is extremely limited and there is no data available for insulation selection. Hence, this chapter presents examination of the spatial and temporal variation of PM_{2.5} density across the country using satellite estimates. Additionally, a PM_{2.5} density map is created for EEP grid regions and for the entire country.

5.2 Introduction

Particulate Matter (PM), a standard parameter used to describe a mixture of solid or liquid airborne particles, is typically measured in micrograms per cubic meter ($\mu\text{g}/\text{m}^3$) of atmospheric air. It includes chemical compounds suspended in indoor or outdoor air, originating from various human activities such as vehicle engine combustion, biomass burning, agricultural activities, mining, and industrial operations, as well as natural causes like wind-blown dust and sand from arid regions and sea salt sprays from coastal areas. PM can be directly released into the atmosphere or formed as a result of pollutants emitted from both human activities and natural sources. It contains organic carbon,

elemental carbon, soil and mineral dust, sea salt, sulfates, nitrates, ammonium ions, and metals (Ambade et al., 2022; Janssen et al., 2013; Khan et al., 2010; Philip et al., 2014; Tefera et al., 2020).

PM density can be measured using devices installed at measuring or monitoring stations in selected locations, such for example as industrial areas, large cities or highly polluted sites. In areas lacking ground-based monitoring, satellite remote sensing technologies are now used to estimate PM densities (Chisholm, 2019a; Hammer et al., 2020; van Donkelaar et al., 2016; van Donkelaar et al., 2015). Recently, researchers have made considerable progress in tracking PM density using both satellite data and ground-based measurements, which typically complement each other. This advancement has enabled a more precise definition of the proportions of various components, including sea salt, human-caused inorganic ions, dust, and carbon black (Chisholm, 2019a; Gutman et al., 2023). According to a study performed in (Philip et al., 2014), the global population-weighted PM_{2.5} composition includes: sea salt (1%), sulfates (17%), nitrates (6%), ammonium (7%), organic mass (32%), carbon black (7%), and mineral dust (30%).

From the total suspended particulates with an aerodynamic diameter of less than 100 μm , PM_{2.5} (particles with an aerodynamic diameter less than 2.5 μm) and PM₁₀ (particles with an aerodynamic diameter less than 10 μm) show greater variation in concentration. In contrast, particles in the size range between PM_{2.5} and PM₁₀ exhibit relatively constant levels and contribute less to pollution (Chisholm, 2019a; Janssen et al., 2013). The deposition rate of these particles on insulator surfaces depends on particle size, wind speed, and the type and surface characteristics of the insulator (e.g., soft polymer versus hard ceramic insulators) (Chisholm, 2019a; CIGRE Taskforce 33.04.01, 2000). This is particularly clear when intense winds in desert regions carry large sand particles (over 200 μm diameter), which can "sandblast" the insulator surface, enhancing its natural cleaning. Smaller particles, those under 100 μm diameter, carried by wind, tend to stick to the insulator surface (CIGRE Taskforce 33.04.01, 2000).

Outdoor fine particulate matter (PM_{2.5} density is significantly influenced by factors such as rainfall intensity and duration, relative humidity, wind speed and its direction. The increased use of various fuels for heating during colder seasons and stable atmospheric conditions also contribute to the extended presence of PM_{2.5} in the atmosphere (Chisholm, 2019a; Khan et al., 2010; Tefera et al., 2020). Moreover, PM_{2.5} pollution levels are expected to rise with intensified urbanization, industrialization, agricultural activities, mining and increased traffic emissions (Brauer et al., 2016). Biomass burning, sand and dust storms from arid regions further contribute to the problem (Brauer et al., 2016; Tefera et al., 2021). Changes in land use and land cover, such as deforestation for agriculture and mining, can also intensify pollution (Global Forest Watch, 2024; Mataveli et al., 2021). In addition, rapid population growth and associated widespread use of solid fuels for cooking, as well as inadequate

air quality monitoring and control measures are possible contributors to elevated PM_{2.5} levels (Hammer et al., 2020; Lim et al., 2020). Studies show that high population density correlates with increased energy consumption, a major source of PM_{2.5} (Borck & Schrauth, 2021; Danek et al., 2022; Han & Sun, 2019; Muzayanah et al., 2022; Wang et al., 2019).

Even minor variations in wind speed between regions can affect pollution levels. Also, topographical features, such as deep basins and valleys as well as transportation infrastructures significantly intensify PM_{2.5} concentration due to creating unique meteorological conditions (Danek et al., 2022; Wang et al., 2019). Moreover, windblown sand and dust from Sahara Desert is one of the major PM_{2.5} contributors in the north and northwest regions of Ethiopia, whereas sea salt sprays are to a limited extent the PM sources in near coastal desert areas in the northeast and southeast of the country (Kumie et al., 2021; Shiferaw et al., 2023; Tefera et al., 2021; Tefera et al., 2020). Furthermore, PM_{2.5}, being a regional pollutant, can be transported to nearby areas or over longer distances depending on the area's topographic characteristics (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008).

In the electrical power transmission sector, the increasing density of these particulate matters (PM_{2.5} or PM₁₀) can have a strong impact on the performance of outdoor insulators of transmission lines and substations. PM_{2.5} pollution sources vary across regions in Ethiopia, with windblown sand and dust from the arid and semiarid areas are the major contributors and have quite high inland penetration. In addition, particulate matter from human activities and alkaline dust from deserts and industrial settings like mining and construction sites, soil dust from ploughing and burning of crop residues during harvest in agricultural areas and sugarcane plantations, coal burning in industries and cement plants, transportation, and household solid fuel burning in rural and urban areas is also the primary sources of PM_{2.5} density in the context of Ethiopia. There are studies suggesting that pollution levels are rising in Ethiopia due to excessive household solid fuel burning, increasing population, urbanization, industrialization, and traffic (Kumie et al., 2021; Shiferaw et al., 2023; Tefera et al., 2021; Tefera et al., 2020).

Many developing countries, including Ethiopia, have limited systems for monitoring air quality. This hinders effective air quality/pollution monitoring and policymaking, leading to a lack of evidence-based actions to reduce its levels. Specifically, this brings difficulties in considering the impact of outdoor particulate matter density during selection and dimensioning of insulators in the electric power systems. To address this gap, this study concentrates on characterizing the spatial and temporal distribution of ambient PM_{2.5} density in Ethiopia on the regional and national levels.

5.3 Methods

Given the limited availability of ground-based PM_{2.5} monitoring stations throughout Ethiopia, this study relied on satellite-derived PM_{2.5} data, offering a spatial resolution of 0.1° x 0.1°. These estimates were provided by the Atmospheric Composition Analysis Group (ACAG) at Dalhousie University and Washington University (ACAG, 2024). Aerosol data, which refers to clouds of solid or liquid particles suspended in air, were collected using multiple instruments, including Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging Spectroradiometer (MISR), and Sea-viewing Wide Field-of-view Sensor (SeaWiFS), all of which are mounted on National Aeronautics and Space Administration (NASA) satellites. ACAG refined its satellite-based PM_{2.5} estimates by calibrating them against ground-level monitoring data using Geographically Weighted Regression (GWR). A more detailed explanation of the methods used is available in van Donkelaar et al. (2021) and van Donkelaar et al. (2016).

The satellite-based PM_{2.5} data for this study were downloaded from the ACAG website, which offers free public access. The annual mean PM_{2.5} density from 1998 to 2022 was extracted from version V5.GL.04 of the dataset for Ethiopian and all EEP grid regions. ArcGIS v10.5 was employed to visualize the downloaded spatial dataset, process raster data, extract and calculate monthly and annual values. It was also used to perform zonal statistics and apply Inverse Distance Weighted (IDW) interpolation techniques to generate the surface map of PM concentration. Monthly and annual mean densities of PM_{2.5} for 25 years period were calculated. Moreover, seasonal variation trends and variability across the grid regions were analyzed.

5.4 Results and Discussion

The average annual mean PM_{2.5} density for entire Ethiopia was found to be 21.99 µg/m³, ranging from 12.17 to 24.65 µg/m³, and displaying a notable increasing trend over the past 25 years. The spatial distribution of PM_{2.5} density is illustrated in Figure 44. With respect to the grid regions, the North-East grid region has the highest annual mean PM_{2.5} density (34.13 µg/m³), followed by North region (32.30 µg/m³), Addis Ababa (26.84 µg/m³), South-West region (23.48 µg/m³), and Central region (23.43 µg/m³). While lower densities are spotted in Southeast (18.17 µg/m³) and South (17.50 µg/m³) region.

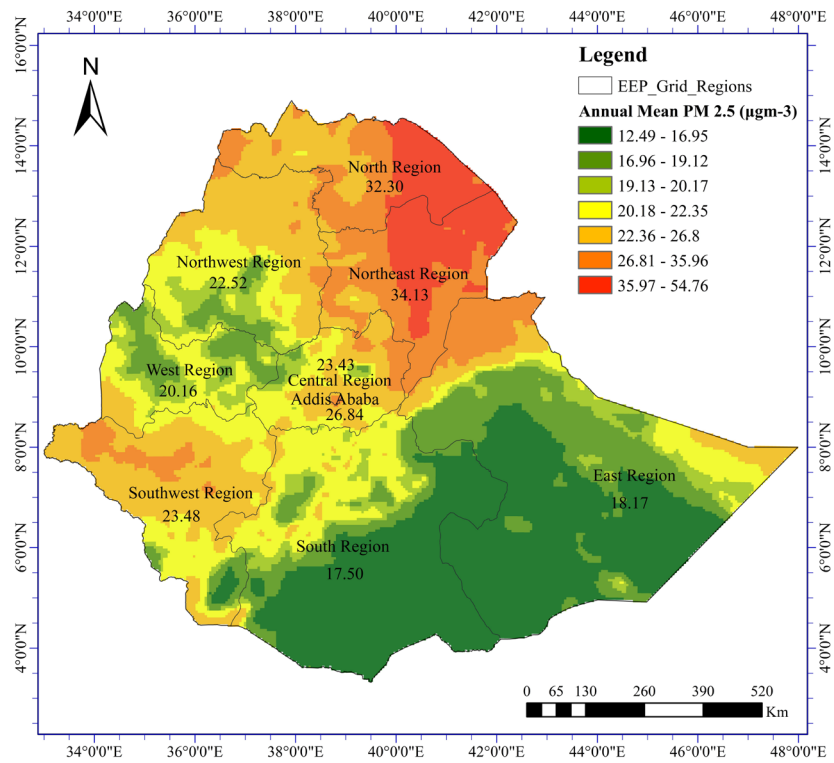


Figure 44: Ethiopia grid regions annual mean fine PM concentration in μgm^{-3} from 1998–2022.

Factors contributing to consistently higher PM_{2.5} density in specific grid regions include population density, solid fuel burning, terrain characteristics, intensive agriculture, industrial pollution, and relatively low wind speeds, as regions with higher population densities, agricultural and mining activities, lower wind speeds, and mountainous terrain tend to experience elevated pollution levels (Asefa et al., 2020; Global Wind Atlas, 2021; OCHA, 2020).

The relatively low wind speeds in North-East, North, North-West, West and South-West grid regions contribute to higher PM_{2.5} levels (Global Wind Atlas, 2021). Additionally, topographical features, like deep basins and valleys, common in North, North-West and Central regions, are associated with elevated PM_{2.5} levels due to their impact on local meteorology and atmospheric conditions (Danek et al., 2022). In contrast, relatively high wind speeds and flat terrain are more common in the East and South regions, leading to lower PM_{2.5} levels (Asefa et al., 2020; Global Wind Atlas, 2021). Moreover, West and South-West grid regions have experienced major deforestation, mainly due to agricultural and mining expansions, both of which are known contributors to increased pollution (Global Forest Watch, 2024; Mataveli et al., 2021).

High density of PM_{2.5} seen in Northeast, North, and parts of Central and East region is also influenced by the major import-export highways passing through these areas, in addition to their proximity to desert and the seacoast area (MoWE, 2020). A study performed in Addis Ababa revealed that traffic contributes to 28% of its PM_{2.5} density, potentially linked to both the population density and the vast number of vehicles moving along these trade routes (Tefera et al., 2021). In Northwest, Northeast and

North regions, the use of agricultural residues, like crop straws and animal dung, as cooking fuel is common due to scarce wood biomass and other alternative sources of energy and contribute much to PM_{2.5} pollution (Geissler et al., 2013). Biomass is the second largest contributor to PM_{2.5} in cities of developing countries (Ambade et al., 2022), including Addis Ababa, where it accounts for 18.3% of PM_{2.5} density (Tefera et al., 2021).

Arid regions, like Northeast (Afar), with sparse tree coverage and including Danakil Desert, are prone to sand and dust storms. These are the major sources of PM_{2.5} and can spread to neighboring regions (UNEP, 2016).

Figure 45 illustrates the trends in PM_{2.5} density for various grid regions of Ethiopia. The North-East, North, North-West, South-West, West, Addis Ababa, and Central regions consistently show higher PM_{2.5} densities in comparison to other areas. The North-East region recorded the highest PM_{2.5} density, while the Southeast region had the lowest across the years. In 2014, lower PM_{2.5} concentrations were seen across all regions.

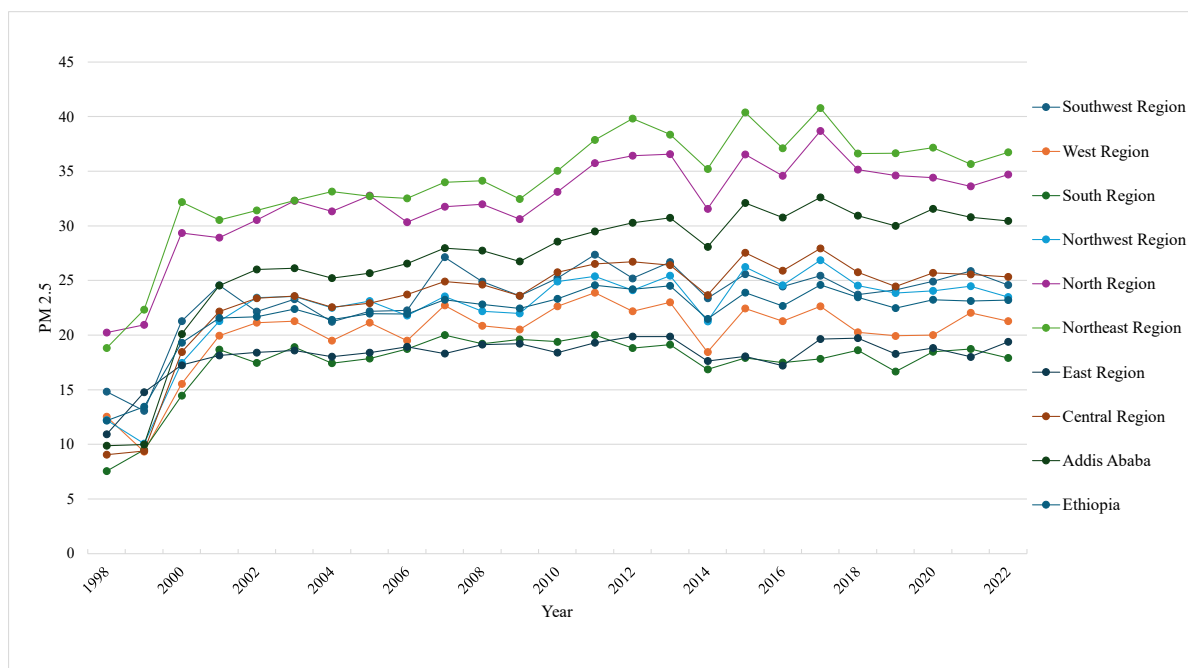
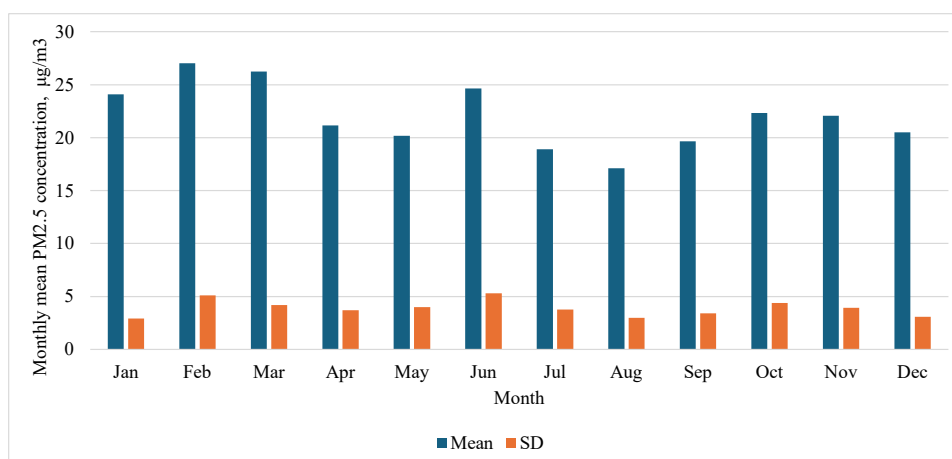


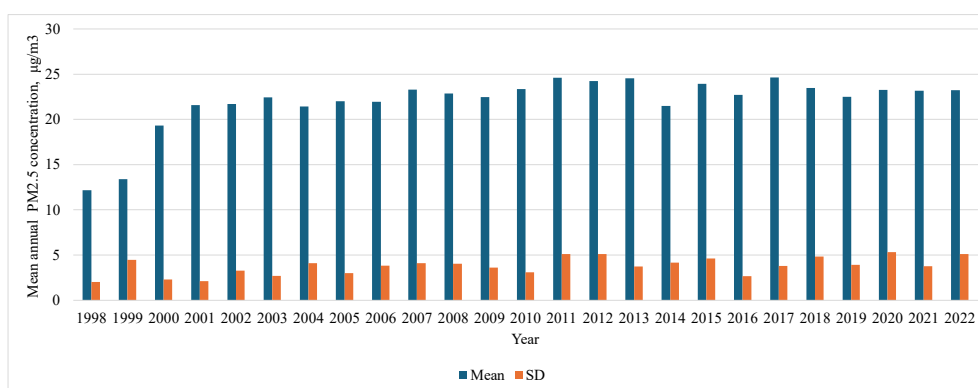
Figure 45: Trends of fine PM 2.5 concentration in $\mu\text{g}/\text{m}^3$ across grid regions in Ethiopia, 1998–2022.

Figure 46 depicts typical statistical parameters derived from PM_{2.5} satellite data, covering the period from 1998 to 2022. The monthly indices, presented in Figure 46a, reveal large variation, with three distinct periods of higher PM_{2.5} density: from January to March, around June, and from October to December. These periods correspond to low rainfall seasons in most parts of Ethiopia. On the other hand, the annual indices, presented in Figure 46b, show minimal fluctuation throughout the analyzed period, remaining relatively constant at above 20 $\mu\text{g}/\text{m}^3$, except for a sharp increase around 2000 and

2001 and a slight decrease in 2014, when lower PM2.5 density was found across all regions, showing a high degree of long-term stability.



(a)



(b)

Figure 46: Statistical characteristics of the mean annual PM2.5 density from satellite data (1998–2022) across Ethiopia; (a) monthly mean variation and (b) long-term annual variation.

To better illustrate the temporal variation in the monthly mean PM2.5 density in Ethiopia, a three-dimensional plot is presented in Figure 47. The monthly pattern shows a distinct seasonal variation, corresponding to the rainfall patterns in Ethiopia. Additionally, after a sharp increase in annual PM2.5 levels until 2001, the density stabilized at around 22.95 $\mu\text{g}/\text{m}^3$ in the subsequent years. This stabilization reflects a saturation point in PM2.5 density following a prolonged cycle of particulate matter emissions and the natural cleansing effects by rains and winds. Temporal patterns of PM2.5 density across EEP grid regions for years 1998-2022 are shown in Appendix D Figure A – 12.

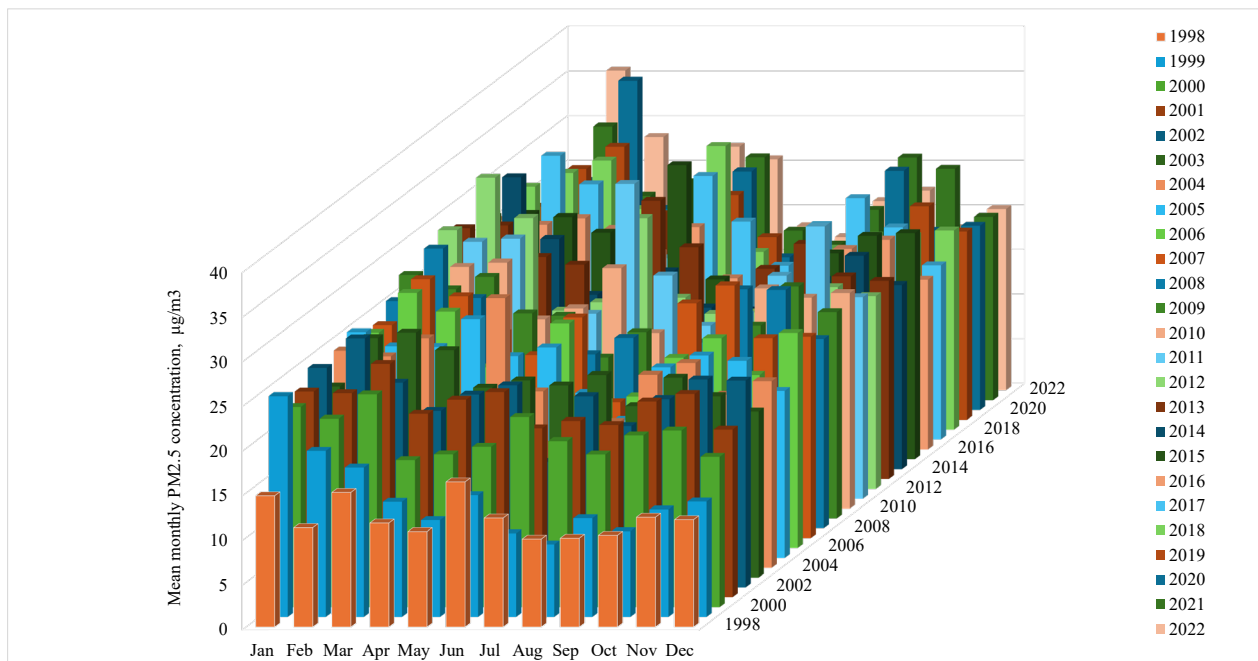


Figure 47: Temporal patterns of PM_{2.5} density in Ethiopia for years 1998-2022.

To compare the variability of PM_{2.5} density among EEP grid regions, a box plot is shown in Figure 48. This plot indicates that North-East, North, and Addis Ababa grid regions reveal higher median values and larger spreads. In contrast, South and East grid regions show lower medians with spreads tightly clustered around the median, thus showing less variation over time. The observed variability within grid regions highlights the need for further investigation into the specific sources and factors influencing fluctuations in ambient PM_{2.5} density.

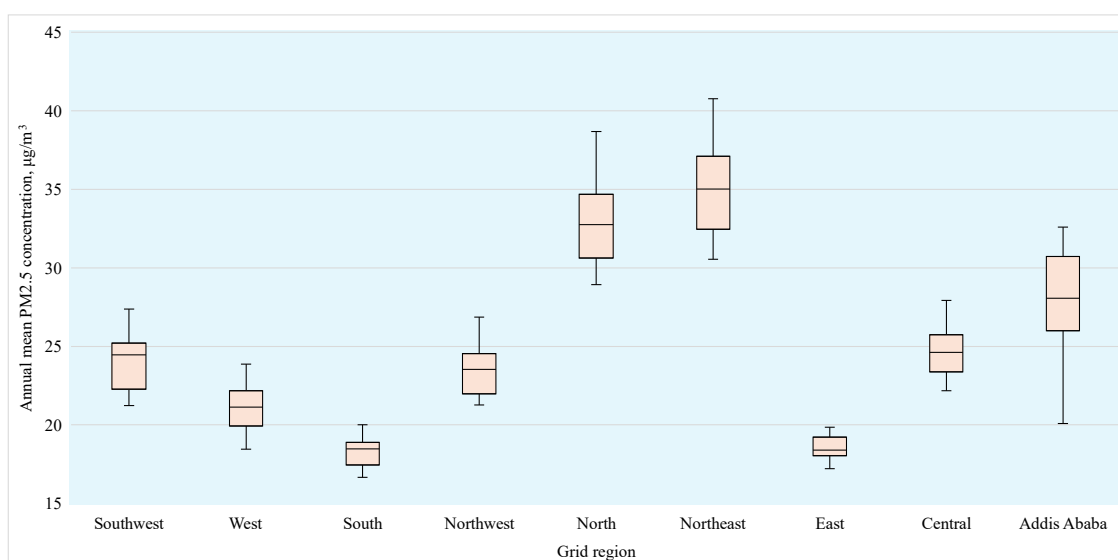


Figure 48: Variation in fine particulate matter (PM) density ($\mu\text{g}/\text{m}^3$) across each grid region in Ethiopia from 1998 to 2022.

To examine the correlation between the spatial distribution of mean annual PM_{2.5} density across Ethiopia from 1998 to 2022 and areas known for pollution-induced flashover problems (indicated by pollution flashover frequency data from 2015 to 2022), Figure 49 presents a map comparing these two

distributions. The map clearly shows that regions with higher PM2.5 density correspond to areas with more frequent pollution-induced flashovers. A strong correlation between the pollution flashover problem areas and PM2.5 density is clear from the map.

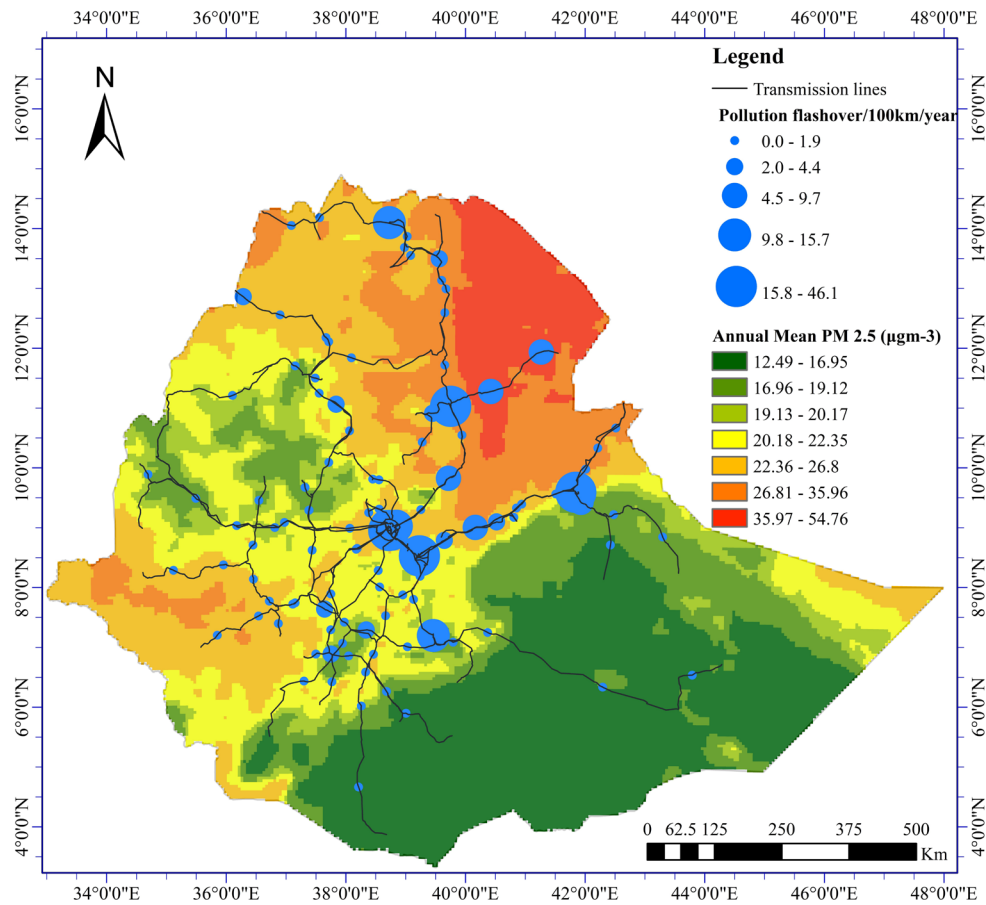


Figure 49: The spatial distribution of PM2.5 density and known pollution flashover problem areas in Ethiopia.

In conclusion, the presented results highlight that PM2.5 density across various regions of Ethiopia have steadily increased over the recent years. This should alert EEP about the impact of an increasing environmental stress level of ambient pollution on its line and substation insulators and to act promptly to mitigate the associated pollution flashover problems. The created, based on the performed PM2.5 analyses, density distribution map correlates the expected environmental stress in different grid regions with the location of the existing power system infrastructure, and allows to extract the corresponding PM2.5 density values for each tower/point of the transmission lines and substations. Moreover, the extracted PM2.5 densities serve as an important addition in the development of insulator pollution severity map based on combination of climatic and environmental factors.

CHAPTER 6

6. Pollution Severity Mapping for the Ethiopian Power Transmission Grid

6.1 Introduction

A power system, including its transmission lines, is designed according to specific standards that define their vulnerability levels. Stresses beyond these thresholds can lead to faults, which may escalate into contingencies and potentially result in blackouts. In the face of the ongoing climate and environmental changes, it is crucial to carefully address such vulnerabilities to ensure the resilience of the power system against climate-related challenges and extreme events (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008; Macey, Vosloo, & de Turreil, 2004; Nigris, 2020; Pigini, 2015).

Among the main challenges in this way are pollution and flashover events of insulators that originate from climatic and environmental stresses. For instance, with climate change, rising temperatures and increased humidity levels are anticipated, along with additional consecutive dry periods, which create an environment for extra accumulation of pollution and can adversely affect the performance of insulators, especially during subsequent wetting events (precipitation, fog and dew etc.) and ultimately lead to outages. Hence, it's crucial to consider future climate and environmental changes when dimensioning outdoor insulators (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008; Macey, Vosloo, & de Turreil, 2004; Nigris, 2023).

Although there has been notable progress in evaluating pollution performance for outdoor insulation over the past few decades (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008), recent global statistics show that pollution flashovers still significantly impact the reliability of transmission networks. Uncertainties in insulator design and subsequent poor pollution performances are linked to the estimation of pollution levels at specific sites. Parameter called site pollution severity (SPS) has been introduced and it allows to specify the environment where the insulators are installed and to monitor its impact for properly dimensioning of insulators and preventing pollution flashover outages. For effective monitoring of SPS level and for alerting Transmission System Operators (TSOs), developing pollution severity map is thus crucial. It provides a vital foundation for addressing threats related to pollution buildup, serving as an essential tool for the selection and sizing of substation and line insulators, and ultimately for enhancing the reliability of power transmission system (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008; Macey, Vosloo, & de Turreil, 2004; Nigris, 2023, 2020; Pigini, 2015). Additionally, it aids in selecting appropriate laboratory pollution performance tests and

establishing acceptance criteria for verifying candidate insulators (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008).

Unfortunately, the Ethiopian Electric Power (EEP) company has so far not used the possibilities offered by this tool. As a result, there is insufficient knowledge to support the process of selection and dimensioning insulators as well as proper record-keeping on pollution related incidences (Desta & Wogari, 2020; Desta et al., 2024b). Thus, the site pollution severity is frequently poorly defined or not considered at all, leading to potential underestimation of necessary insulation level or to less economical oversized solutions. This deficiency in the design of insulators was found to be the main reason for the observed poor performance of its transmission lines (Desta & Wogari, 2020; Desta et al., 2024a, 2024b).

Based on the fault analysis performed in chapter four for the EEP power lines of 132-500 kV for the period from 2015 to 2022 (Desta et al., 2024b), pollution related faults approximately account for 24.7% of the 4,231 unexplained line outages (earth faults). Additionally, a substantial number of these unexplained faults (52.5%) were found inconclusive, which further might increase the percentage of pollution-related cases. The analysis also revealed that, on average, more than 130 pollution induced flashovers occurred annually, with a frequency of about 0.8 faults per 100 km per year, i.e. with the mean time between failures (MTBF) of 1.2 years on each 100 km of line length. This poor performance is significantly below the internationally accepted requirement of 10 to 50 years MTBF for line and substation insulators (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008). Assessments of the previous chapters have also pointed to a lack of regular monitoring of pollution severity based on field measurements and inadequate consideration of environmental parameters. The unavailability of crucial information for selection and sizing of insulators in new and existing projects are the main reasons for this unacceptable performance (Desta & Wogari, 2020; Desta et al., 2024a, 2024b).

It is therefore necessary to prioritize monitoring of SPS along Ethiopian power lines for developing a detail pollution map of the country, which will force understanding of the actual pollution levels in each grid region and how they change over time to properly and optimally select and dimension outdoor insulation. To start with, the objective of this work is to develop a GIS-based pollution severity map for the EEP grid using estimated SPS parameters derived on the analysis of local climatic and environmental conditions as well as on the service experience from the existing transmission lines. Additionally, it also aims to propose representative pollution tests and their parameters, according to IEC requirements, for each point of interest along the existing lines and the substations. Such a newly developed pollution severity map is anticipated to support EEP in following standard approaches while maintaining cost control for ultimately enhancing the reliability of the Ethiopian electric power system.

6.2 Methodology

6.2.1 Procedure for Creating Pollution Severity Map

Depending on the availability of resources and time, TSOs employ various mapping methods, each one with its strengths and limitations. Mapping methods and their level of accuracy varies based on the method used for evaluating the site pollution parameters. In general, the first step in creating a pollution map is to collect georeferenced data, such as meteorological information (on temperature, humidity, number of dry days, wind speed and direction, rainfall and solar radiation intensity), climatic and environmental information (on pollution type, its distribution and source, land cover and use, terrain topography, air quality and particulate matter distribution) and system/grid information (line/substation coordinates, existing insulation configuration, historical pollution flashover incidences and distribution points) (Al-Mubarak et al., 2022; CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; Gutman et al., 2022; IEC/TS 60815-1, 2008; IEC/TS 60815-4, 2016; Nigris, 2022, 2023; Pons & Jeanmaire, 2022; Volpov & Kishcha, 2017; Zhiyi, 2016).

The second important step is to determine preliminary SPS parameters, such as equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD), by measuring or estimating them through carefully selecting representative sites/locations of interest. The next step is to determine the maximum values of these parameters according to the knowledge of local climate and environmental conditions for possible accretion of pollutants and their variation due to natural cleaning by rain and wind. Thereafter the corresponding salt deposit density SDD (for solid layer test) or site equivalent salinity SES (for clean fog test) values are determined for each of the sites according to the dominant pollution type in the region and finally, these SDD or SES values will be used to develop a point pollution map and can then be interpolated to generate a continuous/surface digital pollution map covering entire region or territory (Al-Mubarak et al., 2022; CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; Gutman et al., 2022; IEC/TS 60815-1, 2008; IEC/TS 60815-4, 2016; Nigris, 2022, 2023; Pons & Jeanmaire, 2022; Volpov & Kishcha, 2017; Zhiyi, 2016).

6.2.2 Overview of Methods Available for Evaluating SPS

The approaches recommended for the selection and dimensioning of insulators based on system requirements and environmental conditions are defined in (IEC/TS 60815-1, 2008). The requirements for DC applications are separately listed in (IEC/TS 60815-4, 2016). They present the most current knowledge available in the field and recommend using field measurements or estimation of SPS for optimal selection of insulators in addition to the usage of past operational experience from an existing line or substation or test station experience and laboratory testing. The suitability of each approach depends on the available resources, the time constraints, and the economic factors involved in the

project (IEC/TS 60815-1, 2008). However, accurately quantifying pollution level on insulator surfaces is challenging due to varying insulator types and installation environments. Factors such as insulator material, shape, orientation, voltage type (AC and DC), and environmental conditions influence pollution deposition rates, natural cleaning processes and the cumulative contamination buildup (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008).

Various methods for measurement or estimation of SPS, including direct and indirect pollution assessments are outlined in (IEC/TS 60815-1, 2008) and (IEC/TS 60815-4, 2016), including on-site measurements, the performance of in-service insulators in nearby installations, simulations of meteorological and environmental data, or information provided in (IEC/TS 60815-1, 2008).

6.2.2.1 Using On-Site Measurements

For measurements in situ, different measurement methods are generally used, and are in detail described in Annexes C, D and E of (IEC/TS 60815-1, 2008). Various methods can be applied to assess pollution severity at a specific location through direct measurements, with the most commonly employed being ESDD (Equivalent Salt Deposit Density) and NSDD (Non-Soluble Deposit Density) ESDD and NSDD measurements. For these measurements to be accurately interpreted, it is essential to also gather comprehensive background information regarding the site's climate and the characteristics of the pollution present.

In this method, creating a pollution map entails extensive work, as it requires many evenly distributed measurement sites across a territory. Pollution severity parameters (ESDD/NSDD, SES from on-site leakage current measurements and dust deposit gauge indexes collected by means of the directional dust deposit gauge (DDDGA) measurements must be conducted over an extended period, typically spanning at least one or longer. Subsequently, the collected data need to be statistically analyzed to determine the representative maxima of possible severity levels before interpolation of point values can be used to generate a continuous map across the region of interest (IEC/TS 60815-1, 2008; IEC/TS 60815-4, 2016).

6.2.2.2 Using Information on the Behaviors of In-Service Insulators

Another approach to evaluate SPS involves analyzing information from the behaviors of insulators in lines and substations already in service or in close vicinity to the site along with local meteorological and environmental information (IEC/TS 60815-1, 2008; IEC/TS 60815-4, 2016). Service experiences from an existing overhead line in regions with similar geographical, topographical, and climatic conditions provide reliable data on the interaction between environmental stresses and insulator performance (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS

60815-1, 2008). In this context, estimates of pollution severity can be obtained from comprehensive environmental and climatic data, insulator specifications (material, type, profile, diameter, creepage distance, arcing distance, etc.) and from service performance records (frequency of pollution flashovers annually, number of critical pollution and wetting events leading to flashovers, maximum operating voltage, occurrence of insulator surface degradation or aging). Further details on this methodology can be found in Annex H of (IEC/TS 60815-1, 2008).

Information from lines experiencing pollution flashovers (PFO) can also be analyzed to assess the level of SPS. By reverse calculation one can estimate the intensity of pollution stress that affects the line. A specialized software is required for this purpose to statistically calculate the corresponding ESDD value when parameters of the insulator in-service, the actual outage rate or MTBF, the pollution and critical-wetting events per year, the representative pollution test and the insulator pollution performance curves are known (Al-Mubarak et al., 2022; Gutman et al., 2022; Gutman et al., 2016; Gutman & Lundquist, 2011; IEC/TS 60815-1, 2008; IEC/TS 60815-4, 2016; Radosavljevic et al., 2016 ; Vosloo et al., 2022).

6.2.2.3 Analysis of Environment and Climate in Area of Interest

This method relies on estimating SPS parameters using information derived from the description of typical environments (E1-E7), as defined in (IEC/TS 60815-1, 2008) and presented in Table 9 and Figures 50a and 50b, which depict the relationship between ESDD and NSDD and the site pollution severity classes for AC transmission lines. These figures will be utilized to determine the corresponding estimated ESDD and NSDD values for each typical environment (E1-E7) defined in Table 9. This approach is usually employed when little or no information on site severity is available. While less precise, this method serves as a starting point before exploring into more detailed pollution evaluation methods. While Table 9 lists typical environments for each level of pollution, Figures 50a and 50b depict the relationship between ESDD and NSDD for these pollution levels for reference cap and pin and long rod insulators. It is noteworthy to mention that certain insulator characteristics may also influence the quantity of pollution deposited on them.

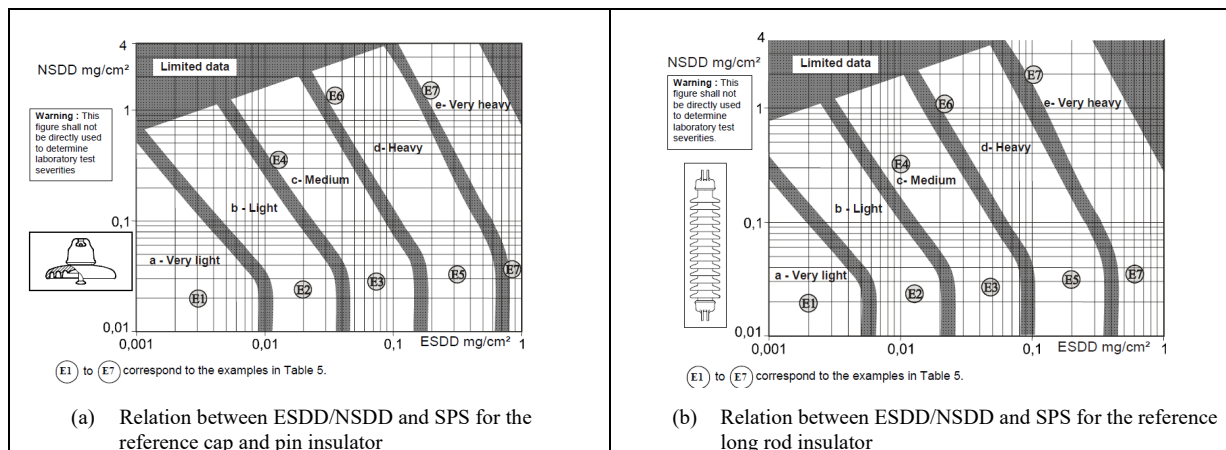


Figure 50: Extracts from (IEC/TS 60815-1, 2008) showing the relation between SPS and ESDD-NSDD for AC application for reference cap-and-pin and long rod insulators.

Table 9 Extracts from (IEC/TS 60815-1, 2008) with examples of typical environments.

Example	Description of typical environments
E1	> 50 km^a from sea, desert, or open dry land > 10 km from man-made pollution sources^b Within a shorter distance than mentioned above of pollution sources, but: • prevailing wind not directly from these pollution sources • and/or with regular monthly rain washing
E2	10-50 km^a from sea, desert, or open dry land 5-10 km from man-made pollution sources^b Within a shorter distance than E1 from pollution sources, but: • prevailing wind not directly from these pollution sources • and/or with regular monthly rain washing
E3	3-10 km^c from sea, desert, or open dry land 1-5 km from man-made pollution sources^b Within a shorter distance than mentioned above from pollution sources, but: • prevailing wind not directly from these pollution sources • and/or with regular monthly rain washing
E4	Further away from pollution sources than mentioned in E3, but: • dense fog (or drizzle) often occurs after a long (several weeks or months) dry pollution accumulation season • and/or heavy, high conductivity rain occurs • and/or there is a high NSDD level, between 5 and 10 times the ESDD

Example	Description of typical environments
E5	Within 3 km^c from sea, desert, or open dry land Within 1 km of man-made pollution sources^b
E6	With a greater distance from pollution sources than mentioned in E5, but: • dense fog (or drizzle) often occurs after a long (several weeks or months) dry pollution accumulation season • and/or there is a high NSDD level, between 5 and 10 times the ESDD
E7	Within the same distance of pollution sources as specified for “heavy” areas and: • directly subjected to sea-spray or dense saline fog • or directly subjected to contaminants with high conductivity, or cement type dust with high density, and with frequent wetting by fog or drizzle • desert areas with fast accumulation of sand and salt, and regular condensation
^a during a storm, the ESDD level at such a distance from the sea may reach a much higher level. ^b a presence of a major city will have an influence over a longer distance, i.e. the distance specified for sea, desert and dry land. ^c depending on the topography of the coastal area and the wind intensity.	

6.2.2.4 Using Simulation of Meteorological and Environmental Parameters

Recent studies (Chisholm, 2019a; Nigris, 2022, 2023, 2020; Pons & Jeanmaire, 2022) have shown a substantial correlation between atmospheric dust concentration and the level of pollution deposited on insulator surfaces. Advanced pollution modeling on insulators using long term meteorological parameters, such as wind speed and direction as well as rain intensity, is also becoming the most promising approach for estimating SPS parameters (Chisholm, 2019a; Gutman et al., 2014; Gutman et al., 2023; Marzinotto, 2022). These findings suggest a potentially new approach by using weather forecasts and air quality modeling for evaluating pollution severity levels on insulators at specific sites and for predicting pollution events. However, utilizing this approach should later be verified by real measurements and service experience information. While the models offer robust capabilities in estimation contamination levels, they require extensive input information that is often not readily available to insulator design engineers and requires handling by specialized expertise. Furthermore, although the models are highly effective, they are so far not adopted for predicting pollution accretion on insulators with irregular shapes and contours, because they have been developed for flat surfaces. It is therefore crucial to adopt these models or to develop new ones, specifically designed for predicting

the deposition on insulator surfaces (Chisholm, 2019a; Gutman et al., 2014; Gutman et al., 2023; Marzinotto, 2022; Nigris, 2022, 2023).

Satellite technology also offers a promising advancement in this respect. Pollution severity can thus be estimated from particulate matter deposition data obtained from satellite or traditional ground-based particulate matter (PM) monitoring of dust and salt and on advanced simulations of weather and environmental parameters, including air quality models. Additionally, extracting information on particulate matter PM_{2.5} or PM₁₀ from satellite data sets and analyzing their spatiotemporal distribution for each grid region can provide an estimate of pollution severity on insulator surfaces (Chisholm, 2019a; Nigris, 2022, 2023).

Site measurement methods offer the advantage of providing real data reflecting the local situation and it can be done for a limited number of sampling points. However, the measurements may not always capture the maximum pollution level due to the sampling limitations and may not capture the right moment when the pollution conditions become extreme, necessitating corrections. Moreover, it takes longer time, usually a few years, to collect enough data of high quality. On the other hand, simulation-based methods provide a faster and broader coverage of the territory but come with inherent limitations on models. It therefore appears that combining both approaches can result in acceptable accuracy (Chisholm, 2019a; IEC/TS 60815-1, 2008; Nigris, 2022, 2023).

In summary, accurately assessing pollution levels on insulator surfaces requires innovative approaches and extensive data collection, posing a significant challenge for transmission line design engineers and TSOs. Depending on the available resources and time constraints, insulation designers may choose among the four different methods to determine pollution severity at a given site, each with varying degree of accuracy, whereas using a combination of these methods can improve the overall accuracy (IEC/TS 60815-1, 2008).

6.2.3 Brief Review of Worldwide Experiences on Insulator Pollution Mapping

The site pollution severity assessment methods outlined in (IEC/TS 60815-1, 2008) have enabled the creation of national and regional pollution maps. Hence, it is essential to review the methods used by different countries and regions for mapping pollution severity. The following are some key experiences from around the world.

The Ethiopian pollution map presented in chapter three provides a qualitative estimated SPS class for each grid region of EEP (Desta & Wogari, 2020). It is based on analyses of local climatic and environmental conditions. The map established for the Greek island of Crete is a point map built on ESDD measurements, representing SPS classes at various measurement stations (Dimitropoulou et al., 2015). The French map refers only to one type of pollutant, i.e. salt (Pons & Jeanmaire, 2022). In

Brazil, a qualitative map has been developed by analyzing interactions between environmental parameters to assess pollution accumulation and wetting on insulators, while there are also ongoing efforts to confirm these results through measurements of ESDD, NSDD, and leakage current (Wesley & Garcia, 2022).

China developed a comprehensive pollution map for its power grid by conducting long-term measurements of key saturated site pollution severity (SPS) parameters, specifically focusing on Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD). This map covers the entire country and is regarded as one of the most detailed of its kind. To create this map, long-term saturated pollution parameters were measured using non-energized, standard cap-and-pin porcelain reference insulators at different monitoring sites. The process involved collecting and analyzing meteorological data and environmental pollution parameters. Starting in 2007, over 10,000 monitoring points were established, and by the end of 2011, more than 1.2 million measurements were gathered. The data collection process was continued, and the map was revised in 2014. It will be updated again if further revisions are deemed necessary (Liang et al., 2020; Zhiyi, 2016).

The pollution map in Israel has been developed using simulations by means of a digital dust sedimentation model developed based on extensive long-term environmental studies. This map has later been validated and calibrated with long-term ESDD and NSDD field measurements as well as ground-based particulate matter PM10 measurements, demonstrating high accuracy and a strong correlation factor (Volpov & Kishcha, 2017).

The first pollution map of Italy, created in the 1990s, was based on analysis of various geographical and local environmental factors, and local ESDD measurements performed on insulators removed from overhead lines. For making this map more precise, a new approach was adopted that incorporated weather forecasting and air quality modeling. The revision also included spatial estimations of particulate matter and sea salt concentrations through measurements conducted across more than 200 sampling sites near high voltage infrastructures and the results were categorized into five pollution severity classes according to IEC 60815 (Nigris, 2022, 2020). Efforts have recently been made to further revise this map. This involved a dual approach combining site measurements of ESDD and NSDD with advanced simulations for calculating these parameters. Advanced simulations of meteorological and environmental data, along with air quality and weather models are used to model SPS (Nigris, 2023). Figure 51 presents typical pollution maps for Ethiopia, China, the Greek island of Crete, and Italy.

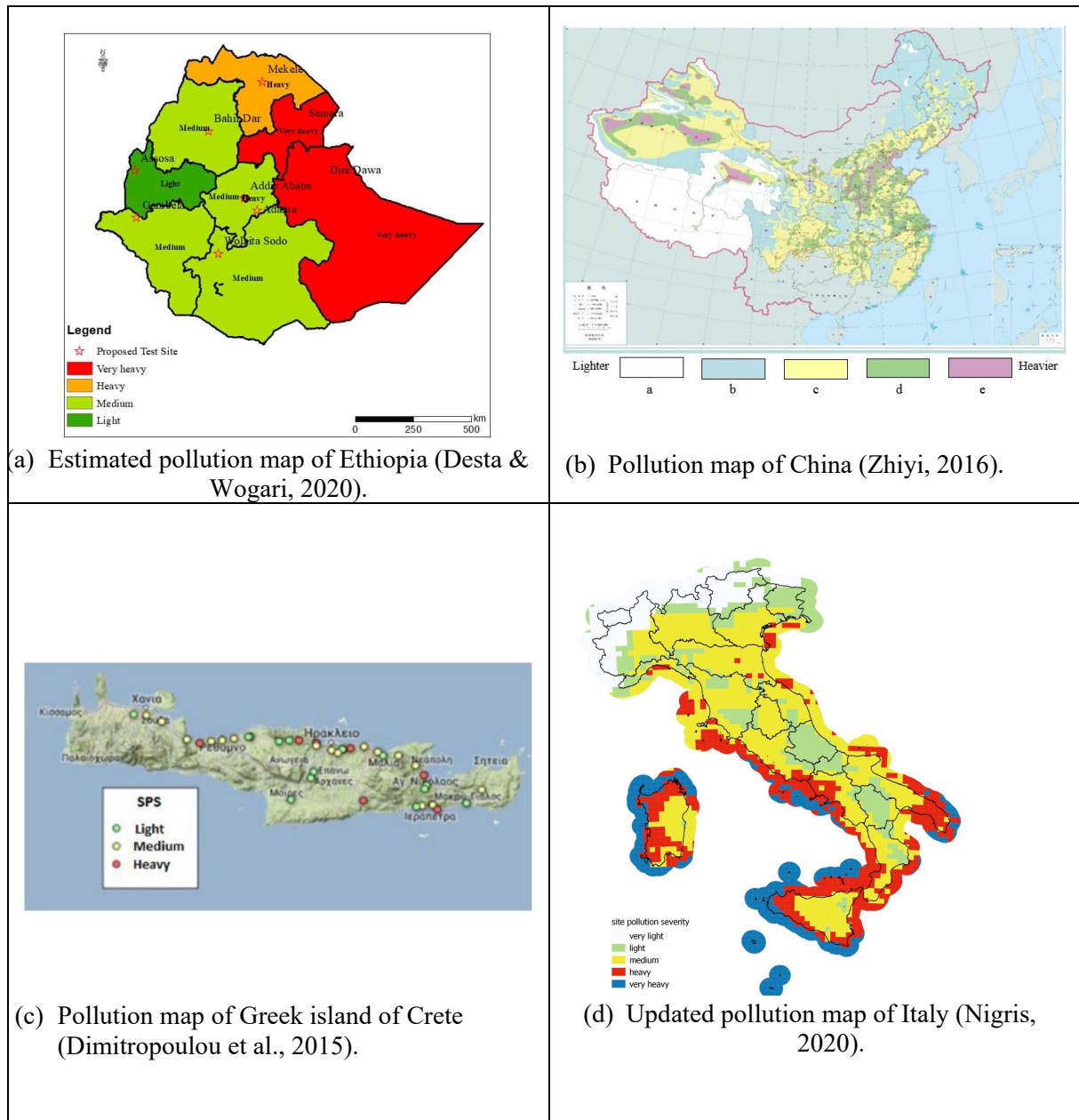


Figure 51: Pollution severity maps for Ethiopia, China, the Greek island of Crete, and Italy.

In certain instances, TSOs may need to develop regional or local pollution maps or update existing ones when their networks frequently encounter problems related to pollution flashovers, despite regular maintenance activities, like for example periodic insulator washing in heavily polluted areas. Regional pollution maps have been created in such countries as Iran, Azerbaijan, and Egypt (Abouelsaad et al., 2013; Shariati et al., 2005; Shariati et al., 2006). These maps were developed using traditional methods of site pollution severity determination based on ESDD, NSDD and directional dust deposit gauge (DDDG) measurements. Most of these regional or local maps primarily consider ESDD levels due to the limited availability of NSDD data. However, IEC strongly recommends considering both ESDD and NSDD values, as NSDD plays a crucial role in accurately determining pollution severity (Gutman et al., 2022; IEC/TS 60815-1, 2008; IEC/TS 60815-4, 2016).

6.2.4 *Methods Used in This Work*

As until now, no one undertaken in Ethiopia any attempts to monitor pollution severity by measurements of SPS parameters. The country is vast and geographically diverse. It is therefore not feasible to use direct onsite measurements for mapping pollution severity across its whole territory. Moreover, unavailability of the measured parameters for validation and calibration makes it difficult to employ simulation methods. Hence, as a starting point, methods that rely on estimation of SPS parameters by analyses of environmental and climatic conditions remain of interest, including information on service operational experiences on the performance of insulators in the existing transmission lines. In this work, no ESDD, NSDD, or any other site-assessment measurements have been conducted. The absence of severity measurements represents a significant limitation. It can however be leveraged by the information on service experience from transmission lines and environmental analyses to better estimate SPS, but such real-life analyses necessitate certain assumptions and considerations.

6.2.4.1 Estimation of Site Pollution Severity Parameters

We propose in this work the following two approaches for estimating the environmental pollution stress parameters (ESDD and NSDD) in accordance with (IEC/TS 60815-1, 2008). The first approach is based on the analysis of climatic and environmental conditions by considering their mutual interactions, according to the guidelines provided in (IEC/TS 60815-1, 2008) and involves two main components. Firstly, it considers climatic, environmental, and topographic characteristics in conjunction with meteorological data on rainfall patterns, distance from natural and artificial pollution sources (representing environmental factors) and secondly, it utilizes information on land cover and use, soil pH, estimated PM_{2.5} density, city types and sizes and inventory of pollution sources (representing pollution sources factors). Then, combining the effects of these two factors leads to determination of the typical environment according to Table 9 and the estimation of SPS class according to Figure 50.

The second approach involves analysis of the operational service experiences of existing transmission lines and the interactions between meteorological and environmental factors on the performance of the insulators for calculating an estimated site pollution severity using specialized software. The Insulator Selection Tool (IST) software developed based on principles of statistical dimensioning of insulators according to (IEC/TS 60815-1, 2008) can be used for this purpose. The software allows to estimate ESDD when the actual outage rate or mean time between flashovers (MTBF), the pollution/critical-wetting events per year, in-service insulator parameters, the representative pollution test type and

generic insulator pollution performance curves are known. The pollution performance (service experience) of in-service insulators from previous chapters is used to estimate the actual MTBF.

The point-based pollution severity evaluation will be done independently, using the two approaches, for carefully selected 364 sites/points along the routes of transmission lines, at substations, and other important locations for future grid expansion, uniformly distributed throughout the country. Since each approach has its own limitations in accurately estimating pollution parameters, the average of the estimated pollution parameters obtained from the two approaches is to be used to develop a pollution severity map for the entire country based on GIS software. Collection, processing, and analyses of georeferenced data are integral in this process. Additionally, identification of all existing overhead lines and substations with their geographic coordinates is essential and information on past incidents of pollution flashovers is a part of it.

The key meteorological parameters collected include the number of days with drizzle or fog, their annual distribution, and any extended intervals without rainfall during periods of pollution buildup. Environmental pollution parameters cover the type and spread of pollutants across regions, the number of emission sources, as well as future industrial developments, transportation networks, and other factors impacting air pollution (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008). Additionally, extracting long-term Particulate Matter PM_{2.5} data from satellite datasets and analyzing their spatiotemporal distribution for each grid region can provide an insight on the level of pollution deposit density on insulator surfaces in specific locations (Chisholm, 2019a; Nigris, 2023; Pons & Jeanmaire, 2022).

The combined impact of the collected parameters and their effects on pollution accumulation and washing of the insulator surface were reviewed monthly to account for seasonal variations for estimating maximum SPS levels, regardless of their occurrence in different months for each estimation point (IEC/TS 60815-1, 2008).

6.2.4.2 Determination of the NSDD/ESDD Ratio

Apart from direct measurement, the following methods can be employed to estimate NSDD for each site:

1. Analysis of the general type of environment helps determine the non-soluble component (NSDD) level in the pollution layer. The (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008) and (IEC/TS 60815-1, 2008) documents specify typical NSDD levels for different environments. For instance, Inland desert environments pollution primarily sourced from soil typically exhibit slow-dissolving salts and have a high NSDD level. Coastal desert areas, influenced by both sea and soil, also have slow-dissolving salts with a high NSDD level. Inland areas exhibit low pollution

levels, while agricultural environments may exhibit medium to high NSDD values. Industrial areas also tend to have medium to high NSDD levels, whereas environments near the coast feature pollution types with quickly dissolving salts and low NSDD.

2. Analyzing the regional distribution of long-term particulate matter (PM_{2.5} or PM₁₀) density also provides additional insights into the level of NSDD for the environment under investigation (Chisholm, 2019b).

3. Selecting an appropriate NSDD/ESDD ratio based on literature sources about the service experience in other countries, having similar environmental conditions (desert, industrial, inland, agricultural, etc.), may also be useful. Researchers indicated that pollution originating from environments such as desert, inland, industrial and agricultural contributes to both ESDD and NSDD, and usually 10-20% is ESDD, whereas pollution originating from marine aerosols (Direct coastal environments within 5 km from the coast) contributes nearly 100% ESDD.) (CIGRE Taskforce 33.04.01, 2000; Marzinotto, 2022).

Hence, by combining the information from these three sources the NSDD/ESDD ratio for each selected estimation point is determined. In Ethiopia, according to the sources of pollution, the general types of environments are Inland, Desert (both coastal and inland), Industrial, and Agricultural. Consequently, the pollution deposits typically have low, medium, and high non-soluble component (NSDD) contents (CIGRE Working Group C4.303, 2008; IEC/TS 60815-1, 2008; IEC/TS 60815-4, 2016). Additionally, satellite data are employed to analyze the long-term distribution of PM_{2.5} levels in Ethiopia for estimating NSDD levels.

Various published studies have been reviewed to estimate NSDD/ESDD ratios for Ethiopian environmental conditions. Table 10 provides an overview of the literature information showing NSDD/ESDD ratios depending on geographic and environmental conditions in different countries.

Table 10 Results of pollution accretion measurements at different countries (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008; Gutman et al., 2022; Pigni, 2020; Volpov & Kishcha, 2017; Zhiyi, 2016).

Country	ESDD (mg/cm ²)	NSDD (mg/cm ²)	NSDD/ESDD p.u,
Saudi Arabia	0.08 – 0.63	0.25 – 5.91	2 – 10
Egypt	0.25 – 2.2	na	na
Iran	0.1 – 1.2	0.2 – 10	1 – 4
Jordan	0.2 – 1 ^a	na	5
Tunisia	0.11 – 0.47	0.6 – 1.63	na
Algeria	0.22 – 0.35	na	10 – 25
Peru	0.03 – 1.05	0.32 – 4.1	5 – 10
China	na	na	2 – 10
Israel	0.45 ^b	2.0 ^b	6–10

^a derived from conductivity measurements

^b considered as representative

na – not available

Therefore, by combining the information from the three methods, estimated NSDD/ESDD ratios for Ethiopia range from 2 to 7, which is assumed representative depending on the specific environment considered. An average ratio of 5:1 has been assumed to represent most of Ethiopian territory and, finally, the NSDD/ESDD ratio is thereafter adjusted for each site by integrating these findings with local environmental characteristics, such as climate, land cover and use, soil type, and wind conditions. Furthermore, the estimated long-term average PM_{2.5} levels are also considered.

Once the NSDD/ESDD ratio is determined, the corresponding NSDD level for each site is calculated. For estimation of SPS by IST software, where ESDD is initially calculated for NSDD of 0.1 mg/cm², the ESDD value is then corrected for the corresponding NSDD at the site. Detailed results of SPS estimation are tabulated in Appendix E Table A – 9.

6.2.4.3 Pollution Mapping Process

The point-based assessment of SPS is done for the selected 364 points/sites. For each of them corresponding environmental and climatic conditions are analyzed. The process has two main components and yields the final estimate by averaging the output of each component. This process is presented in the flow chart shown in Figure 52.

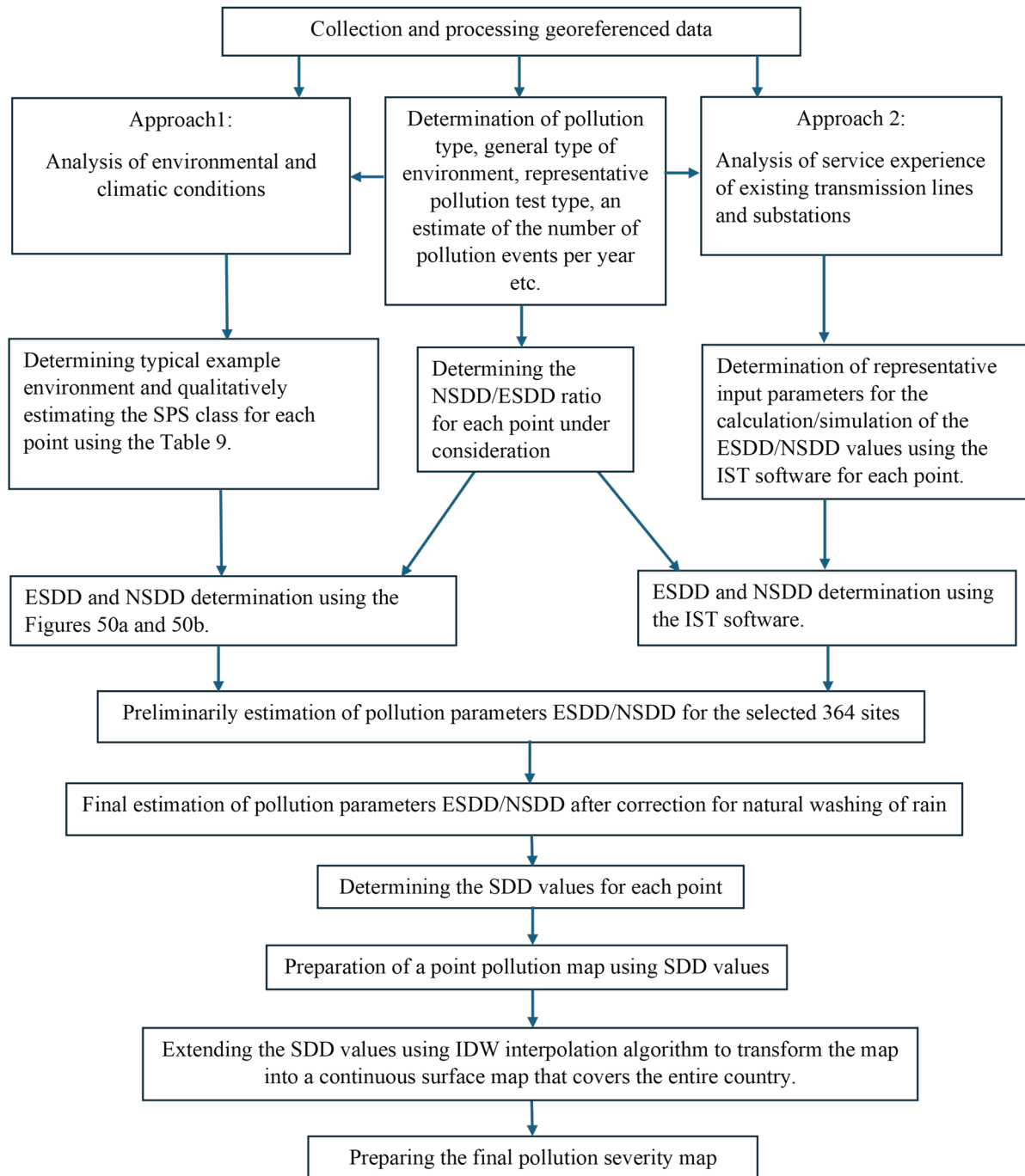


Figure 52: Pollution mapping process.

The following are detailed steps of the pollution mapping procedure categorized into four stages:

(a) The collection, processing and analysis of georeferenced data step includes:

1. Gathering and processing georeferenced meteorological, climatic, environmental and pollution conditions, as well as operational and system data.
2. Analysis of the collected data and determination of the pollution type, the general type of environment, climate, an estimate of the number of pollution events per year and representative laboratory test method for the selected 364 sites.

(b) The evaluation of SPS parameters step includes:

For Approach 1:

3. Determining typical example environment and estimating the SPS class for each point qualitatively using Table 9.
4. Estimation of environmental pollution stress parameters ESDD/NSDD.
5. Determining ESDD and NSDD: Estimating corresponding ESDD/NSDD values based on qualitatively assessed SPS class and installed insulator type using Figures 50a and 50b.

For Approach2:

6. Evaluating service experience of existing transmission lines, substations in terms of pollution performance for determination representative input parameters for calculation/simulation of the ESDD/NSDD by Insulation Selection Tool (IST) software.
7. Calculating/simulating ESDD/NSDD values for each point by Insulation Selection Tool (IST) based on system data, practical service experience, pollution severity information, mean time between failures (MTBF), in-service insulator parameters, the representative pollution test type and local meteorological and environmental information for necessary adjustment.

(c) The determination of final pollution severity parameters by combining the two approaches includes:

8. Preliminarily determination of environmental pollution stress parameters ESDD-NSDD by systematically analyzing the accuracy of various data sources and the approach methodologies. The average ESDD resulting from each of the two approaches is then considered as an output from the above steps.

9. Supplementing site estimations with trend indications linked to real meteorological data to infer the maximum pollution level at the considered site allows for potential correction of estimated pollution severity before the final decision of ESDD-NSDD.
10. Determining the SDD values for each point by converting the ESDD and NSDD values estimated using formulations in (CIGRE Working Group C4.303, 2012; IEC/TS 60815-1, 2008; Nigris, 2023).

(d) The final GIS pollution mapping step includes:

11. Preparation of a local/ point pollution severity map for SDD using ArcGIS software.
12. Extending the SDD values of specific locations, representative of local conditions, into a continuous surface map that covers the entire geographical territory of the country using Inverse Distance Weighting (IDW) interpolation algorithm.
13. Generating the final pollution severity map according to (IEC/TS 60815-1, 2008) standard.

6.3 Meteorological and Environmental Data Used for Pollution Mapping

6.3.1 Climatic and Environmental Data

Key climatic, meteorological, and environmental data, all georeferenced, were utilized in facilitating analysis of climate, environmental conditions, topographic characteristics and service experience of existing lines and substations for evaluation of SPS parameters.

6.3.1.1 Meteorological Parameters

Meteorological parameters can impact pollution levels on insulator surfaces in both positive and negative ways, depending on the location. Interactions between these parameters are considered by judging their various effects. Details of such effects are discussed in chapters three and four (Desta & Wogari, 2020; Desta et al., 2024b) and are based on long-term meteorological data obtained from (CFSR, 2019). Moreover, previous studies (Beck et al., 2018; Berhanu et al., 2014; BirdLife, 2024; MoA; Shanko, 2001; USGS & EROS, 2019a) on climate of Ethiopia were also utilized, which include data on precipitation, number of dry days, minimum and maximum temperature, relative humidity, wind speed and its direction, and solar radiation.

6.3.1.2 Number of Dry Days

Due to climate change, events of consecutive dry days are expected to increase, leading to more frequent situations favorable to the buildup of insulator pollution. An increase in average temperature is likely to elevate humidity levels in ambient air, the critical factor in triggering pollution events (Nigris, 2023, 2020). The monthly average number of dry days map for Ethiopia is presented in Figure

53. This helps to identify the sites where prolonged dry periods occur and pollution accumulation on insulator surface is high and the sites having longer rainy periods, favourable for natural cleaning.

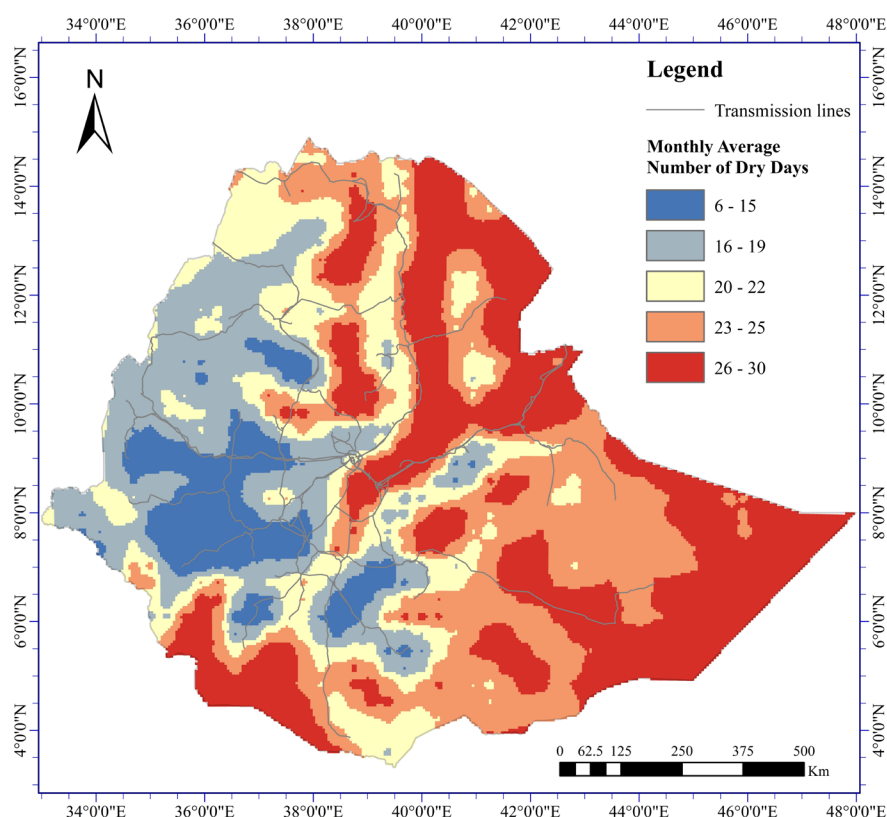


Figure 53: Map showing distribution of the number of dry days across Ethiopia.

6.3.1.3 Climate Classification

The Köppen-Geiger climate classification map for Ethiopia provides a detailed overview of the country's various climate zones. This map categorizes regions based on their temperature and precipitation patterns, offering insights into Ethiopia's diverse climatic conditions. Köppen-Geiger climate classification map for Ethiopia (1980-2016) (Beck et al., 2018) is shown in Figure 54. Due to the extensive size of Ethiopia's territory, the climate exhibits diverse characteristics. There are seven main climate types, each with distinct characteristics, as described in the following:

1. Tropical monsoon climate (Am): Present in the southwestern regions, this climate features a short dry season and a long-wet season, with substantial rainfall.
2. Tropical savanna climate (Aw): Found in the northwestern, western and southwestern lowlands, this climate type is characterized by a distinct wet and dry season, with higher temperatures and seasonal rainfall.
3. Hot desert climate (BWh): Found in the northeastern and southeastern lowlands, this climate is extremely arid, with very high temperatures and minimal rainfall.

4. Hot semi-arid climate (BSh): Common in the northeastern, eastern and far south parts of the country, this climate has high temperatures and low precipitation, leading to arid conditions.
5. Cold semi-arid climate (BSk): Found in the highlands, particularly in the west, southwestern and south regions, this climate experiences moderate temperatures, with a short dry season and a long-wet season, with substantial rainfall.
6. Temperate climate with dry winter (Cwb): Located in the highlands, particularly in the central, northern and eastern regions, this climate experiences moderate temperatures, with dry winters and wet summers.
7. Temperate climate with no dry season (Cfb): This type is present in the southwestern and near south highlands, featuring a long-wet season with moderate temperatures.

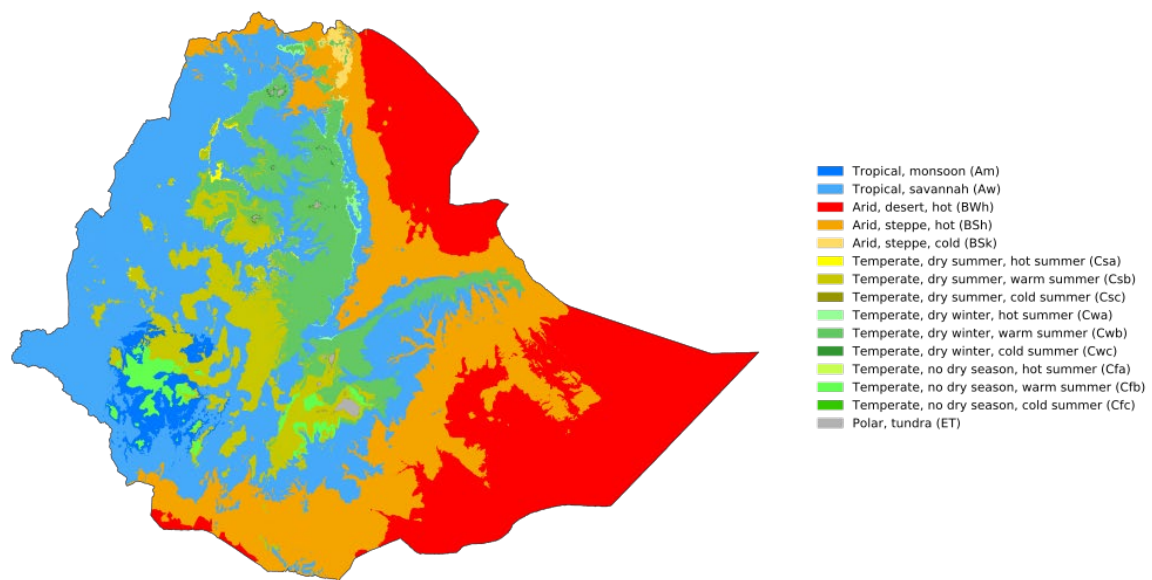


Figure 54: Köppen-Geiger climate classification map for Ethiopia (1980-2016) (Beck et al., 2018).

Figure 55 illustrates the traditional climatic zones of Ethiopia (Berhanu et al., 2014). These zones are classified into five categories based on altitude and temperature, ranging from the very cold to the very hot and dry climatic condition, locally referred to as "Wurich", "Dega", "Weynadega", "Kola", and "Berha". These climatic zones provide important information about the type and source of pollution, the chance of pollution accumulation, and the natural cleaning possibility in different locations. Their physical characteristics, altitude, mean annual rainfall, length of rainy periods, mean annual temperature, and area share is presented in Table 11.

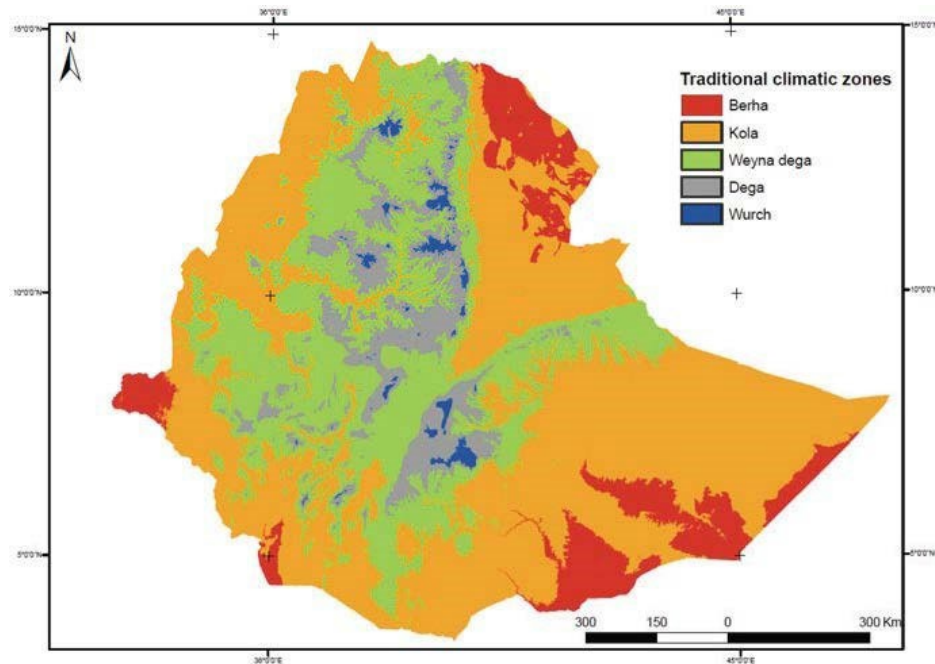


Figure 55: Traditional climatic zones of Ethiopia (Berhanu et al., 2014).

Table 11 Traditional climatic zones of Ethiopia and their physical characteristics (Berhanu et al., 2014).

Zones	Altitude (m)	Mean annual rainfall (mm)	Length of rainy periods (days)	Mean annual temperature (°C)	Area share (%)
Wurich (very cold to moist)	>3,200	900–2,200	211–365	Below 11.5	0.98
Dega (cool to humid)	2,300–3,200	900–1,200	121–210	11.5–17.5	9.94
Weynadega (cool sub humid)	1,500–2,300	800–1,200	91–120	17.5–20.0	26.75
Kola (warm semiarid)	500–1,500	200–800	46–90	20.0–27.5	52.94
Berha (hot arid)	<500	Below 200	0–45	Above 27.5	9.39

6.3.1.4 Analyzing Ethiopia's Topographic Characteristics

Topographic analysis is conducted with a particular focus on altitude patterns to evaluate their influence on pollution withstand performance of insulators and its effect on the distance that pollutants can be transported from desert and seacoast by wind. Utilizing Geographic Information System (GIS) analysis, the variation in altitude across the country was examined from the Digital Elevation Model (DEM) data (USGS & EROS, 2019a). Figure 56 illustrates the results of this analysis, depicting topographic characteristics based on elevation above sea level.

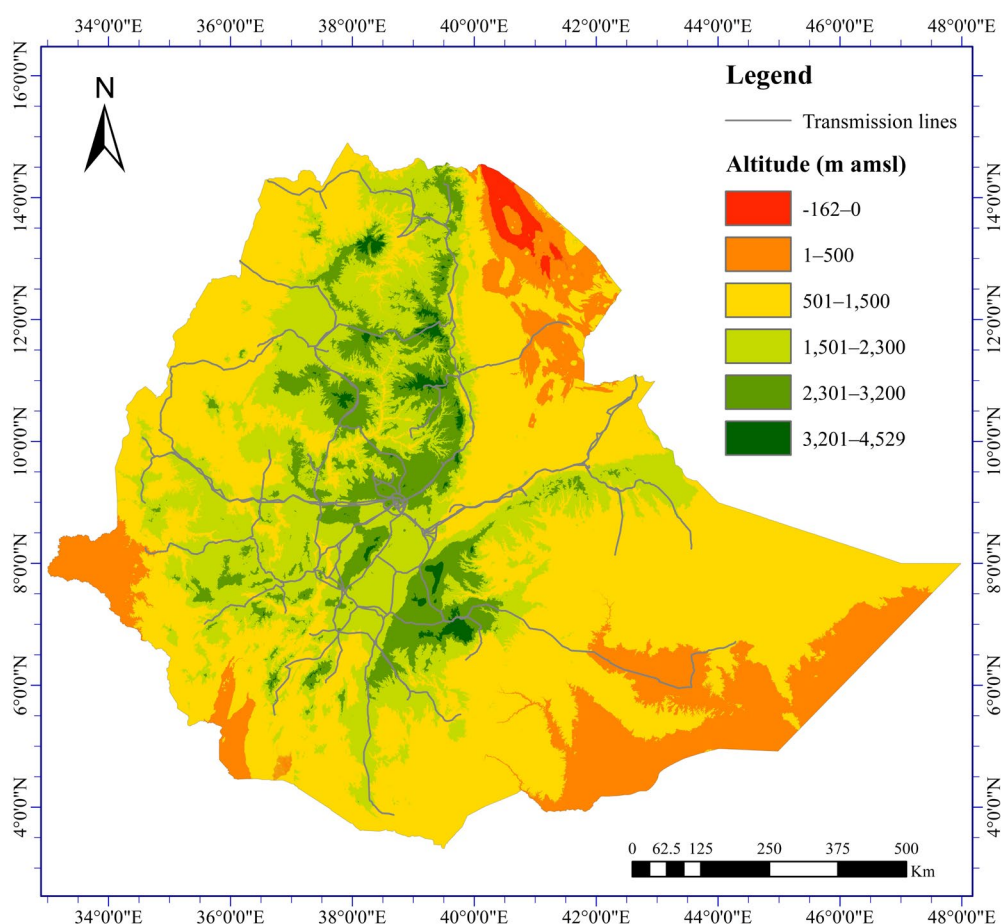


Figure 56: Topographic map of Ethiopia.

The analysis also allowed to compute land areas belonging to these different physiographic topographies, as shown in Table 12. Approximately 14.6 % of the land lies below 500 meters (lowlands and arid areas), while around 51.2% falls within the range of 500 to 1500 meters (plain and semi-arid). Only 34.3% exceeds 1500 meters (mountainous) above sea level where altitude corrections are required (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008). Top of Dashen Mountain, situated in the northern part of Ethiopia, is the highest point at 4500 meters above sea level, whereas the lowest point is found in the Danakil depression, with an altitude dipping to 162 meters below sea level.

Table 12 Computed areas for different physiographic topographies across Ethiopia.

Altitude (m)	Area km ²	%	Primary topographic categories
< 500 m	165943.8	14.6	Lowlands (Arid)
500 m–1500 m	579960.8	51.2	Plain (semi-arid)
1500 m–2300 m	280624.7	24.7	Mountainous
2300 m–3200 m	98144.1	8.7	Mountainous
> 3200 m	8767.3	0.8	Mountainous
Total Area	1,133,440.6		

6.3.2 Environmental and Pollution Data

6.3.2.1 Land Cover and Land Use

Land cover and land use classification for Ethiopia provides a comprehensive view of how land is utilized. This classification is crucial for understanding the general environment and to identifying the environmental pollution sources as well as the quantity and nature of pollutants. Data on land cover and use, obtained from specialized websites (USGS & EROS, 2019b), were processed, classified and mapped. The map presented in Figure 57 provides a detailed overview of Ethiopia's land cover and land use.

This map helps in assessing the dominant type of pollution for the site under consideration and in determining the general environment types. Notably, assessing the Non-Soluble Deposit Density (NSDD) requires comprehensive information and is heavily influenced by vegetation and land use (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008). Table 13 shows details of land cover and land use data for Ethiopia. Nearly 38.6 % of Ethiopia's land is utilized for agricultural purposes and about 55 % is covered by grasslands and sparsely vegetated areas, shrubs and bare areas, both expected to significantly contribute to insulator pollution, as these areas usually have arid and semi-arid climate having long dry day periods and low annual rainfall.

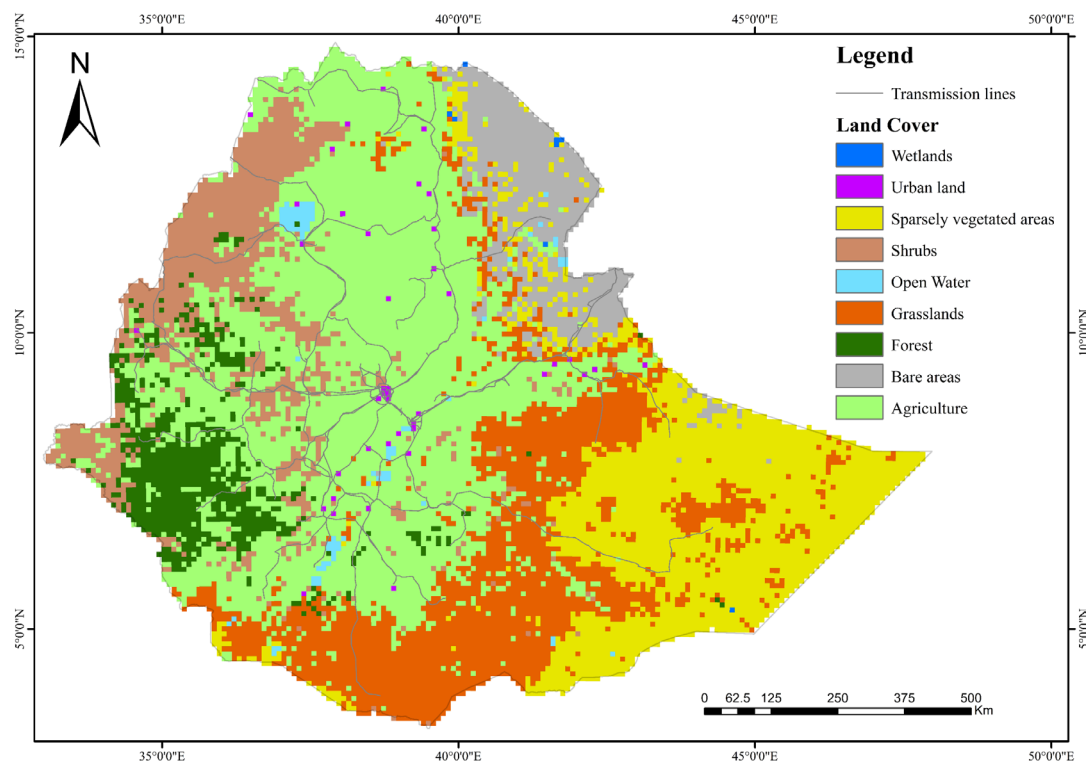


Figure 57: Land cover and land use map for Ethiopia.

Table 13 Land use and land cover classification for Ethiopia (USGS & EROS, 2019b).

Land use	Land cover	Area (km ²)	Area (%)
Forest	Forest - virgin	64035.4	5.6
	Forest - protected		
	Forest - with agricultural activities		
	Forest - with moderate or higher livestock density		
Grasslands	Grasslands - unmanaged	213480.5	18.8
	Grasslands - protected		
	Grasslands - low livestock density		
	Grasslands - moderate livestock density		
	Grasslands - high livestock density		
Shrubs	Shrubs - unmanaged	116949.4	10.3
	Shrubs - protected		
	Shrubs - low livestock density		
	Shrubs - moderate livestock density		
	Shrubs - high livestock density		

(Continued)

Land use	Land cover	Area (km ²)	Area (%)
Agriculture	Rainfed crops (Subsistence/Commercial) Crops and moderate or intensive livestock density Crops and high livestock density Crops, large-scale irrigation, moderate or higher livestock dens. Agriculture - large scale irrigation Agriculture - protected	439646.4	38.6
Urban lands	extensive urban areas	3649.2	0.3
Wetlands	Wetlands - unmanaged Wetlands - mangrove	695.1	0.1
Sparsely vegetated areas	Sparsely vegetated areas - unmanaged Sparsely vegetated areas - protected Sparsely vegetated areas - with low livestock density Sparsely vegetated areas – moderate to high livestock density.	214957.5	18.9
Bare areas	Bare areas - unmanaged Bare areas - protected Bare areas - with low livestock density Bare areas - with moderate livestock density	76547.1	6.7
Open water	Open Water - protected Open Water - inland fisheries	7906.7	0.7

6.3.2.2 Soil pH Map

Another important information about the pollution type can be found from soil pH. Soil pH indicates its level of acidity or alkalinity. The measurement scale spans from 0 (highly acidic) to 14 (highly alkaline), with 7 representing neutrality. The soil pH map, shown in Figure 58, created by Ethiopian Ministry of Agriculture (MoA, 2020), is the result of analyzing extensive field-lab data and satellite information. This map helps to identify the nature of pollutions originating from the local soil/ dust and their severity.

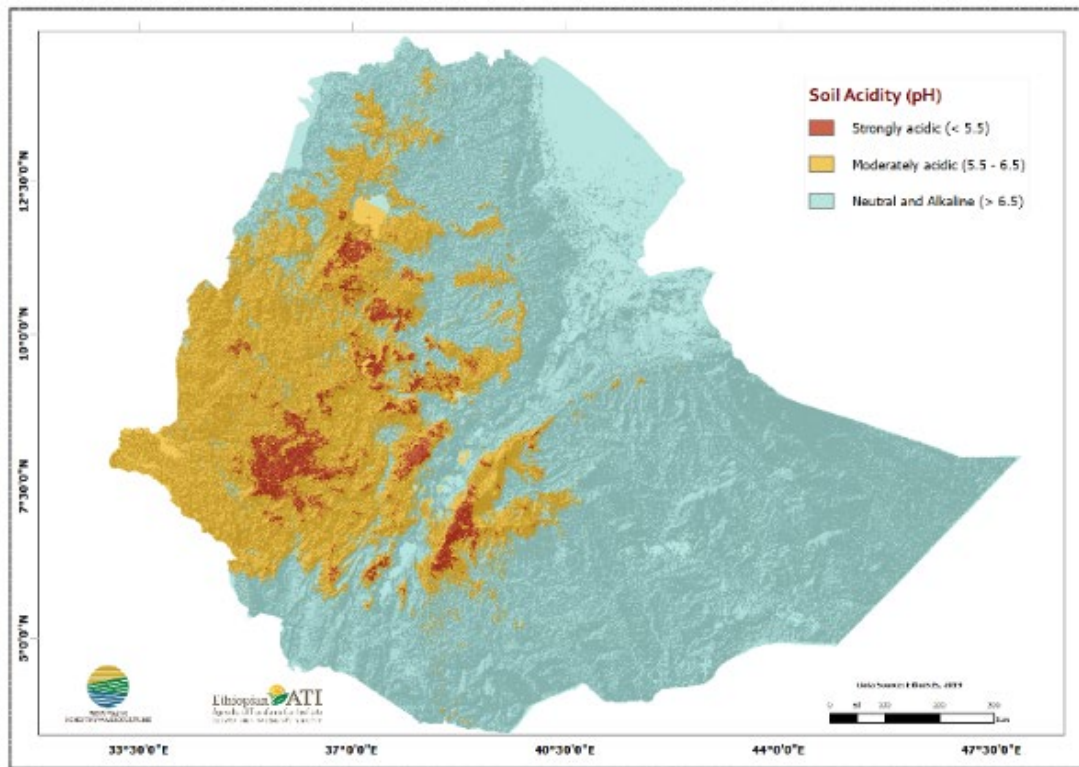


Figure 58: Soil pH map for Ethiopia (MoA, 2020).

According to this study, two major issues affecting Ethiopian soils are soil acidification and salinization. Over 7.5 million hectares of land are impacted by soil acidity, with more than 4 million hectares being classified as strongly acidic ($\text{pH} < 5.5$). This problem is particularly prevalent in the central, northwestern, western, and southwestern highland regions of the country, where annual rainfall is high. Additionally, in the arid and semi-arid regions, where evapotranspiration exceeds the average annual precipitation, soil salinity affects over 11 million hectares. This issue is primarily caused by improper irrigation practices and the use of low-quality irrigation water (MoA, 2020).

6.3.2.3 Major Sources of Pollution in Ethiopia

The influence of pollution on the insulating components of overhead lines and substations has been well-documented for several decades. Pollution sources can originate from natural occurrences or human activities. Certain sources, such as industrial facilities, have localized effects, while others, like coastal areas, desert areas, urban areas and agricultural activities, have more widespread impacts. Moreover, some pollution sources remain constant throughout the year, while others exhibit seasonal variations influenced by climatic characteristics (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008). Wind is the primary agent responsible for transporting pollution particles. The choice and dimensioning of insulation are thus closely tied to the pollution exposure of equipment, with the criticality of surface pollution depending on both its quantity and nature. In this regard, it is essential to have sufficient information about the nature of pollutants

for optimal dimensioning insulators without risk. Therefore, conducting an inventory of major pollution sources is essential.

Conducting a pollution source inventory involves utilizing existing documentation, data from organizations monitoring air quality, making assumptions, and conducting on-site measurements. The following general principles can help to identify locations expected to have higher pollution intensity (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008):

- Proximity to manmade pollution sources such as roads, industrial facilities, mining operations, agricultural activities, and residential areas using coal or wood for heating and cooking.
- Proximity to natural pollution sources like coastal areas, deserts, or open dry lands.
- Environments experiencing extended dry periods, such as prolonged dry seasons or droughts, which facilitate the accumulation of pollutants over time.
- Regions with prolonged periods of low wind speeds, typically below 3 m/s (considered as light breeze).

Additional factors influencing pollution intensity include the effectiveness and frequency of natural cleaning processes on insulators. Insulators that facilitate efficient natural cleaning, either due to their design or installation orientation, may accumulate less pollution. Moreover, through the analysis of operational experience on transmission lines, the distribution of pollution flashover incidents over time can reveal regions where higher site pollution severity (SPS) levels are likely (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012; IEC/TS 60815-1, 2008).

All these factors are carefully considered and used as guidelines in the assessment of pollution sources and estimating the SPS of the selected sites. In this regard, various sources of pollution in Ethiopia were reviewed, and the following are some key factors contributing to insulator pollution:

1. Sand and dust from deserts and open dry lands, which contain significant salt content, along with salt sprays from coastal areas and saline lakes, primarily located in the northeastern and eastern parts of the country, serve as natural sources of pollution.
2. Urban areas, particularly major cities with high population densities, generate a variety of pollution types from fossil fuel use in cooking, heating, and thermal engines etc. These pollutants can significantly impact electrical networks.
3. Mining activities are widespread across the country and include the extraction of gold, tantalite, gemstones, iron, salt, coal, and industrial minerals. The north, northeast, west and south part of

Ethiopia are regions where these mining activities are intense and future large-scale mining is anticipated. For example, rock salt is produced from the Danakil Depression, which spans thousands of square kilometers in the northeast of Ethiopia.

4. Sugar factories and ethanol production plants are spread across the country and are sources of insulator pollution.

5. Industrial pollution from steel and metal smelting, engineering, and assembly industries are mainly concentrated in the Addis Ababa and central region of Ethiopia. Metallic deposits on insulator surfaces are typically found near these industries and mining activities.

6. Areas affected by pollution from cement factories and quarries extend across the north, central, and eastern parts of the country. These facilities also produce dimension stones (such as marble and granite) and construction materials.

7. Agricultural activities in most parts of the country, including the cultivation of coffee, corn, wheat, oilseeds, floriculture, and cotton, contribute to insulator pollution. This is particularly true in sugarcane-growing regions and other crop cultivation areas. Factors such as the presence of salt in soils and dispersal by wind during ploughing, and the use of fertilizers and pesticides through spraying, as well as the burning of crop residues, can lead to increased pollution levels.

8. Given that road transport is the primary logistics system in the country, the extensive road network generates pollutants such as road dust, automobile soot, and smoke.

9. In regions where, large birds inhabit and use transmission line towers for roosting and perching, bird droppings can contribute to insulator pollution. Ethiopia, known for its rich bird diversity with over 821 species, has been recognized by BirdLife International (www.birdlife.org) for having 69 Important Bird Areas (IBA), as shown in Figure 59. The map illustrates their proximity to transmission lines with many of these IBAs (totally account for about 10% of land area) are situated near transmission lines, particularly in wetland areas (BirdLife, 2024).

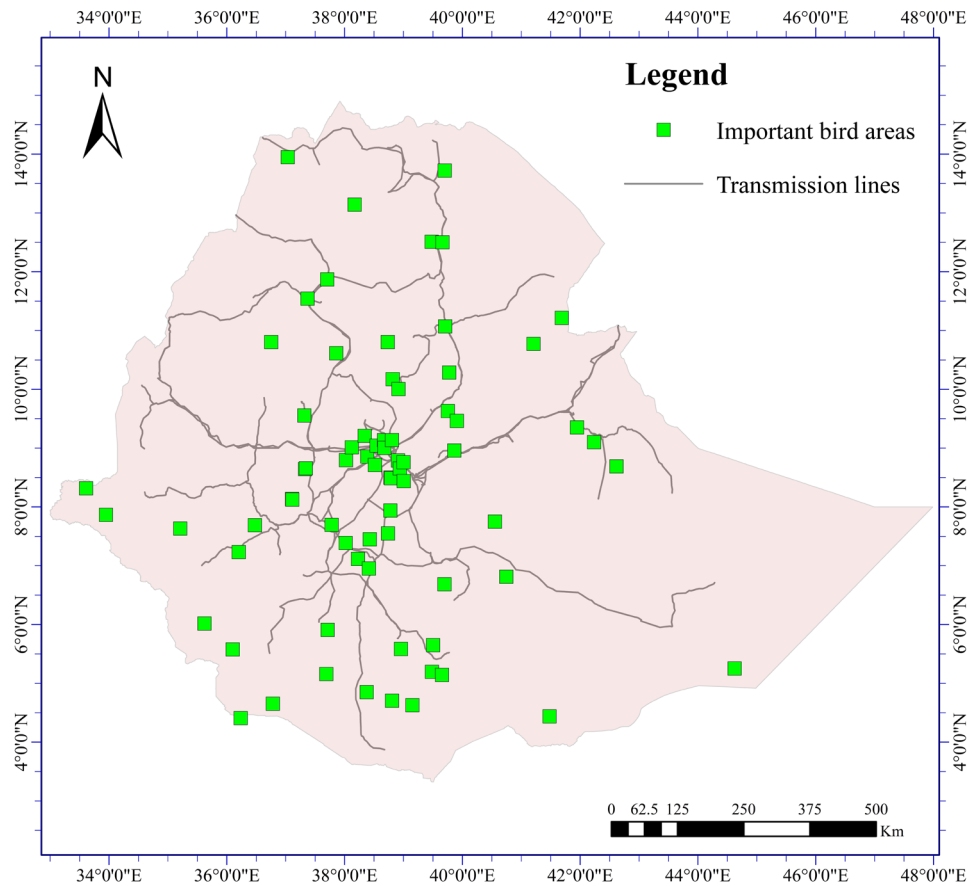


Figure 59: Important Bird Areas (IBA) in Ethiopia (BirdLife, 2024).

Based on these guidelines, assessment of local pollution sources was conducted using data gathered from relevant organizations, existing documentation, and studies (BirdLife, 2024; CSA, 2013; Ethiopian sugar Industry Group; MoA, 2020; MoM; MoM and World Bank, 2014; MoWE, 2020; Mulatu et al., 2018; Tadesse et al., 2003; USGS & EROS, 2019b). These sources were categorized according to their characteristics and influence zones. Figure 60 illustrates the spatial distribution of primary pollution sources expected to contribute to insulator pollution within the EEP grid.

At the start of this research project, we planned to assess pollution parameters through on-site measurements. However, this effort was unsuccessful by challenges related to procuring laboratory equipment and field measuring devices. As a result, we lack precise data on the severity of various pollution sources. Consequently, we have assumed that all sources contribute to some degree to the pollution levels at the sites.

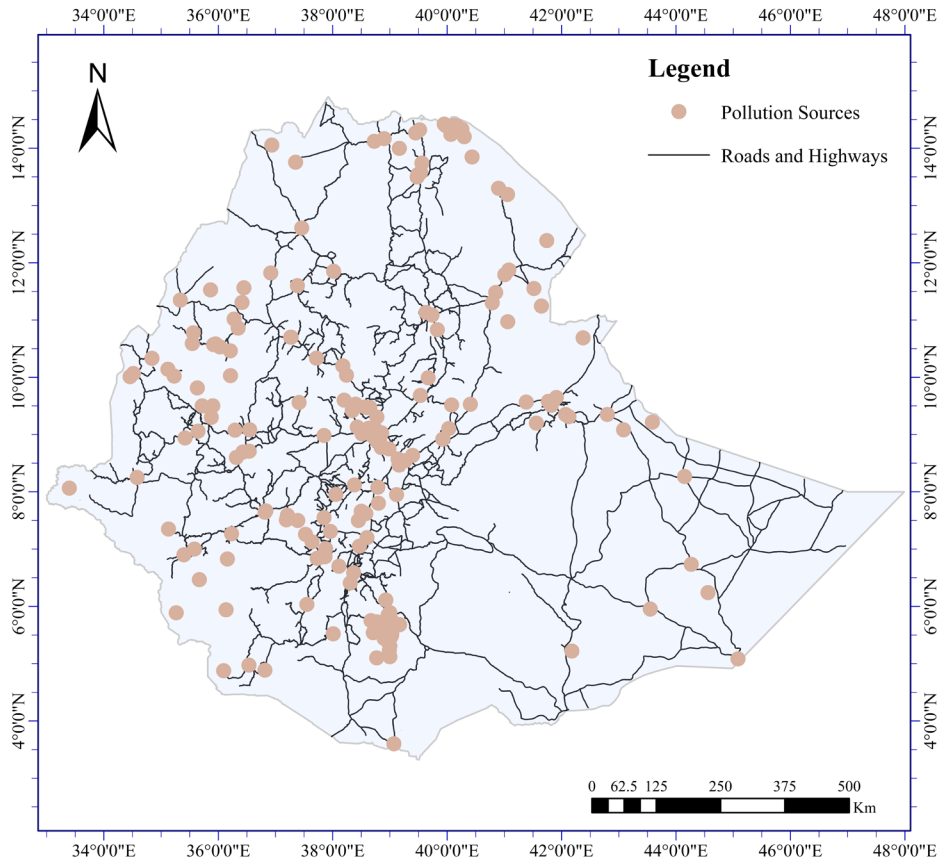


Figure 60: Spatial distribution of local pollution source in Ethiopia.

6.3.2.4 Fine Particulate Matter (PM_{2.5}) Concentration in Ethiopia

Another environmental pollution data used in this work is the satellite derived PM_{2.5} density estimates for Ethiopia with a spatial resolution of $0.1^\circ \times 0.1^\circ$, extracted and processed from the Atmospheric Composition Analysis Group (ACAG) data covering the years 1998 to 2022 (ACAG, 2024). Spatial and temporal variation of PM_{2.5} pollution in Ethiopia helps to identify the characteristics of the airborne pollutants. Annual mean PM_{2.5} concentrations for all EEP grid regions and for the entire territory of Ethiopia were calculated and used as an input in the evaluation of SPS.

6.4 Application Examples of SPS Estimation

In accordance with the site pollution severity evaluation methods outlined in Section 6.2.4, this section presents typical examples of SPS evaluation for two transmission lines, to illustrate the process followed in estimating the SPS for each of the 364 points under consideration.

6.4.1 Analysis of Environmental and Climatic Conditions

In this case, the methodology used to estimate Site Pollution Severity (SPS) considers environmental and pollution factors. The process begins with identifying the dominant type of insulator pollution that could lead to flashover in the specific region. Next, the general types of environments that describe the typical pollution characteristics are determined. The relationship between typical environments and

their corresponding description presented in Table 9, the typical combination of pollution sources and wetting conditions expected in each class, is examined to determine the typical environments (E1-E7) from qualitative indicators for the intended location/site. These indicators include the type of pollution present in the area, the distance from pollution sources in the area (such as seacoast, deserts, open dry land, industries or urban areas and land use/cover), prevailing wind direction and speed, monthly rain-washing frequency, critical wetting events, and the level of NSDD in the area. Using these indicators, typical environments (E1-E7) and NSDD/ESDD ratio will be determined and ultimately the corresponding SPS class (a - e) and the ESDD value for the location under consideration are determined using Figure 50(IEC/TS 60815-1, 2008). These steps are followed to estimate the ESDD-NSDD values for each of the 364 points considered for creating the pollution map. To illustrate this method, two existing transmission lines are considered, and their corresponding average ESDD and NSDD values are determined.

6.4.1.1 Combolcha II—Semera—Dicheto 230 kV Line

The Combolcha II—Semera—Dicheto 230 kV AC line operates since 2011 and stretches 241 km from the Combolcha II substation through Semera to the Dicheto substation (2017) in the northeast part of Ethiopia. This region exhibits desert and semi-arid climatic conditions, characterized by limited rainfall throughout the year. It is situated near the Danakil desert and Red Sea, exposed to direct salt sprays, salty dust, and salty fog carried by strong winds. Additionally, mining contamination from the desert and saline lakes in the region contributes to a combination of type A and type B pollutants, as being situated in desert and indirect coastal environments characterized by pollution deposits with a high non-soluble component (NSDD). The line is insulated with long-rod HTV silicone rubber composite insulators with a USCD of 36 mm/kV and a length of 2.24 m and is known, based on service experience, to perform poorly. A total of 105 pollution-induced flashovers were identified on this line from 2015 to the end of 2022, averaging 13.1 faults per year.

The route of the Combolcha II—Semera—Dicheto 230 kV line is depicted in Figure 61a. Figure 61b (IEC/TS 60815-1, 2008) illustrates the relationship between ESDD, NSDD, and site pollution severity classes. This diagram also outlines typical environments (E1-E7) defined in the standard, based on descriptions provided in Table 9. For instance, environment "E6/E7" corresponds to areas where fog or drizzle frequently follows an extended dry period lasting several weeks or even months, allowing pollution to accumulate, and/or where NSDD levels are significantly high, ranging from 5 to 10 times that of ESDD, similar as that along the right of way of the Combolcha II—Semera section of the line. The Semera —Dicheto section, being closer to the seacoast and located in the desert area, is characterized as environment "E7" - desert areas with fast accumulation of alkaline dust, sand and salt, regular condensation and exposed to sea-spray or dense saline fog. It has also been noticed for both

sections of the line that the pollution level may strongly rise during storms. Therefore, the assigned for the Combolcha II—Semera section the typical environments are E6/E7 with the NSDD/ESDD ratio equal to 6:1. For the Semera —Dicheto section the typical environments are E7 with the NSDD/ESDD ratio equal to 7:1. The estimated ESDD and the corresponding NSDD values for both the sections are summarized in Table 14. Figure 61 shows the relationship between SPS and NSDD/ESDD in (IEC/TS 60815-1, 2008) for reference long rod insulator with colored stars for summarizing the results.

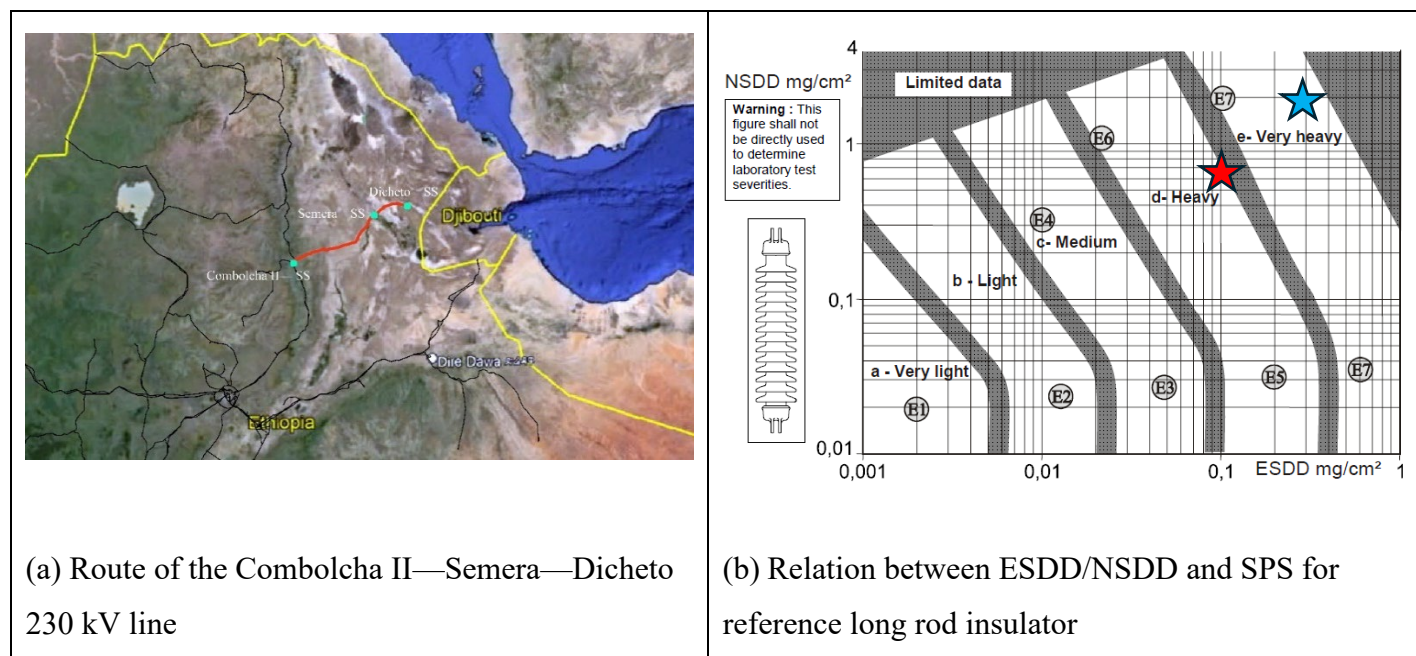


Figure 61: Route of the Combolcha II—Semera—Dicheto 230 kV line (a) and relationship between ESDD and NSDD and environments E1-E7 for the reference long rod insulator (b). The margin of E6/E7 environment is marked by a red star (Combolcha II—Semera) and of E7 marked by blue star (Semera—Dicheto).

6.4.1.2 Bahir Dar II—Debre Markos—Sululta 400 kV Line

The Bahir Dar II—Debre Markos—Sululta 400 kV line spans over 410 km and extends from the northwestern highlands of Ethiopia to Addis Ababa. It traverses subtropical highlands and tropical savanna. Environmental conditions along its route are characterized by a mixture of desert, industrial, and agricultural environments with pollution deposits of medium to high non-soluble NSDD components. Main sources of pollution include transportation, construction, quarry sites, naturally occurring dust from local soils, cement factories, and agricultural activities such as ploughing, fertilizers, crop spraying, and harvesting. The line is insulated with glass cap and pin strings with a USCD of 36 mm/kV and a length of 4.58 m. The line has remained in service for about 14 years and is known to experience a high number of unexplained outages. An analysis of service experience identified a total of 72 pollution-induced faults on this line from 2015 to 2022, averaging 9 faults per year. In addition, the reduction in flashover voltage level (above 10%) due to lowered air density at

high altitudes (~2000 m) and nearly constant temperature along the line's route, could also contribute to the increased outage rate.

The route of the Bahir Dar II—Debre Markos—Sululta 400 kV line is depicted in Figure 62a. A diagram from (IEC/TS 60815-1, 2008), shown in Figure 62b, illustrates the typical environments (E1-E7) defined in the standard based on descriptions in Table 9. The Bahir Dar II—Debre Markos section of the line is characterized as environment "E4", where dense fog or drizzle commonly follows a prolonged dry period, lasting weeks or even months, allowing pollution to accumulate. Additionally, this area experiences heavy rains with high conductivity and NSDD levels are high, reaching between 5 and 10 times the ESDD. Similarly, the Debre Markos—Sululta section, being closer to cement factories and partly passing through a desert area, it is characterized as environment "E6", where dense fog or drizzle commonly follows an extended dry period, lasting several weeks or months, during which pollution accumulates and/or NSDD levels are high, ranging from 5 to 10 times the ESDD. Therefore, the resulting typical environments are assumed as E4 with the NSDD/ESDD ratio equal to 5:1 for the Bahir Dar II—Debre Markos section and E6 with the NSDD/ESDD ratio equal to 6:1 the Debre Markos—Sululta section. The estimated ESDD and the corresponding NSDD values for each section of the line are summarized in Table 14. In Figure 62 the relationship between SPS and NSDD/ESDD in (IEC/TS 60815-1, 2008) graph for the reference cap and pin insulators are marked by colored stars.

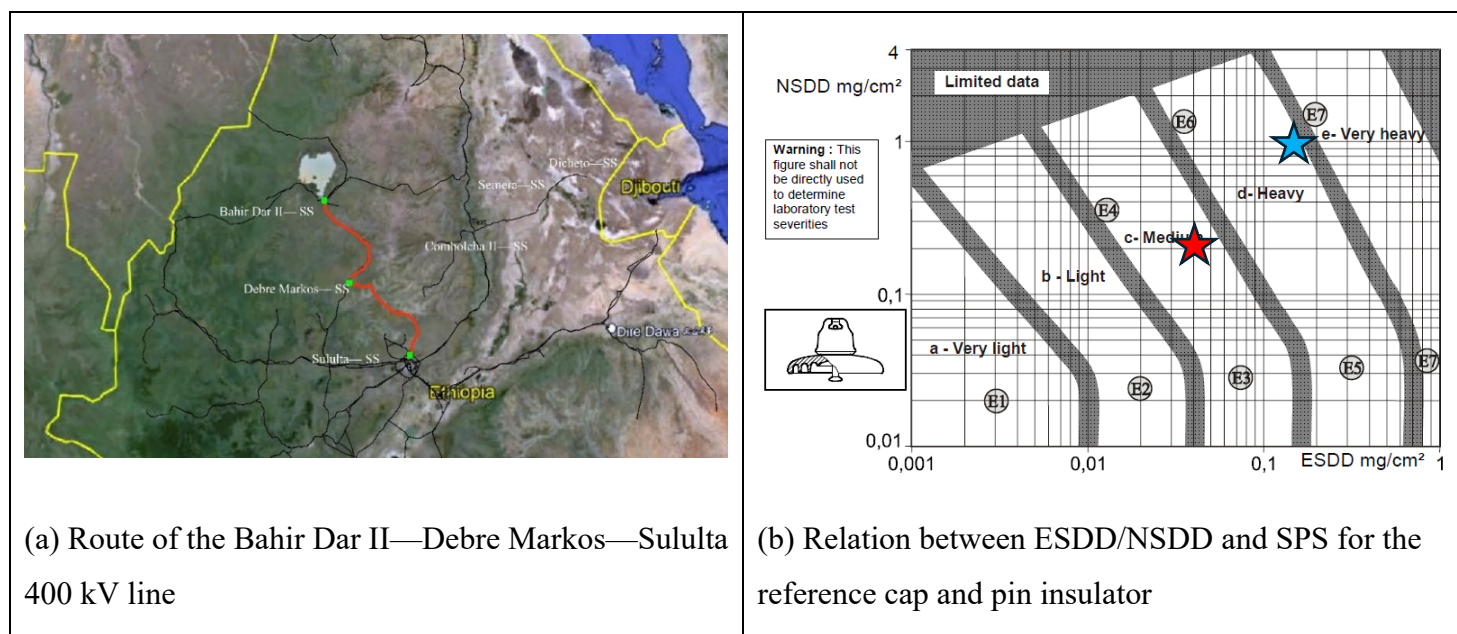


Figure 62: Route of the Bahir Dar II—Debre Markos—Sululta 400 kV line (a) and relationship between ESDD and NSDD and environments E1-E7 for the reference cap and pin insulator (b). The E4 environment is marked by a red star (Bahir Dar II—Debre Markos) and E6 marked by blue star (Debre Markos—Sululta).

Table 14 Summary of results of the environmental analysis method.

No.	Line	ESDD estimated mg/cm ²	NSDD/ESDD estimated mg/cm ²	NSDD mg/cm ²
1	Combolcha II—Semera	0.100	6:1	0.60
2	Semera—Dicheto	0.250	7:1	1.75
3	Bahir Dar II—Debre Markos	0.040	5:1	0.20
4	Debre Markos—Sululta	0.150	6:1	0.90

6.4.2 Analysis of Service Experience of EEP's Transmission Lines in the Area

Examining the operational experience of AC overhead transmission lines alongside environmental and meteorological data provides another approach to estimate the pollution severity parameters (ESDD-NSDD) for existing transmission lines or sites adjacent to them. In this approach, the software Insulator Selection Tool (IST) is used to estimate the ESDD values, based on such factors like the actual unified specific creepage distance (USCD) and insulator length of in-service insulators, pollution and wetting events per year, actual Mean Time Between Flashover (MTBF), and generic pollution performance of the insulator type.

The illustration of this approach is presented here for the same described above two transmission lines. Fault records and the estimated number of pollution flashovers per year (2015-2022) obtained from chapters two and four are first analyzed for calculating the actual MTBF, to gauge pollution performance (Desta et al., 2024a, 2024b). The frequency of pollution accretion and wetting events for each line is determined based on meteorological and environmental analysis. Moreover, generic pollution performance curves for standard disc cap and pin porcelain/glass and long rod composite insulator types available in the IST software, which adhere to the principles of statistical insulator dimensioning outlined in (IEC/TS 60815-1, 2008), are used for reverse calculations of the estimates of minimum uniform pollution present on the insulators, considering their actual length and unified specific creepage distance. The parameters used for calculations in the IST software are outlined in Table 15. Since actual faults records were not available, MTBF for substations was assumed to be equal to their service life.

Table 15 Input parameters used for calculations of ESDD in the IST program.

Line	Parameters									
	Max system voltage (kV)	Altitude (m)	Number of Insulators	Calculated MTBF (Years)	Estimated Pollution/critical wetting events per year	Representative Pollution Test	Type of Insulator	Minimum creepage distance (mm)	USCD (mm/kV)	Insulator length (m)
Combolcha II—Semera	245	663	1275	0.103	120	Solid Layer AC	Long rod composite	5040	36	2.24
Semera—Dicheto	245	383	414	0.222	80	Solid Layer AC	Long rod composite	5040	36	2.24
Bahir Dar II—Debre Markos	420	2393	2562	0.173	84	Solid Layer AC	Cap and pin glass insulator string	8740	36	4.58
Debre Markos—Sululta	420	3138	5568	0.308	74	Solid Layer AC	Cap and pin glass insulator string	8740	36	4.58

Using the input parameters described above, the IST estimates yielded ESDD values at NSDD equal to 0.1 mg/cm^2 and they had to be corrected to the actual NSDD level. The corrected ESDD values for the line sections are presented in Table 16 and are considered as final output of this method.

Table 16: Summary of results from service experience analysis.

No.	Line	ESDD at NSDD=0.1 mg/cm^2	NSDD (mg/cm^2)	Corrected ESDD (mg/cm^2)
1	Combolcha II—Semera	0.431	0.60	0.182
2	Semera—Dicheto	0.438	1.75	0.11
3	Bahir Dar II—Debre Markos	0.04	0.20	0.029
4	Debre Markos—Sululta	0.029	0.90	0.010

Examples of calculations for long rod composite and standard disc cap and pin porcelain/glass insulators are illustrated in Figures 63-66. Similar calculations were performed for all 364 points used for the creation of the pollution map. Detail SPS estimation results for both approaches can be found in Appendix E.

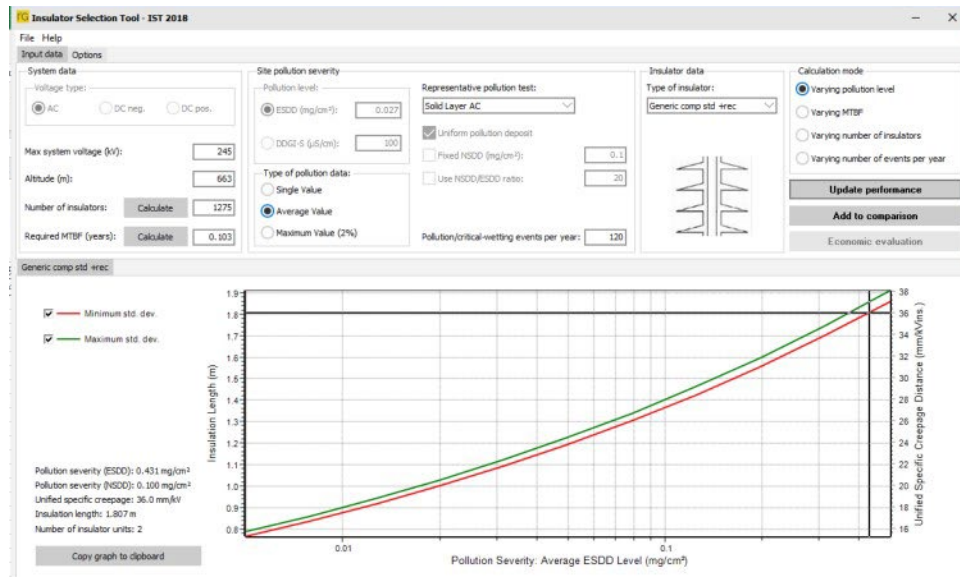


Figure 63: Example of IST calculation for long rod composite insulator (Combolcha II—Semera).

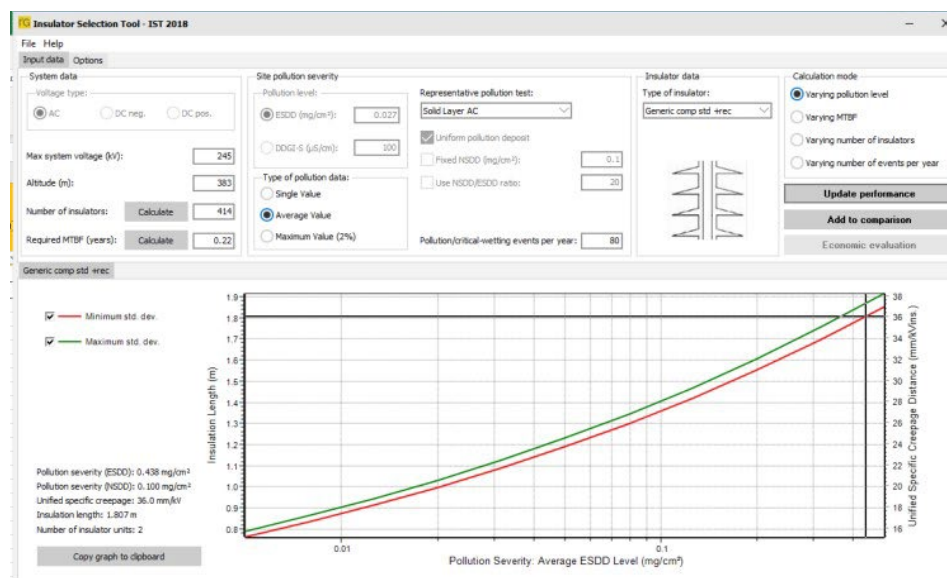


Figure 64: Example of IST calculation for long rod composite insulator (Semera—Dicheto).

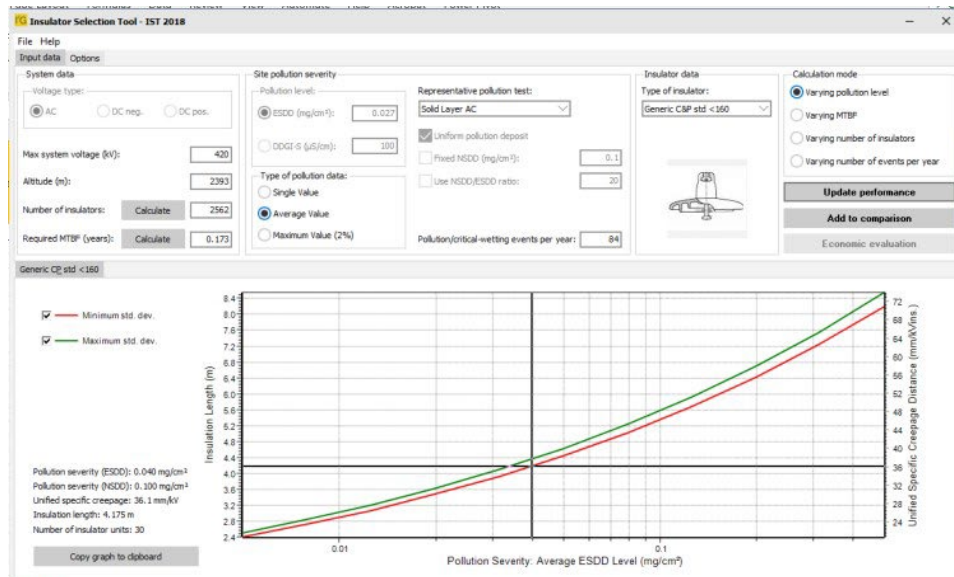


Figure 65: Example of IST calculation for cap and pin glass insulator (Bahir Dar II—Debre Markos).

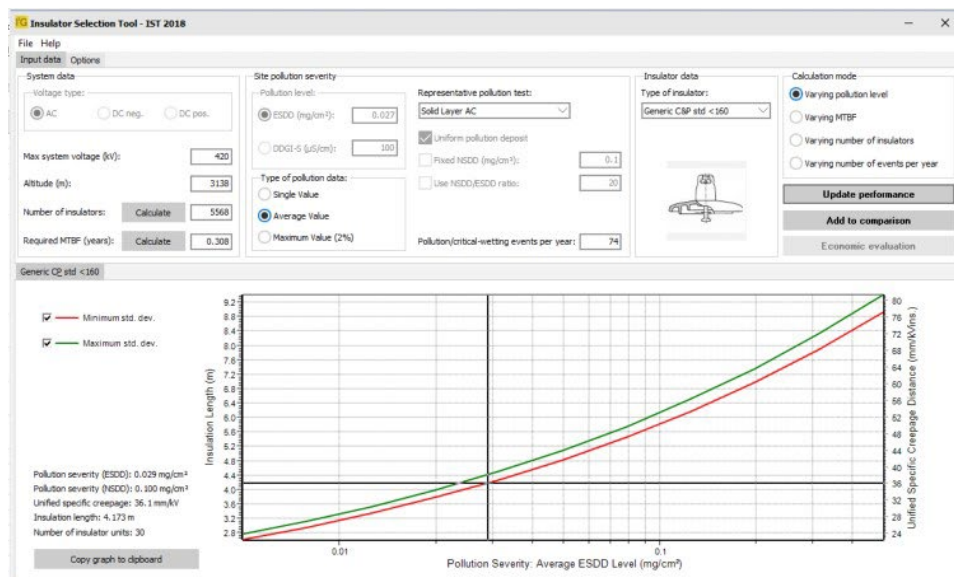


Figure 66: Example of IST calculation for cap and pin glass insulator (Debre Markos—Sululta).

The estimations of ESDD and NSDD values for each line are summarized in Table 17, detailing the results obtained from the two methods. The ESDD estimate from service experience is slightly higher, reflecting the impact of the statistical approach to reverse calculate ESDD based on pollution and wetting characteristics and past operating experience. On the contrary, the results obtained from the environmental analysis, as per (IEC/TS 60815-1, 2008), are somewhat lower and may not correspond to the highest ESDD levels, as the approach already includes uncertainties related to qualitative estimations. Given these uncertainties, the ESDD from the two approaches are averaged, slightly erring on the conservative side. This outcome likely provides a more accurate estimate of the actual maximum ESDD and NSDD levels at representative points (geographic centroids) on the route of the lines.

Table 17 Summary of ESDD-NSDD estimation from the two methods.

Lines	ESDD (mg/cm ²) Estimation from environment analysis	NSDD/ ESDD	NSDD (mg/cm ²)	ESDD (mg/cm ²) Estimation based on service experience	Corrected ESDD (mg/cm ²)	Average ESDD (mg/cm ²)	SDD (mg/cm ²)
Combolcha II—Semera	0.100	6	0.60	0.431	0.182	0.141	0.334
Semera—Dicheto	0.250	7	1.75	0.438	0.110	0.180	0.715
Bahir Dar II—Debre Markos	0.040	5	0.20	0.040	0.029	0.034	0.048
Debre Markos— Sululta	0.150	6	0.90	0.029	0.010	0.080	0.231

Supplementing the preliminary ESDD-NSDD estimations with trend indications linked to real environmental and meteorological data and by systematically analyzing the accuracy of various data sources and methodologies to infer the maximum pollution level is crucial and it allows for introducing potential correction of estimated ESDD-NSDD for each point. This is considered as an output of the pollution severity estimation process. The detailed results of the SPS estimation are presented in Appendix E.

6.5 Developing the Pollution Severity Map

After obtaining site severity estimations, in a similar procedure, for all 364 locations, the estimated ESDD-NSDD values are converted into corresponding salt deposit density (SDD) values. An SDD value represents the equivalent laboratory test severity, used in standard testing of insulators contaminated with a slurry containing the required amount of salt and 40 g/liter of kaolin, corresponding to a reference NSDD of approximately 0.1 mg/cm² (CIGRE Taskforce 33.04.01, 2000).

The SDD values of each site can be determined using the following formula (CIGRE Taskforce 33.04.01, 2000; CIGRE Working Group C4.303, 2008, 2012).

$$SDD = K_{NSDD} * ESDD \quad \text{where: } K_{NSDD} = 0.46 \quad \text{if } NSDD \leq 0.02 \text{ (mg/cm}^2\text{)}$$

$$K_{NSDD} = \left[\frac{NSDD}{0.1} \right]^{\frac{0.106}{b}} \quad \text{if } NSDD > 0.02 \text{ (mg/cm}^2\text{)}$$

$$b = 0.22$$

where K_{NSDD} is a factor to correct for NSDD to a reference value of 0.1 mg/cm² and the slope parameter b , can be estimated from published laboratory data on insulator flashover strength.

The next step is to create a point pollution map based on the SDD values. The resulting map, shown in Figure 67, illustrates the geographic distribution of the sites considered for severity estimation and their respective SDD values, representing local conditions.

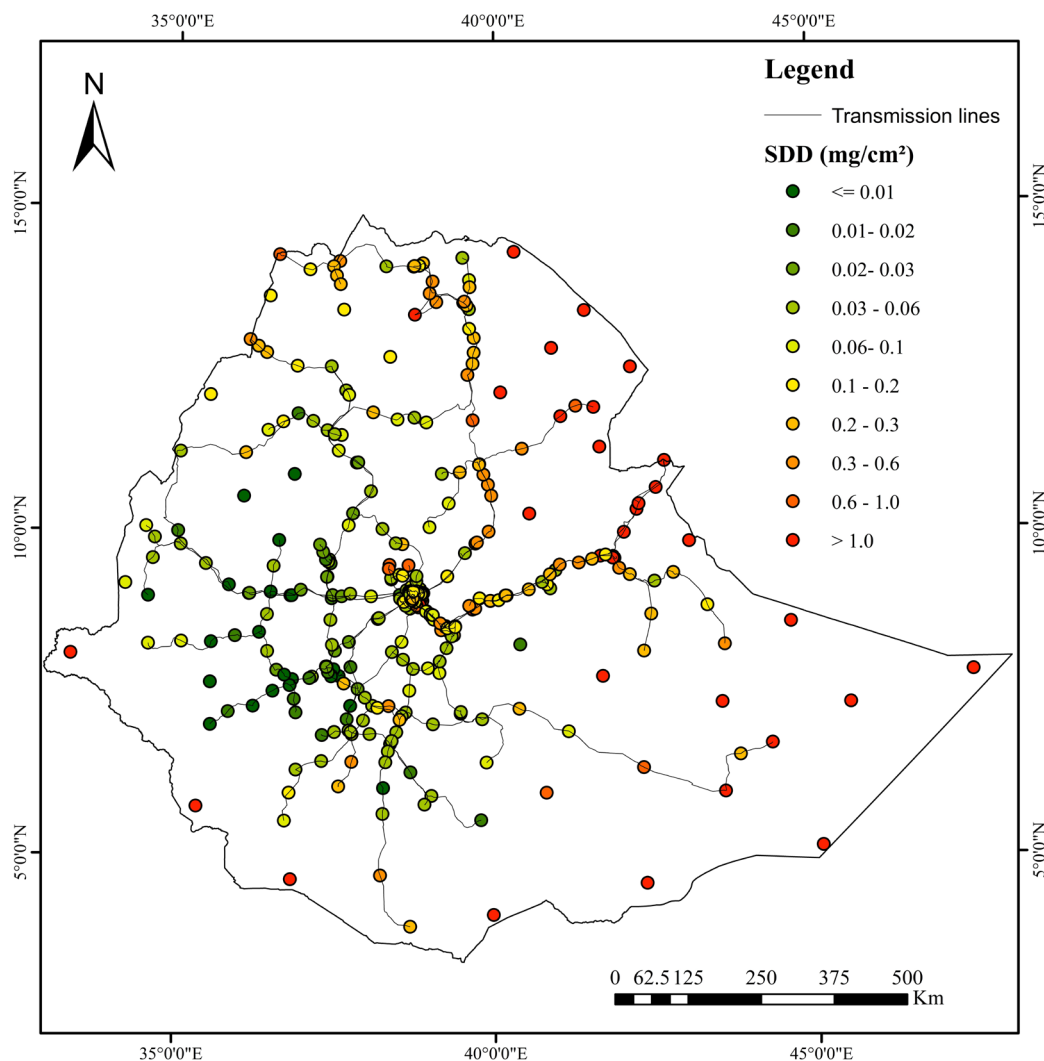


Figure 67: Representative estimation points of SDD based pollution map for Ethiopia.

By extending these SDD values of specific points/locations using Inverse Distance Weighting (IDW) algorithm, a continuous SDD pollution map is generated using ArcGIS software, which covers the entire geographical territory of Ethiopia. The generated GIS based pollution map is shown Figure 68.

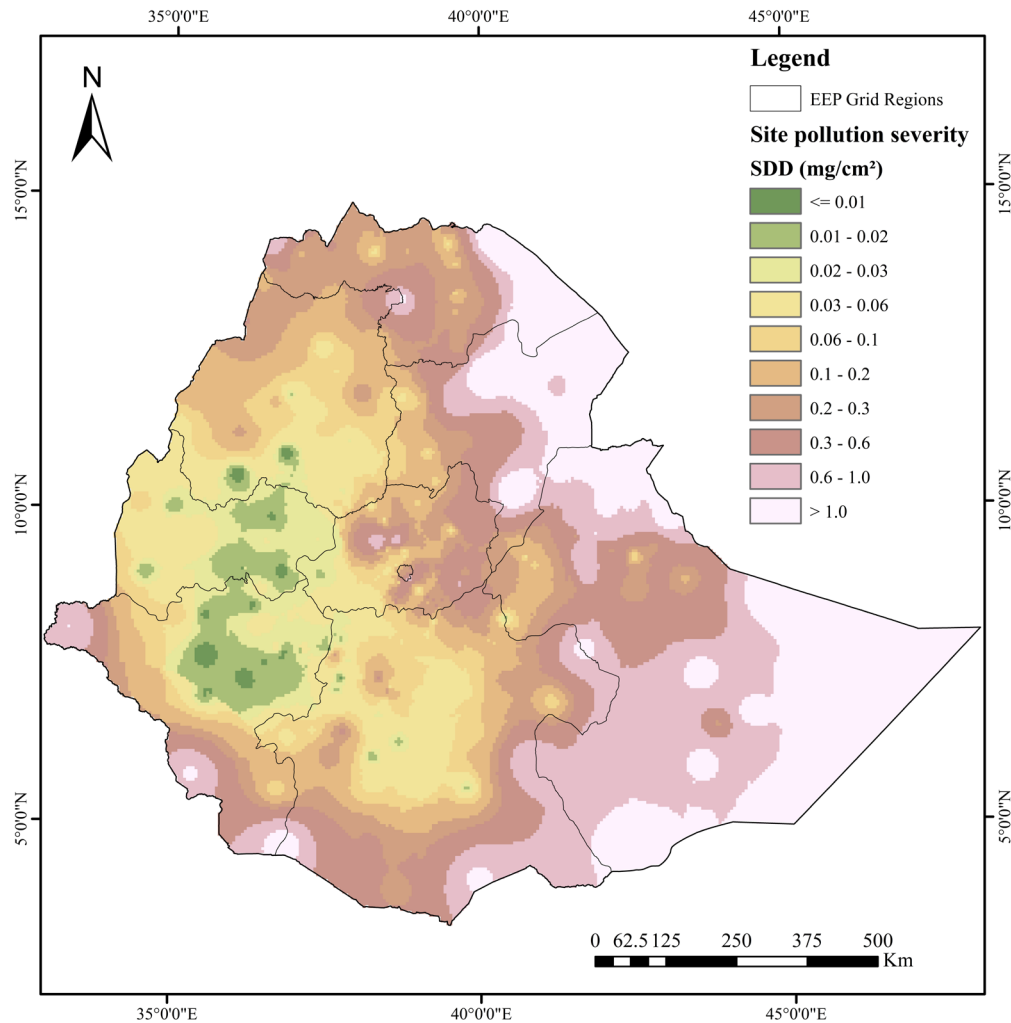


Figure 68: The generated SDD based pollution map for Ethiopia.

The final step in the mapping process involves converting the SDD map into a site pollution severity map by applying the classification criteria for the five severity classes (IEC/TS 60815-1, 2008). Figure 69 depicts the resulting pollution severity map of Ethiopia, composed of square pixels of 500 m in length. It enables to visualize the pollution severity at relatively high resolution and to extract corresponding severity parameters (SDD values) at individual transmission tower levels. All five SPS pollution classes are therefore depicted on the map, reflecting the variations in the pollution stress level for different grid regions of Ethiopia. The pollution map reveals that among operational regions of EEP, the contamination impact on insulators is considerably more severe in the North-East, East, North and Central regions than in the West and South-West grid regions.

Moreover, the map categorizes the country into five SPS classes. Inland desert and near-coastal areas, stretching from the northeast to the southeast along the Red Sea and the Arabian Sea, are classified as regions with very heavy pollution. Addis Ababa, along with some locations in central, northern, and far-southern areas, experience medium to very heavy industrial pollution levels. A mixture of agricultural areas, inland deserts, and light industrial regions in the north, northwest, central, and mid-

south are categorized as medium to heavily polluted regions. Finally, agricultural and forest areas in the west and southwest of Ethiopia, known for their long rainy seasons, are classified as having very light to light pollution levels. This classification helps in understanding and addressing the specific insulation needs of each region.

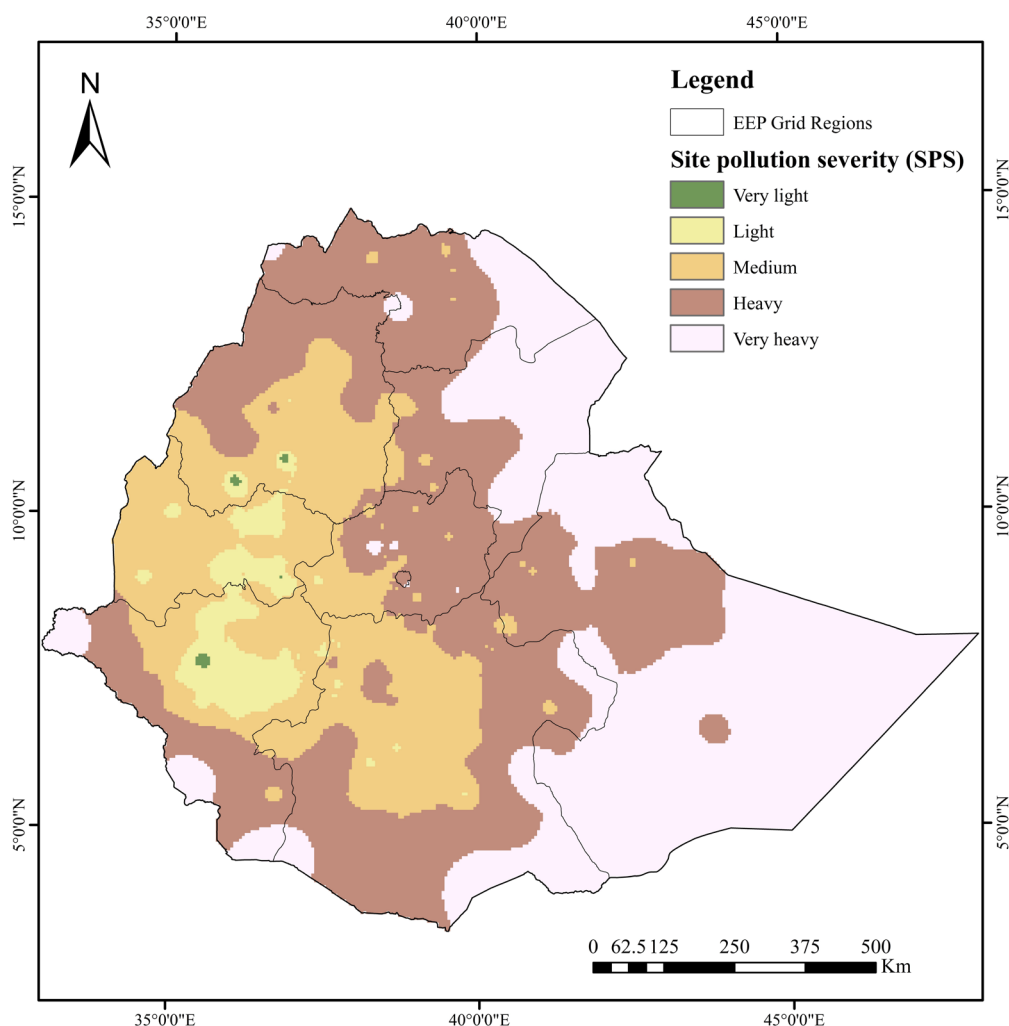


Figure 69: Ethiopian pollution severity map (2024).

Additionally, the analysis indicates that type A pollution is dominant throughout the country, except for the near coastal desert in the north, northeast, central and east regions and a few industrial areas in the central part of the country that can be characterize by a mixture of both pollution types A and B. Details of the classification results of the general types of environments, pollution types and corresponding SPS classes for each site can be found in Appendix E.

The pollution map of Ethiopia, depicted in Figure 69, is so far initial in its character. It has been derived from analyzing various topographical, climatic, and environmental factors related to insulator pollution and historical operational service experience of EEP network. However, these results should be further verified and supplemented with field measurements and continuously updated information within the system.

This developed approximate map serves as an initial step towards developing a more detailed map and requires validation and refinement through comparisons with ESDD and NSDD measurements, which will be obtained from field test and monitoring stations located near high-voltage infrastructures. However, the level of detail in the map enables a strong correlation between the locations of transmission lines and substations and the pollution severity parameter outlined in the map.

This pollution severity map allows EEP to identify regions with high pollution severities and visualize varying pollution levels across areas. This helps prioritize resources and maintenance efforts, focusing on areas most at risk for pollution-induced flashovers. Moreover, it informs targeted maintenance activities, such as regular cleaning and inspections in high-pollution areas, minimizing the risk of flashovers and reducing the likelihood of power outages. By providing detailed data on local pollution characteristics, the map guides the selection and dimensioning of insulators with materials and designs best suited to the specific environmental challenges of each region. This enhances insulator resilience and operational lifespan.

Beyond immediate maintenance and design applications, the pollution map allows for a standardized approach to classifying pollution severity (SPS class) across regions, ensuring consistent maintenance practices and operational guidelines. It plays a key role in planning new transmission lines or substations, by providing insights into expected pollution levels, allowing engineers to design infrastructure that is resilient to local environmental conditions. Moreover, the map will also enable to perform representative pollution withstand voltage and performance tests for candidate insulator during project works.

The data from the map allows for continuous monitoring of pollution trends, enabling EEP to adapt maintenance and operational strategies to changing environmental conditions and pollution levels over time. By understanding long-term pollution trends, EEP can make informed decisions about infrastructure investments, upgrades, and policy adjustments, supporting the development of a more resilient power grid. Ultimately, pollution severity mapping enhances understanding of pollution's effects on transmission lines and informing best practices for pollution management, providing EEP with a robust foundation for managing pollution-related risks proactively and making power systems more reliable, adaptable, and capable of meeting future environmental and operational challenges.

With these key elements implemented, it is expected that frequent large-scale pollution flashover outages will be effectively prevented, trip-out rates from pollution flashover in EEP network will be greatly reduced, and the reliability of the entire system will be improved. Therefore, this work marks the initial step in a comprehensive journey towards effectively managing the impact of insulator pollution in the Ethiopian power system reliability.

CHAPTER 7

7. Conclusions

7.1 Summary and Conclusions

This study analyzed 8,891 fault records in the Ethiopian electric power system from 2015 to 2022. The results revealed that approximately 47% of these faults had no identified cause, a rate significantly exceeding the internationally accepted threshold for unexplained outages. The study then classified unexplained faults analyzing environmental and contextual fault features such as local climate and pollution levels, fault time stamp, and locations and developed criteria to differentiate between pollution-induced and other environmental causes. This approach identified pollution as a significant factor, attributing 27% of these faults to pollution-related causes, followed by lightning (19%), fire-related issues (11%), and other external interferences (43%). The classification offers a clear picture of the environmental stressors impacting EEP's transmission network and provides insights into the most vulnerable sections of the grid, as well as the lines experiencing the most frequent faults. These findings lay a foundation for future targeted interventions in network design and maintenance to better manage these issues.

Building upon these findings, the study critically assessed EEP's current practices for selecting, dimensioning, and maintaining outdoor insulators. The analysis revealed that high-voltage insulator selection lacked a standardized methodology informed by site-specific pollution severity data that accounts for local environmental conditions or historical performance insights, leading to inconsistent practices.

These gaps often resulted in premature insulator failures, increased maintenance costs, and reduced network reliability. In response, this research developed a framework for classifying environmental pollution levels across Ethiopia, considering factors such as pollution types, sources, and local meteorological conditions. The classification scheme was then used for the development of an estimated pollution severity map, which offers a crucial tool for determining site-specific insulator requirements based on pollution severity. The findings suggest that if insulator selection does not consider these localized conditions, pollution-related flashovers could become more frequent. Consequently, this study strongly recommends that EEP adopt a more systematic approach to insulation practices to address the challenges posed by pollution-related outages effectively.

A major contribution of this research is its detailed analysis of pollution-induced flashover events on insulators, identified as a substantial cause of unexplained outages. A detailed and refined methodology was developed to identify faults caused by insulator pollution flashover, that associate

fault characteristics with local meteorological and environmental conditions. Results revealed that approximately 24.7% of the previously unexplained faults likely stemmed from pollution-related flashovers, particularly in desert areas and regions with high particulate matter (PM) density. These findings underscore that pollution-related outages within the Ethiopia transmission network occur at rates significantly above internationally acceptable standards, reinforcing the need for proactive mitigation measures to safeguard the stability and reliability of the power system.

The study also indicated that porcelain insulators being the most affected by pollution-related issues. The performance of silicone rubber insulators, which are widely considered more resilient to environmental stress, was also found to be unsatisfactory under Ethiopia conditions. This finding shows that even advanced insulation materials for high-voltage transmission lines require careful selection and dimensioning based on detailed knowledge of local environmental conditions and pollution levels. The research highlighted the need for improved monitoring of pollution levels across the country to mitigate the risk of future flashover events.

To address pollution-related challenges, the study developed a methodology for mapping pollution severity across Ethiopia based on estimated site pollution severity and PM_{2.5} density data obtained from satellite sources. Recognizing the rising PM_{2.5} levels in certain areas, the study created a PM_{2.5} density distribution map that correlates pollution hotspots with transmission lines and substations, equipping EEP engineers and planners with vital information for insulator selection and dimensioning. This map, however, requires validation through ground-based measurements due to inherent errors associated with satellite data, underscoring the need for dedicated monitoring stations to capture pollution severity data with higher precision.

In the final phase, site pollution severity parameters, including Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD), were estimated at carefully selected sites to generate a GIS-based pollution severity map. This map integrates multiple data sources, including satellite-derived PM_{2.5} density, meteorological, climate and environmental records, topography, and land use data, alongside operational experiences from existing transmission lines. The result is a detailed visual representation of pollution severity across different regions of Ethiopia, offering a practical resource for planning the insulation requirements of future transmission and substation projects. By revealing localized pollution variations and identifying high-risk regions, the GIS-based pollution severity map also facilitates predictive maintenance and resource optimization, particularly in high-severity pollution areas, thereby reducing the frequency and impact of flashovers and subsequent power outages.

Beyond immediate maintenance optimization, the map provides an invaluable tool for EEP engineers and maintenance teams, enabling more accurate insulator selection, targeted inspections, and predictive maintenance strategies tailored to various grid regions. The study presents more cost-effective and time-saving methods for estimating site pollution severity and mapping pollution levels. These approaches provide estimations with acceptable technical accuracy, particularly valuable in situations where measured pollution severity data are unavailable, or when conducting long-term field measurement campaigns are technically impractical or financially unfeasible. Despite the limitations associated with input data accuracy, this map marks a significant step forward in proactive pollution management for Ethiopia's transmission network, enabling utilities to anticipate and mitigate pollution-related issues before they lead to widespread outages in the face of ever-changing environmental conditions.

In summary, this research introduces several key contributions that significantly advance the understanding of unexplained faults in power transmission lines and pollution-related issues affecting high-voltage insulators, particularly in the context of Ethiopia's unique environmental conditions. It provides EEP with actionable tools and a strategic framework to manage environmental impacts on its power systems. The findings have broad implications, offering valuable insights for policymakers, planners, and operators in creating more stable, efficient, and sustainable power infrastructure within Ethiopia. Additionally, these insights can also guide power systems in other pollution-prone regions, contributing to sustainable energy security.

7.2 Limitations of the Research and Directions for Future Work

While this study offers valuable insights into the challenges posed by pollution-induced insulation issues within Ethiopia's power transmission network, certain limitations should be acknowledged, providing directions for future research. One limitation lies in the lack of complete fault voltage and current waveform data linked to the fault's root cause. This deficiency restricted fault classification to contextual features alone, which complicates the use of advanced methods, such as machine learning, for automating fault classification. Therefore, it is recommended that EEP improve its fault data recording practices by capturing detailed root cause information and waveform data while adhering to standardized formats. Future efforts should consider developing advanced classification algorithms that integrate both contextual features and waveform data to improve the accuracy of fault diagnostics and classification.

This study focused on transmission voltages between 132 and 400 kV, excluding both the newer 500 kV and HVDC lines and lower-voltage distribution lines (≤ 66 kV) due to data availability limitations. Future research should consider expanding the analysis across a broader voltage range, which would

provide a more comprehensive understanding of pollution-related insulation issues across Ethiopia's entire power grid.

Moreover, the study's reliance on satellite-derived pollution data, specifically PM_{2.5} density estimates, introduced some inherent inaccuracies. While satellite data was essential for creating the pollution severity map, validation through ground-based measurements is necessary to confirm its accuracy. Establishing localized environmental monitoring stations would improve data reliability, providing real-time insights into pollution levels near critical transmission sites.

In terms of the GIS-based pollution severity map, further work is needed to refine it through regular, field-based measurements of Equivalent Salt Deposit Density (ESDD) and Non-Soluble Deposit Density (NSDD), complemented by PM_{2.5} and PM₁₀ density readings. A dedicated network of ground-based meteorological and environmental monitoring and measurement stations would significantly enhance the reliability of pollution density data, thus improving the precision of pollution severity estimations and predictions. Finally, the static nature of the pollution severity map limits its adaptability for real-time decision-making and forecasting. Future research could prioritize the development of a dynamic mapping tool that integrates real-time pollution data and predictive capabilities.

References

- Abebe, D. (2010). Future Climate of Ethiopia from PRECIS Regional Climate Model Experimental Design Ethiopia. Climate Strategies Forum, November 2010. Available online: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/applied-science/precis/precis_experimental_design_dawit.pdf (accessed on 18 April 2022).
- Abouelsaad, M. A., Abouelatta, M. A., Arafa, B., & Ibrahim, M. E. (2013,). Environmental pollution effects on insulators of northern Egypt HV transmission lines. 20-23 Oct. 2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena,
- ACAG. (2024). *Atmospheric Composition Analysis Group (ACAG): Satellite-derived PM2.5*. Available at: [https:// sites.wustl.edu/acag/datasets/surface-pm2-5/](https://sites.wustl.edu/acag/datasets/surface-pm2-5/)
- Al-Hamoudi, I. Y., & Al-Hamouz, Z. M. (2003). Reliability and cost effectiveness of silicone rubber insulators in the eastern coastal industrial area of Saudi Arabia. 2003 IEEE 10th International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance, 2003. 2003 IEEE ESMO., 6-10 April 2003.
- Al-Mubarak, A. H., Ardito, A., Banchi, I., & Pigini, A. (2022). Designing Insulators for 600 kV DC Lines in Harsh Desert Environment. In Proceedings of the INMR World Congress,
- Alam, M., Mishra, B., & Thakur, S. S. (2018, 1-3 March 2018). Assessment of the Impact of Line Outage in Modern Power System. 2018 International Conference on Current Trends towards Converging Technologies (ICCTCT),
- Ambade, B., Sankar, T. K., Sahu, L. K., & Dumka, U. C. (2022). Understanding Sources and Composition of Black Carbon and PM2.5 in Urban Environments in East India. *Urban Science*, 6(3).
- Asefa, M., Cao, M., He, Y., Mekonnen, E., Song, X., & Yang, J. (2020). Ethiopian vegetation types, climate and topography. *Plant Diversity*, 42(4), 302-311. <https://doi.org/https://doi.org/10.1016/j.pld.2020.04.004>
- Baker, A. C., Farzaneh, M., Gorur, R. S., Gubanski, S. M., Hill, R. J., Karady, G. G., & Schneider, H. M. (2009). Insulator Selection for AC Overhead Lines With Respect to Contamination. *IEEE Transactions on Power Delivery*, 24(3), 1633-1641. <https://doi.org/10.1109/TPWRD.2009.2024666>
- Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, 5(1), 180214. <https://doi.org/10.1038/sdata.2018.214>
- Bekker, H. J. J., & Hoch, D. A. (2002). Analysis of factors contributing to unexplained transmission line faults on a high voltage transmission network. IEEE AFRICON. 6th Africon Conference in Africa, 2-4 Oct. 2002.
- Benguesmia, H., M'Ziou, N., & Boubakeur, A. (2015). AC Flashover: An Analysis with Influence of the Pollution, Potential and Electric Field Distribution on High Voltage Insulator. Multiphysics Modelling and Simulation for Systems Design and Monitoring, Cham.
- Berhanu, B., Seleshi, Y., & Melesse, A. M. (2014). Surface Water and Groundwater Resources of Ethiopia: Potentials and Challenges of Water Resources Development. In A. M. Melesse, W. Abtew, & S. G. Setegn (Eds.), *Nile River Basin: Ecohydrological Challenges, Climate Change and Hydropolitics* (pp. 97-117). Springer International Publishing. https://doi.org/10.1007/978-3-319-02720-3_6

- Bevanger, K. (1994). Bird interactions with utility structures: collision and electrocution, causes and mitigating measures. *Ibis*, 136(4), 412-425. <https://doi.org/https://doi.org/10.1111/j.1474-919X.1994.tb01116.x>
- Bin, S., Koval, D., Wilsun, X., Salmon, J., & Shen, S. (1998). An analysis of extreme-weather-related transmission line outages. Conference Proceedings. IEEE Canadian Conference on Electrical and Computer Engineering (Cat. No.98TH8341), 25-28 May 1998.
- Bin, X. (2010). Lightning Fault Location and Recognition Technologies in Transmission Line. *High Voltage Engineering*.
- BirdLife. (2024). *BirdLife International (2024) Country profile: Ethiopia*. Retrieved 19 July 2024 from <https://datazone.birdlife.org/country/ethiopia>
- Borck, R., & Schrauth, P. (2021). Population density and urban air quality. *Regional Science and Urban Economics*, 86, 103596. <https://doi.org/https://doi.org/10.1016/j.regsciurbeco.2020.103596>
- Brauer, M., Freedman, G., Frostad, J., van Donkelaar, A., Martin, R. V., Dentener, F., Dingenen, R. v., Estep, K., Amini, H., Apte, J. S., Balakrishnan, K., Barregard, L., Broday, D., Feigin, V., Ghosh, S., Hopke, P. K., Knibbs, L. D., Kokubo, Y., Liu, Y.,...Cohen, A. (2016). Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013. *Environmental Science & Technology*, 50(1), 79-88. <https://doi.org/10.1021/acs.est.5b03709>
- Burnham, J. T. (1995). Bird streamer flashovers on FPL transmission lines. *IEEE Transactions on Power Delivery*, 10(2), 970-977. <https://doi.org/10.1109/61.400832>
- CFSR. (2019). *Climate Forecast System Reanalysis: Global Weather Data*. Retrieved 12 April 2019) from <https://globalweather.tamu.edu/>
- Chao, Y., Xin, S., Haiyan, Y., Yangyang, L., Wanjie, Z., & Xin, W. (2017, 2017/12). Automatic Diagnosis Technology of Lightning Fault in Transmission Line. Proceedings of the 2017 2nd International Conference on Electrical, Control and Automation Engineering (ECAE 2017),
- Che, C., Yan, B., Zhao, J., Zhao, J., Zhao, Z., & Zhu, X. (2024, 2024//). Analysis on the Pollution Flashover Cause of Transmission Line Insulators in Inner Mongolia. 2023 International Conference on Energy Engineering, Singapore.
- Chen, B. (2020). Fault Statistics and Analysis of 220-kV and Above Transmission Lines in a Southern Coastal Provincial Power Grid of China. *IEEE Open Access Journal of Power and Energy*, 7, 122-129. <https://doi.org/10.1109/OAJPE.2020.2975665>
- Chisholm, W. A. (2019a, 20–23 October 2019). Dust and Sea Salt Pollution Mapping: Satellite versus Ground truth results. In Proceedings of the INMR World Congress 2019, Arizona, USA, Arizona, USA.
- Chisholm, W. A. (2019b). Non-Soluble Surface Deposits on Insulators, . INMR World Congress 2019,
- CIESIN, & CIAT. (2019). *Global Gridded Population Database*. Center for International Earth Science Network (CIESIN) at Columbia University and International Center for Tropical Agriculture (CIAT). Retrieved 21 August, 2029 from <http://sedac.ciesin.columbia.edu/data/collection/gpw-v4>
- CIGRE Taskforce 33.04.01. (2000). Polluted Insulators: A Review of Current Knowledge. In *CIGRE Technical Publication 158*. Paris, France, 2000: CIGRE.
- CIGRE Working Group 33.04. (1979). The Measurement of Site Pollution Severity and its Application to Insulator Dimensioning for AC Systems. *Electra No. 64*, p. 101 - 116.

- CIGRE Working Group C4.303. (2008). Outdoor Insulation in Polluted Conditions: Guidelines for Selection and Dimensioning—Part 1: General Principles and the a.c. Case. In *CIGRE Technical Publication 361*. Paris, France, 2008: CIGRE.
- CIGRE Working Group C4.303. (2012). Outdoor insulation in polluted conditions: Guidelines for selection and dimensioning: Part 2: The DC case. In *Technical Brochure No. 518*. Paris, France: CIGRE.
- CSA. (2013). *Central Statistical Agency, Population Projections for Ethiopia: 2007- 2037*.
- Danek, T., Weglinska, E., & Zareba, M. (2022). The influence of meteorological factors and terrain on air pollution concentration and migration: a geostatistical case study from Krakow, Poland. *Scientific Reports*, 12(1), 11050. <https://doi.org/10.1038/s41598-022-15160-3>
- Denis, J., & Schrorch, J. (1981). Continuous measurement method of the site pollution severity and its use for insulator dimensioning. International Conference on large HV electrical system, Stockholm.
- Desta, Z. B., & Wogari, M. M. (2020). Assessment of external insulation problems related to pollution and climatic conditions in Ethiopia. *IEEE Electrical Insulation Magazine*, 36(4), 36-46. <https://doi.org/10.1109/MEI.2020.9111098>
- Desta, Z. B., Wogari, M. M., & Gubanski, M. S. (2024a). Analyses of unexplained faults in transmission lines in the power grid of Ethiopia. *Electric Power Systems Research*, 231, 110293. <https://doi.org/10.1016/j.epsr.2024.110293>
- Desta, Z. B., Wogari, M. M., & Gubanski, M. S. (2024b). Investigation on Pollution-Induced Flashovers of In-Service Insulators in Ethiopian Power Transmission Lines. *Energies*, 17(9).
- Dimitropoulou, M., Siderakis, K., Pylarinos, D., Thalassinakis, E., & Danikas, M. G. (2015, 19-22 July 2015). Insulation coordination and pollution measurements in the island of Crete. 2015 IEEE 11th International Conference on the Properties and Applications of Dielectric Materials (ICPADM),
- Ding, Y., Zhou, J., Li, C., Liu, G., Wang, H., Yao, X., Wang, X., & Wang, S. (2021). Bird-related fault analysis and prevention measures of ± 400 kV Qinghai-Tibet DC transmission line. *Energy Reports*, 7, 426-433. <https://doi.org/https://doi.org/10.1016/j.egyr.2021.08.022>
- EEP. (2020). Ethiopian Electric Power (EEP): National grid Load Dispatch Center (LDC): Transmission lines operational report from July 2018 to January 2020. In.
- EEP. (2022). Ethiopian Electric Power (EEP): 132 kV and above transmission lines operational and fault data from 2015 to 2022. In.
- Ethiopian sugar Industry Group. (2024). *Ethiopian sugar Industry Group*: <https://etsugar.com/esig/>. Retrieved 19 June 2024 from <https://etsugar.com/esig/>
- Feilat, E. A., & Al-Maqrashi, A. (2011, 19-22 Feb. 2011). ESDD- and DDDG-based assessment of insulator pollution levels in Oman. 2011 IEEE GCC Conference and Exhibition (GCC),
- Fernando, M. A. R. M. (1999). *Performance of Non-Ceramic Insulators in Tropical Environments* PhD Thesis, Chalmers University of Technology. Sweden.
- Fernando, M. A. R. M., & Gubanski, S. M. (2000). Performance of nonceramic insulators under tropical field conditions. *IEEE Transactions on Power Delivery*, 15(1), 355-360. <https://doi.org/10.1109/61.847273>
- Fontana, E., Oliveira, S. C., Cavalcanti, F. J. M. M., Lima, R. B., Martins-Filho, J. F., & Meneses-Pacheco, E. (2006). Novel sensor system for leakage current detection on insulator strings of

- overhead transmission lines. *IEEE Transactions on Power Delivery*, 21(4), 2064-2070. <https://doi.org/10.1109/TPWRD.2006.877099>
- Geissler, S., Hagauer, D., Horst, A., Krause, M., & Sutcliffe, P. (2013). Biomass energy strategy Ethiopia. *Ethiopia Ministry of Water and Energy and European Union Energy Initiative (EUEI)*.
- Global Forest Watch, W. R. I. (2024). *Location of tree cover loss in Ethiopia*. Available: www.globalforestwatch.org. Retrieved 18, August 2024 from Available: www.globalforestwatch.org
- Global Wind Atlas. (2021). *Global Wind Atlas, Ethiopia: Mean Wind Speed. 2021*. Available: <https://globalwindatlas.info/en/area/Ethiopia>. Retrieved 18, August 2024 from <https://globalwindatlas.info/en/area/Ethiopia>
- Gubanski, S. M. (2005). Modern outdoor insulation - concerns and challenges. *IEEE Electrical Insulation Magazine*, 21(6), 5-11. <https://doi.org/10.1109/MEI.2005.1541483>
- Gutman, I., Ahlholm, C., Halsan, K., Eide, R., Carlshem, L., Vosloo, W. L., & Goffinet, J.-F. (2014). Application of weather models for the evaluation of design ESDD for harsh pollution conditions. CIGRE Session Paris, France.
- Gutman, I., Ahlholm, C., Halsan, K., Thorsteinsson, B., Radosavljevic, M., Rezaei, K., Varli, K., Vosloo, W., Wagner, A., & Wesley, R. (2022). Development of IEC-Based Methodology for Site Severity Assessment. In Proceedings of the INMR World Congress, Berlin, Germany.
- Gutman, I., Ahlholm, C., Thorsteinsson, B., & Halsan, K. (2016, May 9-11, 2016). *Optimal selection of insulation for Nord Link ±525 kV DC transmission line in Norway* CIGRE-IEC Colloquium, Montréal, QC, Canada.
- Gutman, I., C.Ahlholm, Halsan, K., & Thorsteinsson, B. (2023, 12–15 November 2023). Advanced Pollution Modeling on Insulators: Verification by Direct Measurements & Service Experience. In Proceedings of the INMR World Congress 2023, Bangkok, Thailand, 12–15 November 2023, Bangkok, Thailand.
- Gutman, I., & Lundquist, J. (2011, 17-20 April 2011). Optimization of AC and DC Insulation Using Software for Statistical Dimensioning. World Congress & Exhibition on Insulators, Arresters & Bushings, Seoul, Korea.
- Hammer, M. S., van Donkelaar, A., Li, C., Lyapustin, A., Sayer, A. M., Hsu, N. C., Levy, R. C., Garay, M. J., Kalashnikova, O. V., Kahn, R. A., Brauer, M., Apte, J. S., Henze, D. K., Zhang, L., Zhang, Q., Ford, B., Pierce, J. R., & Martin, R. V. (2020). Global Estimates and Long-Term Trends of Fine Particulate Matter Concentrations (1998–2018). *Environmental Science & Technology*, 54(13), 7879-7890. <https://doi.org/10.1021/acs.est.0c01764>
- Hamza, A. H., Ghania, S. M., Emam, A. M., & Shafy, A. S. (2019). Failure risk analysis under switching surges in power transmission systems. *Electric Power Systems Research*, 166, 190-198. <https://doi.org/https://doi.org/10.1016/j.epsr.2018.10.010>
- Han, S., & Sun, B. (2019). Impact of Population Density on PM2.5 Concentrations: A Case Study in Shanghai, China. *Sustainability*, 11(7).
- Hathout, I., & Callery, K. (2015). Impact of Extreme Weather on Transmission Line Structures. *Electrical Transmission and Substation Structures* 2015, 550-564. <https://doi.org/doi:10.1061/9780784479414.044> (Proceedings)

- He, J., Wang, X., Yu, Z., & Zeng, R. (2015). Statistical Analysis on Lightning Performance of Transmission Lines in Several Regions of China. *IEEE Transactions on Power Delivery*, 30(3), 1543-1551. <https://doi.org/10.1109/TPWRD.2014.2363122>
- Herman, R., & Gaunt, T. (2010, 14-17 June 2010). Probabilistic interpretation of customer interruption cost (CIC) applied to South African systems. 2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems,
- Hu, Y. (2007). Analysis on operation faults of transmission line and countermeasures. *Gaodianya Jishu/ High Voltage Engineering*, 33(3), pp.1-8.
- IEC/TS 60815-1. (2008). Selection and Dimensioning of High-Voltage Insulators Intended for Use in Polluted Conditions—Part 1: Definitions, Information and General Principles. In. Geneva, Switzerland: International Electrotechnical Commission.
- IEC/TS 60815-4. (2016). Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 4: Insulators for d.c. systems. In. Geneva, Switzerland: International Electrotechnical Commission.
- IEC/TS 60815–2. (2008). Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 2:
Ceramic and glass insulators for a.c. systems. In. Geneva, Switzerland: International Electrotechnical Commission.
- IEC/TS 60815–3. (2008). Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 3:
Polymer insulators for a.c. systems. In. Geneva, Switzerland: International Electrotechnical Commission.
- Janssen, N. A. H., Fischer, P., Marra, M., Ameling, C., & Cassee, F. R. (2013). Short-term effects of PM_{2.5}, PM₁₀ and PM_{2.5–10} on daily mortality in the Netherlands. *Science of The Total Environment*, 463-464, 20-26. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2013.05.062>
- Jean, C., & Weiser, R. (2022, 25-28 April 2022). Transmission Line and Substation Insulators Asset Health and Preventive Maintenance. 2022 IEEE/PES Transmission and Distribution Conference and Exposition (T&D),
- Jenkins, N., & Ekanayake, J. (2017). *Renewable Energy Engineering*. Cambridge University Press. <https://doi.org/DOI: 10.1017/9781139236256>
- Jian, S., Peng, X., Yuan, H., Lai, C. S., & Lai, L. L. (2021). Transmission Line Fault-Cause Identification Based on Hierarchical Multiview Feature Selection. *Applied Sciences*, 11(17).
- Jiang, Y., McMeekin, S. G., Reid, A. J., Nekahi, A., Judd, M. D., & Wilson, A. (2016, 19-22 June 2016). High voltage insulator contamination level online monitoring with conventional and novel methods. 2016 IEEE Electrical Insulation Conference (EIC),
- José A. Ramos Hernanz, José Joaquín Campayo Martín, Joseba Motrico Gogeochea, & Belver, I. Z. (2006). Insulator pollution in transmission lines. *Renewable energy & power quality journal*.
- Khan, M. F., Shirasuna, Y., Hirano, K., & Masunaga, S. (2010). Characterization of PM_{2.5}, PM_{2.5–10} and PM_{>10} in ambient air, Yokohama, Japan. *Atmospheric Research*, 96(1), 159-172. <https://doi.org/https://doi.org/10.1016/j.atmosres.2009.12.009>
- Kleinmans, K. (2005). *Investigation into Possible Mechanisms of Light Pollution Flashover of 275kV Transmission Lines as a Cause of Unknown Outages* Master's Thesis, University of Stellenbosch. Stellenbosch, South Africa.

- Koval, D. O., & Chowdhury, A. A. (2005, 16-16 June 2005). An investigation into extreme-weather-caused transmission line unavailability. IEEE Power Engineering Society General Meeting, 2005,
- Kumara, S., & Fernando, M. (2020). Performance of outdoor insulators in tropical conditions of Sri Lanka. *IEEE Electrical Insulation Magazine*, 36(4), 26-35. <https://doi.org/10.1109/MEI.2020.9111097>
- Kumie, A., Worku, A., Tazu, Z., Tefera, W., Asfaw, A., Boja, G., Mekashu, M., Siraw, D., Teferra, S., Zacharias, K., Patz, J., Samet, J., & Berhane, K. (2021). Fine particulate pollution concentration in Addis Ababa exceeds the WHO guideline value: Results of 3 years of continuous monitoring and health impact assessment. *Environmental Epidemiology*, 5(3). https://journals.lww.com/environepidem/fulltext/2021/06000/fine_particulate_pollution_concentration_in_addis.10.aspx
- Lambeth, P. J. (1971). Effect of pollution on high-voltage outdoor insulators. *Proceedings of the Institution of Electrical Engineers*, 118(9R), 1107-1130. <https://digital-library.theiet.org/content/journals/10.1049/piee.1971.0245>
- Landegren, F., Johansson, J., & Samuelsson, O. (2019). Quality of supply regulations versus societal priorities regarding electricity outage consequences: Case study in a Swedish context. *International Journal of Critical Infrastructure Protection*, 26, 100307. <https://doi.org/https://doi.org/10.1016/j.ijcip.2019.100307>
- Lawton, P. T. (1996, 16-18 April 1996). Costing of transmission outages. Fourth International Conference on Power System Control and Management (Conf. Publ. No. 421),
- Li, J., Sun, C., Sima, W., Yang, Q., & Hu, J. (2010). Contamination Level Prediction of Insulators Based on the Characteristics of Leakage Current. *IEEE Transactions on Power Delivery*, 25(1), 417-424. <https://doi.org/10.1109/TPWRD.2009.2035426>
- Li, K., Zhao, B., Liu, M., Wang, X., Zhang, G., & Sun, M. (2020, 12-14 June 2020). Automated Diagnosis of Lightning Faults on Transmission Lines. 2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC),
- Liang, X., Li, S., Gao, Y., Su, Z., & Zhou, J. (2020). Improving the outdoor insulation performance of Chinese EHV and UHV AC and DC overhead transmission lines. *IEEE Electrical Insulation Magazine*, 36(4), 7-25. <https://doi.org/10.1109/MEI.2020.9111096>
- Lim, C.-H., Ryu, J., Choi, Y., Jeon, S. W., & Lee, W.-K. (2020). Understanding global PM2.5 concentrations and their drivers in recent decades (1998–2016). *Environment International*, 144, 106011. <https://doi.org/https://doi.org/10.1016/j.envint.2020.106011>
- Łoboda, M., & Lenarczyk, K. (2014, 11-18 Oct. 2014). Correlation between recorded CG lightning discharges and shut-downs of selected HV overhead power transmission lines in Poland. 2014 International Conference on Lightning Protection (ICLP),
- Macey, R., Vosloo, W., & Turreil, C. d. (2004). *Environmental considerations, in: The Practical Guide to Outdoor High Voltage Insulators, Eskom Power Series* (Vol. 3). Crown Publications.
- Maehl, D. R. (1996). *Investigation of bird induced outages on Montana Power Company's 500 kV transmission lines* Master's Thesis, Montana State University. Bozeman, Montana, USA.
- Major, M. (1993). *Investigation of Contamination Flashover as a Possible Cause for Unexplained Faults on the Montana Power Company's 500 kV Transmission Lines* Master's Thesis, Montana St. University. Bozeman, Montana, USA.

- Martin, L. (2016). Transmission structure risk management. *IEEE Power and Energy Magazine*, 14(5 Supplement), 28-33. <https://doi.org/10.1109/MPAE.0.7564228>
- Marzinotto, M. (2022, 16–19 October 2022). Estimating Insulator Contamination from Site Meteorological Parameters. In Proceedings of the INMR World Congress 2022, Berlin, Germany.
- Mataveli, G. A. V., Pereira, G., Chaves, M. E. D., Cardozo, F. d. S., Stark, S. C., Shimabukuro, Y. E., Aragão, L. E. O. C., de Oliveira, G., & Chen, J. M. (2021). Deforestation and land use and land cover changes in protected areas of the Brazilian Cerrado: impacts on the fire-driven emissions of fine particulate aerosols pollutants. *Remote Sensing Letters*, 12(1), 79-92. <https://doi.org/10.1080/2150704X.2021.1875147>
- Mavrikakis, N. C., Koudoumas, E., Siderakis, K., Pylarinos, D., Thalassinakis, E., Kokkinaki, O., Klini, A., Kalpouzos, C., Polychronaki, M., & Anglos, D. (2017, 28-31 Aug. 2017). Insulators' pollution problem: Experience from the coastal transmission system of Crete. 2017 52nd International Universities Power Engineering Conference (UPEC),
- McSweeney, C., New, M., & Lizcano, G. (2012). *UNDP Climate Change Country Profiles Ethiopia*. <http://countryprofiles.geog.ox.ac.uk/>
- Minnaar, U. J., Gaunt, C. T., & Nicolls, F. (2012). Characterisation of power system events on South African transmission power lines. *Electric Power Systems Research*, 88, 25-32. <https://doi.org/https://doi.org/10.1016/j.epsr.2012.01.015>
- Minnaar, U. J., Nicolls, F., & Gaunt, C. T. (2016). Automating Transmission-Line Fault Root Cause Analysis. *IEEE Transactions on Power Delivery*, 31(4), 1692-1700. <https://doi.org/10.1109/TPWRD.2015.2503478>
- Mitchell, J. W. (2013). Power line failures and catastrophic wildfires under extreme weather conditions. *Engineering Failure Analysis*, 35, 726-735. <https://doi.org/https://doi.org/10.1016/j.engfailanal.2013.07.006>
- MoA. (2020). *Ethiopian Ministry of Agriculture (MoA): Soil pH data*. Ethiopian Ministry of Agriculture (MoA). Retrieved 17 May 2024 from <https://nsis.moa.gov.et/ethiopian-soil/>
- MoM. (2021). *Ministry of Mines and Petroleum (Ethiopia): Mining in Ethiopia- Investor Guide*. <https://www.mom.gov.et>
- MoM and World Bank. (2014). *Ministry of Mines and Development of Ethiopia and World Bank Group: Strategic Assessment of the Ethiopian Mineral Sector, Final report*
- Montoya Tena, G., Hernández C, R., & Montoya T, J. I. (2010). Failures in outdoor insulation caused by bird excrement. *Electric Power Systems Research*, 80(6), 716-722. <https://doi.org/https://doi.org/10.1016/j.epsr.2009.11.002>
- Moreira, F., Martins, R. C., Aguilar, F. F., Canhoto, A., Martins, J., Moreira, J., & Bernardino, J. (2023). Long-term management practices successfully reduce bird-related electrical faults in a transmission grid increasingly used by white storks for nesting. *Journal of Environmental Management*, 327, 116897. <https://doi.org/https://doi.org/10.1016/j.jenvman.2022.116897>
- MoWE. (2020). *Ministry of Water and Energy of Ethiopia, GIS department of Ethiopian highways and road network data*. Retrieved 12 June 2024 from <https://www.mowe.gov.et/>
- Mulatu, D., Habte, L., & Ahn, J.-W. (2018). The Cement Industry in Ethiopia. *Journal of Energy Engineering*, Vol. 27, No. 3, , pp.68-73. <https://doi.org/https://doi.org/10.5855/ENERGY.2018.27.3.068>

- Muzayanah, I. F. U., Lean, H. H., Hartono, D., Indraswari, K. D., & Partama, R. (2022). Population density and energy consumption: A study in Indonesian provinces. *Heliyon*, 8(9), e10634. <https://doi.org/https://doi.org/10.1016/j.heliyon.2022.e10634>
- Nigris, M. d. (2022, 16–19 October 2022). Impact of insulator pollution on resilience of power networks: Experience in Italy. In Proceedings of the INMR World Congress 2022, Berlin, Germany.
- Nigris, M. d. (2023, 12–15 November 2023). Monitoring and mapping the threat of surface contamination to enhance resilience of overhead transmission lines in Italy. In Proceedings of the INMR World Congress Bangkok, Thailand.
- Nigris, M. d. (2020). Impact of Climate Change on Power Systems & Electrical Insulation. In Proceedings of the INMR World Congress,
- NMA. (2010). National Meteorology Agency (NMA): Ground flash density map of Ethiopia, 1 March 2006 to 1 March 2010 (10km resolution). In.
- NMSA. (1996). *Climatic and agroclimatic resources of Ethiopia* (National meteorological services agency of Ethiopia, Meteorol. Res. Rep Ser 1, Issue.
- Novosel, D. (2013). Transmission Blackouts: Risk, Causes, and Mitigation. In M. M. Begovic (Ed.), *Electrical Transmission Systems and Smart Grids: Selected Entries from the Encyclopedia of Sustainability Science and Technology* (pp. 99-127). Springer New York. https://doi.org/10.1007/978-1-4614-5830-2_4
- O, A. d. I., & Gorur, R. S. (1998). Flashover of contaminated nonceramic outdoor insulators in a wet atmosphere. *IEEE Transactions on Dielectrics and Electrical Insulation*, 5(6), 814-823. <https://doi.org/10.1109/94.740762>
- OCHA. (2020). *United Nations Office for the Coordination of Humanitarian Affairs (OCHA), Ethiopia: Population density, People per km2 (2020)*, Available: <https://reliefweb.int/map/ethiopia/ethiopia-populationdensity>. Retrieved 18, August 2024 from Available: <https://reliefweb.int/map/ethiopia/ethiopia-populationdensity>
- Parsons Brinckerhoff, & EEP. (2014). Ethiopian Power System Expansion Master Plan Study: Transmission Planning Final Report. In (Vol. 4). Addis Ababa, Ethiopia:
- .
- Peter, L., & Vajeth, R. (2005, 11-15 July 2005). Strategies for bating enviromental influences on overhead lines to improve quality of supply. 2005 IEEE Power Engineering Society Inaugural Conference and Exposition in Africa,
- Philip, S., Martin, R. V., van Donkelaar, A., Lo, J. W.-H., Wang, Y., Chen, D., Zhang, L., Kasibhatla, P. S., Wang, S., Zhang, Q., Lu, Z., Streets, D. G., Bittman, S., & Macdonald, D. J. (2014). Global Chemical Composition of Ambient Fine Particulate Matter for Exposure Assessment. *Environmental Science & Technology*, 48(22), 13060-13068. <https://doi.org/10.1021/es502965b>
- Pigini, A. (2015). Designing Insulation for Harsh Service Environments. In Proceedings of the INMR World Congress 2015,
- Pigini, A. (2020). Optimal insulator type and dimensioning in harsh service environment. INMR World Congress 2020,

- Pons, C., & Jeanmaire, A. (2022, 16–19 October 2022). Influence of Different Pollution Sources on Performance of Insulation. In Proceedings of the INMR World Congress 2022, Berlin, Germany, 16–19 October 2022, Berlin, Germany.
- Poudineh, R., & Jamasb, T. (2017). Electricity Supply Interruptions: Sectoral Interdependencies and the Cost of Energy Not Served for the Scottish Economy. *The Energy Journal*, 38(1), 51-76. <https://doi.org/10.5547/01956574.38.1.rpou>
- Pu, Z.-h., Ruan, J.-j., Huang, D.-c., Wu, T., & Li, P. (2015). Study on the breakdown characteristics of the transmission line gap under forest fire conditions. *International Transactions on Electrical Energy Systems*, 25(11), 2731-2744. <https://doi.org/https://doi.org/10.1002/etep.1988>
- Pylarinos, D., Siderakis, K., & Thalassinakis, E. (2015). Comparative investigation of silicone rubber composite and room temperature vulcanized coated glass insulators installed in coastal overhead transmission lines. *IEEE Electrical Insulation Magazine*, 31(2), 23-29. <https://doi.org/10.1109/MEI.2015.7048134>
- Radosavljevic, M., Lindquist, T., Gutman, I., & Dernfalk, A. (2016 May 9-11, 2016). *Design considerations for modern 400 kV AC substation in coastal area: what is missing in IEC/CIGRE requirements* CIGRE-IEC Colloquium Montréal, QC, Canada.
- Reddy, D. Y. A., Divya, S., Bhargav, I. N., Bhanusree, A., & Neha, C. (2022). Transmission Line Fault Classification using Supervised Machine Learning. *International journal of engineering and advanced technology*, 12(1), 47-49. <https://doi.org/10.35940/ijeat.a3832.1012122>
- Richards, C. S., Benner, C. L., Butler-Purpy, K. L., & Russell, B. D. (2003). Electrical behavior of contaminated distribution insulators exposed to natural wetting. *IEEE Transactions on Power Delivery*, 18(2), 551-558. <https://doi.org/10.1109/TPWRD.2003.809682>
- Rooyen, C. v., Vosloo, H., & Harness, R. (2002, 5-7 May 2002). Eliminating bird streamers as a cause of faulting on transmission lines. 2002 Rural Electric Power Conference. Papers Presented at the 46th Annual Conference (Cat. No. 02CH37360),
- Salem, A. A., Lau, K. Y., Rahiman, W., Abdul-Malek, Z., Al-Gailani, S. A., Mohammed, N., Rahman, R. A., & Al-Ameri, S. M. (2022). Pollution Flashover Voltage of Transmission Line Insulators: Systematic Review of Experimental Works. *IEEE Access*, 10, 10416-10444. <https://doi.org/10.1109/ACCESS.2022.3143534>
- Sandhu, K. S., et al. (1988). *A Joint Utility Investigation of Unexplained Transmission Line Outages : Final Report* (EPRI publication EL-5735 Issue.
- Seleshi, Y., & Zanke, U. (2004). Recent Changes in Rainfall and Rainy Days in Ethiopia. *International Journal of Climatology*, 24, 973-983. <https://doi.org/10.1002/joc.1052>
- Shaikh, M. M., Karady, G. G., & Dalal, S. B. (2018, 9-11 Sept. 2018). Investigating Switching Surges On EHV Lines And Substations - A Practical Utility Case. 2018 North American Power Symposium (NAPS),
- Shanko, D. (2001, 15-20 July 2001). *Fog Climatology in Ethiopia* Conference on Fog and Fog Collection, St. John's, Canada.
- Shariati, M. R., Moradian, A. R., Rezaei, M., & Vaseai, S. J. A. (2005, 18-18 Aug. 2005). Providing the Pollution Map in South West Provinces of Iran Based on DDG Method. 2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific,

- Shariati, M. R., Vaseai, S. J. A., Rezaei, M., & Abyazi, S. (2006, 10-12 April 2006). New approaches to study environmental pollution effects on insulation of West Azarbayjan Electric Power Distribution Co. 2006 IEEE Power India Conference,
- Shiferaw, A. B., Kumie, A., & Tefera, W. (2023). The spatial and temporal variation of fine particulate matter pollution in Ethiopia: Data from the Atmospheric Composition Analysis Group (1998–2019). *PLOS ONE*, *18*(3), e0283457. <https://doi.org/10.1371/journal.pone.0283457>
- Sklenicka, V. (2023). *Investigating Unexplained Reclosures on Power Grid; INMR: Kelowna, BC, Canada, 2023*. Retrieved 21 October 2023 from <https://www.inmr.com/analyzing-unexplained-reclosures/>
- Sukhnandan, A., & Hoch, D. A. (2002, 2-4 Oct. 2002). Fire induced flashovers of transmission lines: theoretical models. IEEE AFRICON. 6th Africon Conference in Africa,
- Tadesse, S., Milesi, J.-P., & Deschamps, Y. (2003). Geology and mineral potential of Ethiopia: a note on geology and mineral map of Ethiopia. *Journal of African Earth Sciences*, *36*(4), 273-313. [https://doi.org/https://doi.org/10.1016/S0899-5362\(03\)00048-4](https://doi.org/https://doi.org/10.1016/S0899-5362(03)00048-4)
- Taklaja, P., Oidram, R., Niitsoo, J., & Palu, I. (2013). Causes of indefinite faults in Estonian 110 kV overhead power grid. *Oil Shale*, *30*, 225–243. <https://doi.org/10.3176/oil.2013.2S.04>
- Tefera, W., Kumie, A., Berhane, K., Gilliland, F., Lai, A., Sricharoenvech, P., Patz, J., Samet, J., & Schauer, J. J. (2021). Source Apportionment of Fine Organic Particulate Matter (PM_{2.5}) in Central Addis Ababa, Ethiopia. *International Journal of Environmental Research and Public Health*, *18*(21).
- Tefera, W., Kumie, A., Berhane, K., Gilliland, F., Lai, A., Sricharoenvech, P., Samet, J., Patz, J., & Schauer, J. J. (2020). Chemical Characterization and Seasonality of Ambient Particles (PM_{2.5}) in the City Centre of Addis Ababa. *International Journal of Environmental Research and Public Health*, *17*(19).
- Todorovi, I., Isakov, I., Dobri, G., & arkovi, M. (2023). Electric energy utilization in modern industrial environments version 1; peer review: 1 approved, 1 approved with reservations. *Open Research Europe*, *3*(4). <https://doi.org/10.12688/openreseurope.15286.1>
- Tutt, T. E., Singh, I., Popova, E., & Kee, E. (2012, 23-26 Jan. 2012). Outage performance improvement by Preventive Maintenance optimization. 2012 Proceedings Annual Reliability and Maintainability Symposium,
- UNEP, W., UNCCD,. (2016). *United Nations Environment Programme (UNEP), World Meteorological Organization (WMO) and United Nations Convention to Combat Desertification (UNCCD): Global Assessment of Sand and Dust Storms*. UNEP. <https://library.wmo.int/idurl/4/35074>
- USGS, & EROS. (2019a). *U.S Geological Survey (USGS), Center for Earth Resources Observation and Science (EROS): Altitude data*. U.S Geological Survey (USGS), Center for Earth Resources Observation and Science (EROS). Retrieved 18 August 2019 from <https://earthexplorer.usgs.gov/>
- USGS, & EROS. (2019b). *U.S Geological Survey (USGS), Center for Earth Resources Observation and Science (EROS): Land cover and land use data*. Retrieved 18 August 2024 from <https://earthexplorer.usgs.gov/>
- Vaisala's National Lightning Detection Network NLDN, & Global Lightning Detection Network GLD360. (2022). *Lightning data: Ethiopia from 2016 to 2022*. Retrieved 17 March 2023 from <https://interactive-lightning-map.vaisala.com/>

- van Donkelaar, A., Hammer, M. S., Bindle, L., Brauer, M., Brook, J. R., Garay, M. J., Hsu, N. C., Kalashnikova, O. V., Kahn, R. A., Lee, C., Levy, R. C., Lyapustin, A., Sayer, A. M., & Martin, R. V. (2021). Monthly Global Estimates of Fine Particulate Matter and Their Uncertainty. *Environmental Science & Technology*, 55(22), 15287-15300. <https://doi.org/10.1021/acs.est.1c05309>
- van Donkelaar, A., Martin, R. V., Brauer, M., Hsu, N. C., Kahn, R. A., Levy, R. C., Lyapustin, A., Sayer, A. M., & Winker, D. M. (2016). Global Estimates of Fine Particulate Matter using a Combined Geophysical-Statistical Method with Information from Satellites, Models, and Monitors. *Environmental Science & Technology*, 50(7), 3762-3772. <https://doi.org/10.1021/acs.est.5b05833>
- van Donkelaar, A., Martin Rv Fau - Brauer, M., Brauer M Fau - Boys, B. L., & Boys, B. L. (2015). Use of satellite observations for long-term exposure assessment of global concentrations of fine particulate matter. *Environmental Health Perspectives*, 123(1552-9924 (Electronic)).
- Vasileva, M., & Stanchev, D. (2020, 12-14 Nov. 2020). Switching transients in overhead transmission line 220 kV. 2020 7th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE),
- Volpov, E., & Katz, E. (2016). Characterization of Local Environmental Data and Lightning-Caused Outages in the IECo Transmission-Line Network. *IEEE Transactions on Power Delivery*, 31(2), 640-647. <https://doi.org/10.1109/TPWRD.2015.2443032>
- Volpov, E., & Kishcha, P. (2017). An advanced technique for outdoor insulation pollution mapping in the israel electric company power grid. *IEEE Transactions on Dielectrics and Electrical Insulation*, 24(6), 3539-3548. <https://doi.org/10.1109/TDEI.2017.006917>
- Vosloo, H. F. (2009). *The need for and contents of a Life Cycle Management Plan for Eskom Transmission Line Servitudes* Master's Thesis, University of Johannesburg. Johannesburg, South Africa.
- Vosloo, W., Davey, R., & Bekker, J. (2022, 16–19 October 2022). Selecting Insulators for Polluted Environments: Utility Perspective. In Proceedings of the INMR World Congress 2022, Berlin, Germany.
- Vosloo, W. L. (2002). *A Comparison of the Performance of High-Voltage Insulator Materials in a Severely Polluted Coastal Environment* PhD Thesis, University of Stellenbosch. South Africa.
- Wang, Q., Kwan, M.-P., Zhou, K., Fan, J., Wang, Y., & Zhan, D. (2019). The impacts of urbanization on fine particulate matter (PM_{2.5}) concentrations: Empirical evidence from 135 countries worldwide. *Environmental Pollution*, 247, 989-998. <https://doi.org/https://doi.org/10.1016/j.envpol.2019.01.086>
- Wesley, R., & Garcia, S. (2022, 16–19 October 2022). Using Environmental Parameters to Create Pollution Maps for Power Utilities: Experience in Brazil. In Proceedings of the INMR World Congress 2022, Berlin, Germany.
- Wijayatunga, P. D. C., & Jayalath, M. S. (2008). Economic impact of electricity supply interruptions on the industrial sector of Bangladesh. *Energy for Sustainable Development*, 12(3), 5-12. [https://doi.org/https://doi.org/10.1016/S0973-0826\(08\)60433-0](https://doi.org/https://doi.org/10.1016/S0973-0826(08)60433-0)
- Yang, H. (2022, 20-22 Jan. 2022). Transmission Line Fault Detection Based on Multi-layer Perceptron. 2022 International Conference on Big Data, Information and Computer Network (BDICN),

- Yao, C., Wu, H., Long, Y., Mi, Y., Ma, Y., Shen, Y., & Wang, L. (2014). A novel method to locate a fault of transmission lines by shielding failure. *IEEE Transactions on Dielectrics and Electrical Insulation*, 21(4), 1573-1583. <https://doi.org/10.1109/TDEI.2014.004321>
- Zedan, F. M., & Akabar, M. A. (1991). Performance of HV transmission line insulators in desert conditions. IV. Study of insulators at a semicoastal site in the eastern region of Saudi Arabia. *IEEE Transactions on Power Delivery*, 6(1), 439-447. <https://doi.org/10.1109/61.103769>
- Zhiyi, S. (2016). Classifying Pollution Severity for HVAC & HVDC. In Proceedings of the INMR 2016,
- Zhou, Y. X., Xu, X., Nie, Q., Liang, X. D., Guan, Z. C., Cui, J. F., Li, Z. Y., Yuan, Y. C., Chen, Y., & Yu, D. M. (2009). Bird streamer caused flashover in EHV transmission line. *IEEE Transactions on Dielectrics and Electrical Insulation*, 16(1), 69-76. <https://doi.org/10.1109/TDEI.2009.4784553>
- Zidan, A., & El-Saadany, E. F. (2015). Incorporating customers' reliability requirements and interruption characteristics in service restoration plans for distribution systems. *Energy*, 87, 192-200. <https://doi.org/https://doi.org/10.1016/j.energy.2015.04.067>
- Zohuri, B. (2016). Electricity, an Essential Necessity in Our Life. In B. Zohuri (Ed.), *Application of Compact Heat Exchangers For Combined Cycle Driven Efficiency In Next Generation Nuclear Power Plants: A Novel Approach* (pp. 17-35). Springer International Publishing. https://doi.org/10.1007/978-3-319-23537-0_2

Appendices

Appendix A: Published articles

Paper-I



Analyses of unexplained faults in transmission lines in the power grid of Ethiopia

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ARTICLE INFO

Keywords:

Ethiopian power transmission system
Unexplained outages
Lightning faults
Pollution flashover faults
Fire related faults
Climatic conditions of Ethiopia

ABSTRACT

Ethiopian power transmission lines operating at 132 kV, 230 kV and 400 kV are encountering unacceptably high number of unexplained outages caused by external factors, which compromise the reliability of the system. It is therefore crucial to examine the characteristics and underlying causes of these outages through analyses of long-term records of the faults for identifying their probable causes for best targeting future mitigation measures.

A method is presented to identify, in retrospect, the major possible root causes of unexplained outages that combines information on fault time-of-the day and time-of-the year records with flashover characteristic of known fault causes and local climatic and environmental information. The analyses are based on data covering an 8-year period from 2015 to 2022. A total of 8891 fault records were compiled and among them 4231 faults (47 %) were unexplained faults. Results show statistical variations in the frequency of unexplained faults with respect to spatiotemporal occurrence of the faults, voltage level and local climate.

Moreover, the analyses indicate that out of the total number of 4231 unexplained faults, 787 faults could be attributed to lightning (19 %), 1135 faults to pollution events (27 %), 479 were fire related (11 %) and 1830 faults caused by external interferences (43 %).

1. Introduction

Exposed to environmental conditions, overhead transmission lines are subject to a variety of effects influencing their performance, such as lightning, pollution, and others. If not properly designed and maintained, these environmental effects yield a decline in the power system reliability, resulting in costly consequences [1,2]. The analysis of transmission line faults is thus of a paramount importance, helping to find out the main causes of line outages and finding means of their prevention.

The transmission system of Ethiopian national grid, operated by Ethiopian Electric Power company (EEP), extends over a total length of 19,305 km and operates at standard voltage levels, of which 6053 km are 132 kV lines, 7996 km are 230 kV lines, and 5256 km are 400 kV and 500 kV lines [3]. These lines, with an average width of 40 m, cover a total area of 772.2 km², excluding the areas occupied by substations or power stations. The management of line faults at EEP was until 2015 to some extent unorganized, as a standard list of fault categories and consistent fault reports were missing. After 2015, the fault records could

be easier found, although there is still a lack of consistent descriptions of their origin that allows to trace their root causes. Despite of this improvement, EEP's line fault management is still more concerned on fault detecting, fault locating, and phase selection, while less attention is given to diagnosis of the faults triggered by external factors, originating from environmental or surrounding activities. Thus, such faults are generally assigned into the general class of Earth faults and their root causes remain unexplained.

Power outage records collected from the national load dispatch and control center (LDC), a unit of EEP, which is responsible for planning, operation, and monitoring of the national transmission grid, as well as from substation logbooks are used in this paper for presented analyses. 8891 unplanned outages were recorded during the period 2015 to 2022. The fault dataset includes information about EEP grid region, transmission line name, line length, system voltage, outage and restoration dates, as well as daytime of the fault and its reason. The data were further completed with a Geographic Information System (GIS) database which includes information on the geographic location of each transmission tower.

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<https://doi.org/10.1016/j.epsr.2024.110293>

Received 8 June 2023; Received in revised form 11 February 2024; Accepted 1 March 2024

Available online 13 March 2024

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For these analyses, the data were grouped into five primary categories. These include: (i) Earth faults, caused by lightning strikes on towers or earth wires, insulator failures, environmental and bird caused pollution flashovers of insulators, fire, foreign object and animal interference, and external damage; (ii) Overload and (iii) Overvoltage faults, caused by internal system operational events, such as transformer or line outages due to overloading, load changes, switching surge, voltage dips or swells; (iv) Miscellaneous faults internal to the power system, including outages due to grid disturbances like phase to phase short circuit events, large motor starting, transformer energizing, hardware failures, poor workmanship, mechanical failures, fires in equipment, protection malfunctions etc., and finally (v) Unknown/No signal faults, which root causes could not be determined due to insufficient fault location, small flash marks, lack of post fault investigations or no relay signals.

The fault data were compiled, and the analysis results are shown in Fig. 1, providing an insight into the overall performance of the system. 35 % were Earth faults, 22 % Overload faults, 13 % Overvoltage faults, 18 % Miscellaneous faults, and 12 % Unknown/No signal faults. Additionally, the fault data serves as an important record of historical line performance that can be combined with information on weather and climatic cycles, helping to determine their primary causes and proposing optimal mitigation measures.

In this work Earth faults along with Unknown/No signal faults are grouped under unexplained faults as their root causes remain unclear for both categories. Thus, 47 % of the total faults i.e., 4231 were Earth and Unknown/No signal faults, forming a group of unexplained faults. These types of faults are commonly of single phase-to-ground type and have relatively high reclosing success rate (self-clearing). This indicates that the EEP transmission network is suffering from an excessive number of unexplained faults and signifies a necessity to identifying primary causes of these faults and taking appropriate corrective actions.

This paper focuses on statistical analyses of the unexplained faults and the goal is to show their characteristics across time of the day, seasonal occurrence in various grid regions (location), as well as rainfall regimes to identify their spatial and temporal distribution patterns. This knowledge will further influence the designs, construction, and operation of Ethiopian transmission system [4,5]. Moreover, it will also allow to define appropriate monitoring, maintenance procedures and inspection techniques for the existing lines [5–7].

2. Identification method of unexplained line faults

To identify the root causes of the unexplained faults, verification procedures concentrated on looking for trends, which might suggest or be in accordance with the known characteristics of the major probable

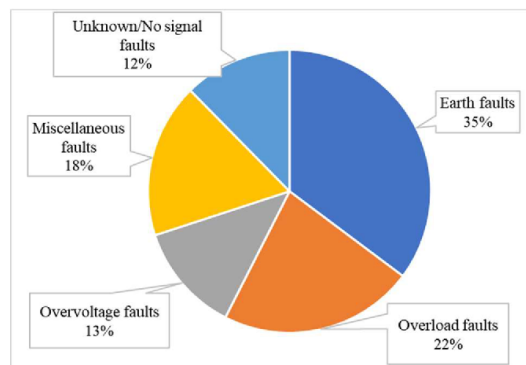


Fig. 1. The relative occurrence of the major fault types on transmission line from 132 to 400 kV for the period between 2015 and 2022 [3].

causes, such as lightning, pollution, bird streamers, fire, etc. Contextual fault information such as time of the day, time of the year (season) of occurrence and geographic location as well as climatic and environmental conditions of the region where the faults occur are highly relevant to identifying its primary external cause [2,7,8,9]. Moreover, information on fault duration, voltage level, and service experience can also be useful [2,7,10,9].

Line faults caused by environmental factors are not always easy to identify. However, there exist certain contextual characteristic patterns helping in identifying them [2,4,5,9]. These are as presented in more detail manner below.

2.1. Time-of-day of faults occurrence

For the data to be consistent with lightning caused faults, the fault incidence should be clustered during the late afternoon (13:00–19:00) of rainy season [2,8,11–13]. This pattern can slightly be shifted, as its duration may vary depending on the local rainfall conditions. Flashovers induced by wetting pre-deposited pollution are believed to occur mainly between midnight and early morning (up to 8:00) when dew or mist are most likely to be formed [2,8,11,14]. As humidity increases during the night, the pollution induced outages become more frequent and reach a peak just before sunrise at about 06:00 and virtually no such faults appear during daytime [2,8,14,15]. Bird streamer type of faults usually have two peaks of occurrence, one early in the evening, centered around 22:00, and another in the morning around 06:00, associated with bird's digestive function [2,11,16]. This type of faults was found to be similar in studies conducted in Florida and South Africa [2,4,11]. Fig. 2 illustrates the typical daily distribution curves for the three main causes of flashovers based on long-term analyses performed in Florida, USA [4,11] and South Africa [2]. In analysis of this work pollution faults refer to all types of pollution flashover mechanisms, including pre-deposit pollution and wetting mechanism of type A and instantaneous pollution events of type B, according to IEC/TS 60815-1 [17].

Pollution (from the environment and bird streamers) and lightning is responsible for a significant percentage of the outages considered as unexplained outages. However, other causes, such as tree contact, fire, and other types of interferences by foreign object, are also likely to contribute [7,18]. Fire and smoke that occur under transmission lines and line servitudes can bridge phase-to-phase and conductor-to-ground clearances, causing flashovers. Most fire induced flashovers usually occur at the midspan of the lines during hot periods of midday from 11:00 to 16:00 on dry months [5,7,8,18,19]. Similarly, faults caused by tree contacts of transmission lines, following the sagging of lines during hot and overloaded periods of the day, occur during midday around the midspan of the line [8]. Other classes of unpredictable faults include foreign object interferences, external damages, theft, and vandalism and

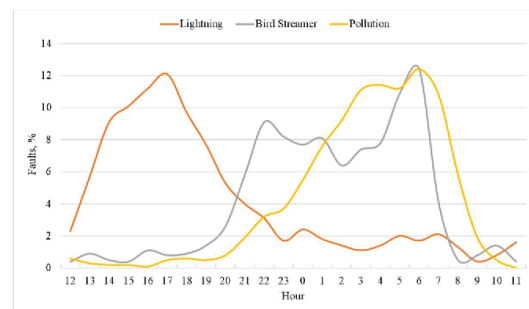


Fig. 2. The typical time-of-day flashover occurrence characteristics of faults caused by lightning, pollution, and bird streamers in Florida, USA and South Africa [2,11].

do not have a clear temporal pattern. However, most of these faults are associated with frequent human and animal activities (for example due to bird collision or nesting) and strong winds that apparently are more intense during daytime and early evening hours [7,18].

2.2. Seasonality of faults occurrence

In terms of the fault occurrence in relation to the time of year, lightning related faults are typically limited to specific rainy months [2, 4,10]. Frequent heavy rainfall reduces the chance of pollution accumulation on insulators, so most pollution induced outages occur during drier periods and on the transition of seasons when fog and light rains occur after the dry season [1,6,14,17]. Bird streamer faults follow the seasonal pattern related to presence of birds or their feeding habits and tend to increase in frequency during spring [2,4,11,16]. Many fire-induced flashovers normally occur during harvesting and dry months of the year [7,10,18,19].

2.3. Geographic distribution of line faults

Spatial distribution of a fault can also help in identifying the root causes [5,7,10]. In this regard, lightning caused faults are more likely to occur in areas with high rainfall distribution and higher elevations [10, 12,20]. Pollution induced faults, which are highly influenced by the environmental conditions, are expected to occur near areas having sources of dust or pollution such as areas of industrial and intense agricultural activity, busy roads as well as close seacoast [1,6,14,15,17]. In locations that support bird life with abundant water and food sources, bird streamer type of faults are likely to occur [11,16,21–23]. Moreover, fire caused faults are expected to happen on lines passing through desert and semi-arid areas where the temperature is high and there is abundant amount combustible material present like grass, shrubs, bushes, and sugar cane farms [7,19]. External interference caused faults are typical in densely populated areas [7,18]. Therefore, understanding the geographical location of a fault is valuable in identifying the cause and preventing future occurrences [1,2,5,17].

2.4. Climatic and meteorological conditions

Many studies have shown the impact of meteorological factors such as wind direction and speed, precipitation, relative humidity, and temperature in facilitating the occurrence of faults on transmission lines. Therefore, understanding the climatic and meteorological conditions where a fault occurred is important [1,2,4,5,17].

In this work, the geographic coordinates of each transmission line tower in the entire transmission network were determined. The meteorological parameters were extracted for each tower coordinate using ArcGIS software and the average of all point was taken to represent the meteorological parameters of the entire line.

2.5. System voltage of the line

Voltage level of a transmission line determines its design parameters, such as the ground clearance, tower window size, insulator's arcing and creepage distances as well as type of material to be used [6,7,17]. It thus also impacts on the type of possible faults. For example, higher voltage lines have a larger ground clearance and tower window size, making them less susceptible to bird streamer faults. Lightning impulse flashovers are dominant at system voltages below 300 kV [1,10,12,20], while pollution flashovers are more frequent at higher system voltages [1,17]. Hence, if the reason for the fault remains uncertain, the voltage level of the affected transmission line can provide insight into the nature of the fault.

The entire dataset was in detail analyzed for consistency with the above elucidated fault characteristics and if there were enough tendency to satisfy one of a particular type then the fault was assigned to it.

3. Statistics of spatiotemporal distribution of unexplained line faults

3.1. Spatial distribution of unexplained faults across grid regions of EEP

The distribution across region, time-of-day and time-of-year of fault occurrence and voltage level are analyzed. Fig. 3 presents the distribution of grid disturbances in each operational region of EEP during the period 2015–2022. Among these regions, Addis Ababa region suffered 905 (21.4 %) faults, the highest number of disturbances. South and Northwest regions also had higher number of unexplained faults during this period.

Moreover, to enable comparisons and study the spatial distribution of unexplained faults, the centroids of each transmission line circuit are used to assign a geographic location to each event and estimate the prevalence of unexplained faults in terms of faults per unit length and unit time. For each circuit, the number of faults per 100 km of transmission line per year were computed. This information was then integrated into the GIS database and using ArcGIS software centroids were determined for each circuit to create a national-level map displaying spatial patterns. Fig. 4 illustrates the transmission grid in Ethiopia (132–400 kV) as of 2022 (represented by grey lines), along with the average number of unexplained faults registered per year per 100 km of line for each circuit. The representation is depicted through circles with proportionally varying radii.

In terms of spatial variations, unexplained faults were observed in 191 circuits, ranging from 0.062 to 66.67 faults per 100 km per year, with an average of 9.96 faults. These circuits were primarily concentrated in central, southern, and eastern part of Ethiopia as indicated in Fig. 4.

Standard requirements for high voltage transmission lines typically allow for occurrence of 1–2 unexplained faults per 100 miles (161 km) per year, which is equivalent to 0.62–1.24 unexplained faults per 100 km per year [4,16]. The acceptable number of flashovers per kilometer of transmission line per year depends on the importance and location of the line. In most European countries, a rate of approximately one flashover per 150 km of line per year is generally considered acceptable [23]. Therefore, based on these benchmarks, the Ethiopia (132–400 kV) power grid exhibits an excessively high rate of indefinite faults that are one way, or another related to line insulation flashover. Examples of fault frequency for badly performing EEP's 400, 230, and 132 kV transmission lines for the period from 2015 to 2022 are shown in Table 1. These lines experience unacceptably high rates of unexplained outages, which are many times higher than the expected design rates and the first step in reducing these numbers is to determine their root causes.

Scrutiny of the fault data revealed that yearly trend of unexplained faults varied from one year to another, peaking in 2021, as shown in Fig. 5. The reason could be variations in meteorological and environmental conditions, aging of infrastructure, and maintenance practices. Further investigation is needed to elucidate causes of this trend and to find ways to reduce the number of faults in the future.

3.2. Temporal (time-of-day and seasonal) analysis of unexplained faults

In this section, the daily and annual trends of the unexplained faults is presented. The daily occurrence of unexplained faults, as shown in Fig. 6, displays a pattern having three peaks, first one around midnight and second centered around 06:00. The latter can result from pollution flashovers occurring in the early morning. Third peak is in the afternoon, around 14:00–15:00, it can likely be due to a combination of lightning caused faults that occur during afternoon hours of summer rainy season and other unknown reasons, like tree contact, mechanical failures due to component aging, vandalism and fires of dry season.

The seasonal trend of fault occurrence is shown in Fig. 7. It exhibits a maximum of 510 faults in August and a minimum number of 229 faults

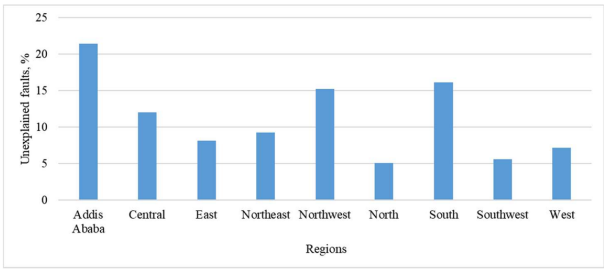


Fig. 3. Distribution of unexplained faults across EEP regions during the years 2015–2022.

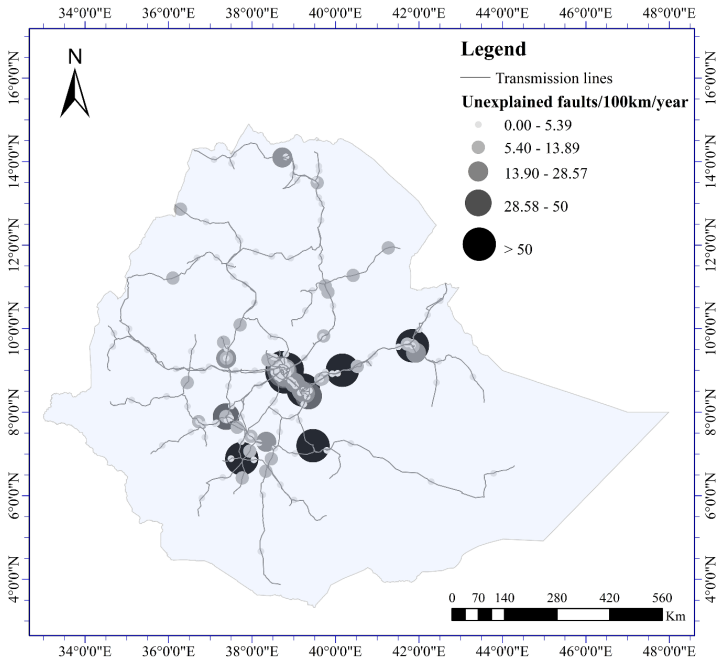


Fig. 4. Spatial distribution of unexplained faults per 100 km per year across Ethiopia during the years 2015–2022.

Table 1
Unexplained fault rates of selected EEP 400, 230, and 132 kV transmission lines during the period from 2015 to 2022.

Transmission line name	Region	Circuit length (km)	In -service year (G.C.)	Voltage (kV)	Total unexplained fault	Number of faults per 100 km per year	Calculated Ground flash density per line
Bahir Dar II - Alamata	North West & North East	348.00	1998	230	150	5.39	21
Beles - GERD	North West	241.00	2014	400	130	6.74	23
Combolcha 2 - Semera	North East	174.80	2011	230	93	6.65	14
Shashemene - Alaba	South	63.23	2000	132	89	17.59	14
Combolcha 2 - Legetafo	North East & Addis Ababa	287.00	2012	230	88	3.83	20
Wolayita Soddo - Arba Minch	South	109.13	1986	132	83	9.51	5
Metema - Sudan Boarder	North West	76.96	2008	230	81	13.16	42

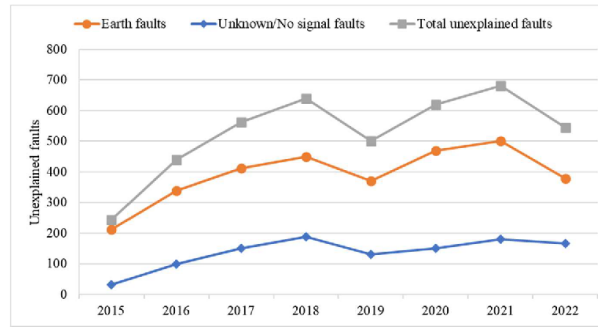


Fig. 5. Yearly variation of unexplained faults in EEP network [3].

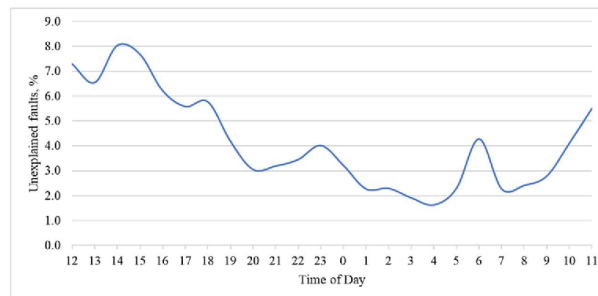


Fig. 6. The time-of-day trend of unexplained faults in EEP network.

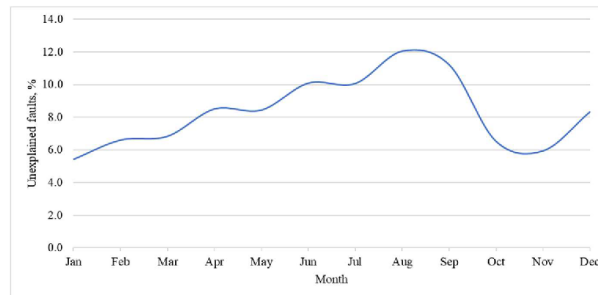


Fig. 7. Annual trend of unexplained faults in EEP network.

in January. A total of 1838 faults is registered from June to September, which falls during the rainy summer season in Ethiopia and can mainly be assigned to external object interference and lightning induced faults occurred in the late afternoons. The faults that occur in the remaining part of the year are likely caused by pollution, bird streamers, fires and other unknown reasons.

Annual trends of the unexplained faults per 100 km of lines during the period 2015–2022 across the EEP grid management regions are shown for all the voltages levels in Fig. 8. It shows that Addis Ababa, Northeast, Northwest, and South grid regions experience much higher frequency of outages than normally expected due to unclear root causes.

These results indicate a poor performance of the transmission lines. The reasons can be different, depending on the environmental and climatic condition in each region. For example, in Addis Ababa region, lightning flash density is high and air pollution due to industrial

emission, vehicle exhaust and households extensive. In the Northeast region, the environment is of desert type, with heavy salty sand/dust accumulation, so pollution is the most likely cause. The South, Southwest and Northwest region also have a higher frequency of unexplained outages. These regions get in contrast high rainfall and have intense agricultural activities. Thus, the poor line performance can originate from lightning, pollution, fires, and crop burning.

The unexplained fault frequency statistics for the major voltage levels per 100 km per year are presented in Fig. 9. 132 kV lines suffer most of the faults with 4.9 faults/100 km/year, which is twice the amount suffered by 230 kV lines (2.6 faults/100 km/year). These lines are poorly performing indeed. The 400 kV lines have lower fault frequency, with 1.13 faults/100 km/year. Most of the 132 and 230 kV lines were constructed before 2005 and the reason for their poor performance is attributed to aging infrastructure in addition to environmental

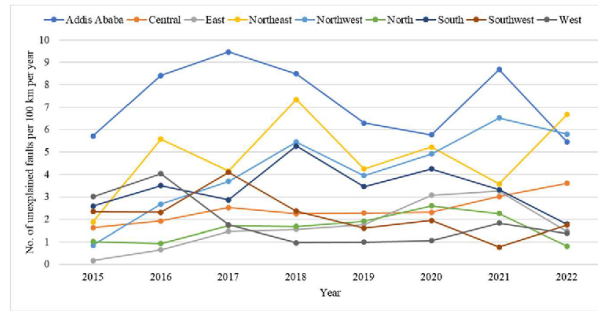


Fig. 8. Reginal distribution of unexplained faults per 100 km of lines during the period 2015–2022 in EEP grid management regions.

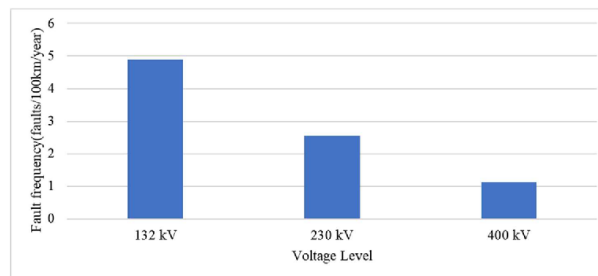


Fig. 9. Unexplained fault frequency per 100 km per year for 132, 230 and 400 kV transmission lines.

reasons.

4. The climatic and meteorological conditions of Ethiopia

One of the aims of this study was to reveal how the unexplained faults vary in the wet and dry climatic cycles. The focus in this section is to discuss the climatic and meteorological conditions of Ethiopia, which help to classify the country into distinct rainfall regimes characterizing their seasonal distribution at specific places and provide a convenient framework for the analysis of unexplained fault with respect to climatic conditions.

4.1. Rainfall regimes in Ethiopia

As climate in Ethiopia is in general tropical and the weather conditions are characterized by distinct wet and dry seasons, with different precipitation and temperature [24,25]. Ethiopia has three distinct seasons, known locally as "Bega", "Belg", and "Kiremt". Bega is the dry season, occurring from October to January and is characterized by hot, dry days and cool nights. It is chilly in the early mornings, with occasional frost over most highland areas. Kiremt is the main rainy season, coming from June to September and characterized by frequent rains and homogeneous temperatures. The rainfall usually occurs in the afternoon and in the evening. Belg is the light rainy season, often with considerably less rainfall occurring from February to May, which is highly variable in time and space and high maximum temperatures [24,26,27]. These unimodal and bimodal rainfall conditions in Ethiopia form the basis for categorizing the country into three rainfall regimes [25], which are commonly referred to as Regime A, Regime B, and Regime C.

As illustrated in Fig. 10, regime A covers the central and eastern parts of the country, where the bimodal rainfall system is composed of the long rainy season (June–September) and the short rainy season (March–May). Regime B is a rainfall region in the western part of the country that

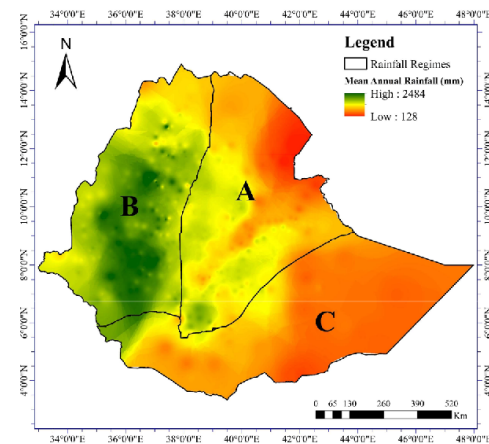


Fig. 10. Annual average rainfall map of Ethiopia showing the three rainfall regimes [24,25].

stretches from southwest to northwest and has a unimodal rainfall pattern from February to November, but the rainy period ranges vary on the way from southwest to northwest. Regime C comprises the south and southeastern parts of the country and has two distinct wet and dry seasons. The main rainy season occurs from February to May, followed by short rains from October to November. The dry periods are from June to September and December to February [24–26]. It is important to note that most of the transmission lines are subjected to varying levels of rainfall for most part of the year, which impacts on their performance [28].

4.2. Lightning density in Ethiopia

Overhead transmission line faults resulting from lightning can be attributed to three mechanisms according to the struck location of the lightning leader, namely back-flashover from tower top or shielding wire to a phase, shielding failure that lets lightning to terminate on the phase conductor (direct flashover), and induced surges caused by lightning strikes to the ground near the line. The likelihood of shield failure and back-flashover is mainly influenced by the design and installation of the transmission line, which is typically specific to the line voltage. These two factors can be aggregated and adjusted according to the lightning ground flash density (Ng) [10,12]. Fig. 11 shows a map of spatial distribution of ground flash density (Ng) for the whole Ethiopia together with the transmission line routes. It illustrates average Ng values for 10 km² blocks and each transmission line tower within a square is assigned Ng value equal to that of the square within which it is located. The flash density per line is calculated by averaging Ng for all the line towers [10,20].

The annual incidence of lightning in Ethiopia varies considerably, from less than 3 flash/km²/year in East and Southeast regions to more than 75 flashes/km²/year in the North, Northwest and West regions. Most of the identified problematic lines fall within the high lightning incidence areas, mostly taking place from late afternoon to midnight of the rainy months from June to September. Table 2 shows the average ground flash density for each grid region of EEP, based on data collected between 2016 and 2022 by Vaisala's Global Lightning Detection Network (GLD360) [30].

5. Analysis of unexplained faults in relation to climatic condition, time-of-day and time-of-year

This section presents an analysis relating the frequency of unexplained faults and local climate conditions based on time-of-day and time-of-year (season) [10,23,31]. The analysis involves three important steps. The first step is to prepare a fault dataset for the analysis. The second step is to associate each transmission line to a specific grid region (as a geographic indicator) and to a rainfall regime (as a climatic representation). This step helps to identify the regions that are more likely to suffer from unexplained faults due to environmental and climatic factors. Finally, the faults are characterized according to time-of-day and time-of-year (season) quadrants. This step helps to identify any seasonal or daily patterns. In general, this analysis helps to relate frequency of faults to local climate and to identify their spatiotemporal

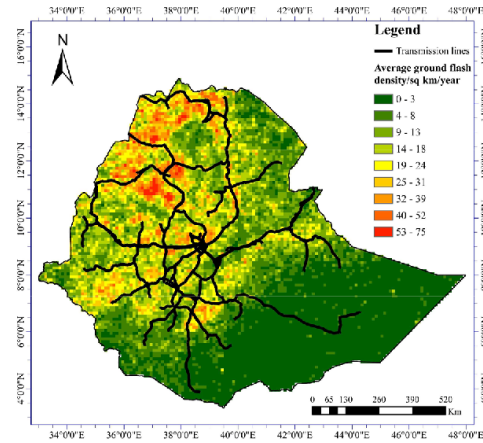


Fig. 11. Map of average ground flash density (Ng) in Ethiopia with power transmission line routes for the period 2006–2010 [29].

Table 2

The average ground flash density for transmission lines of EEP grid management regions, from 2016 to 2022 [30].

Grid region	Average ground flash density from 2016 to 2022 (flashes/km ² /year)
Addis Ababa	15.3
Central	6.9
East	2.3
Northeast	12
Northwest	17.7
North	23.5
South	6.9
Southwest	7.1
West	16.9

Table 3

Yearly average frequency of unexplained faults in the rainfall regimes of Ethiopia.

Rainfall regime	Grid region	Total length of lines(km)	Fault frequency (faults/100 km/year)	Std. Dev.
Regime A	North	9868	3.17	0.58
	Northeast			
	Central			
	Addis Ababa			
	East			
Regime B	West	6516	2.53	0.42
	Northwest			
Regime C	Southwest	2921	3.38	0.98
	South			
Total		19,305	2.98	0.47

patterns.

The EEP grid management regions are grouped according to rainfall regimes. Thus, the Addis Ababa, Central, North, Northeast and East grid regions fall into Regime A. Northwest, West and Southwest regions fall into Regime B and the South region falls into Regime C, as listed in Table 3. The results indicate that there is clear variation in fault frequency across different rainfall regimes. Transmission lines located within the rainfall regime C have higher fault frequency than those within the regime A and regime B. Regime A has 19–75 ground flash/km²/year (see Fig. 11). This higher fault frequency can be caused by lightning induced faults that usually occur during afternoons and nights of the rainy season. It should however be also noticed that a large portion of the total line length falls in rainfall regime A, about 51 % of the total length.

The unexplained fault frequency in relation to the voltage level of transmission lines is depicted in Fig. 12. The frequency of faults occurring on 132 kV lines is highest in rainfall regime A. As these lines also show large variation between the rainfall regimes, it suggests they are more influenced by the climatic conditions than the lines of the other voltage levels. The frequency of faults occurring on 230 kV lines is slightly lower in regime A as compared to those in regimes B and C, but the difference is minor. The frequency of faults occurring on 400 kV lines is even lower, with a tendency for higher value in rainfall regime B. It is likely that most of the faults are related to the high rainfall intensity in the area. This also provides an indication which of the unexplained faults are less influenced by local climate for 400 kV lines.

Time-of-day interval distribution of unexplained faults is shown in Fig. 13. For all voltage levels, 40 % of the unexplained faults occurred during daytime, from 13:00 to 19:00. The reasons are likely to be lightning, fire, theft, vandalism, tree contact, or unknown operational faults. The faults occurring during night and early morning between 19:00 to 08:00, account for 38 % of the total number and are probably caused due to bird steamers and pollution. The impact of time-of-day and time-of-year on fault occurrence can be analyzed simultaneously,

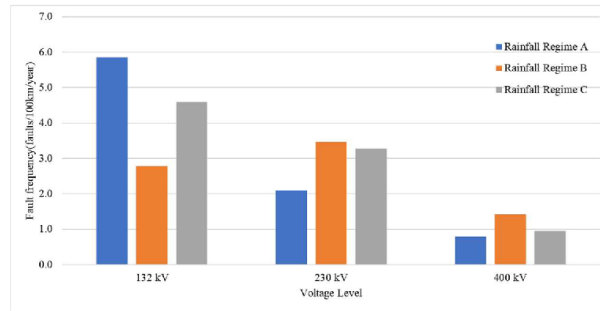


Fig. 12. Fault frequency per 100 km per year in different rainfall regimes.

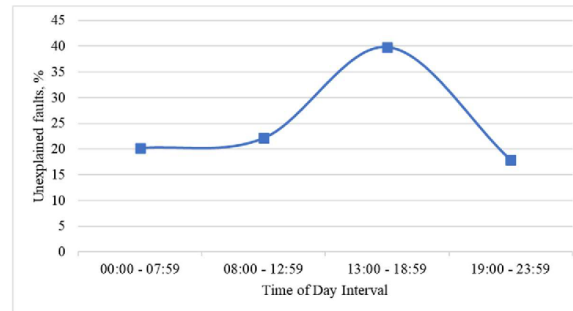


Fig. 13. Time-of-day distribution of unexplained faults on 132, 230, 400 kV lines based on data from 2015–2022.

as proposed in [10,31].

Of the total 4231 unexplained faults that occurred during 2015 to 2022 in the EEP network, 2250 (53 %) were on 132 kV lines, 1597 (38 %) on 230 kV lines and 384 (9 %) on 400 kV lines. When the fault frequency is independently evaluated for each voltage level, for 400 kV network the highest frequency of faults is 0.23 faults/100 km/year took place during Bega season, primarily during the afternoon, 13:00–19:00. For 230 kV lines the frequency of faults reached its peak of 0.46 faults/100 km/year during Kiremt season at the same afternoon hours. The fault frequency on 132 kV lines also reached its peak at 0.89 faults/100 km/year in the afternoons of Kiremt season. Fig. 14 presents the results of the time-season dependent characterization of unexplained fault frequency/100 km/year for the entire EEP network. The results indicate that for the entire EEP network the highest fault frequency occurred in the time interval from 13:00 to 18:59 in the Kiremt rainy season.

6. Classification of unexplained faults according to their root cause and possible mitigation measures

6.1. Criteria for unexplained faults root cause classification

As reported in [9], the best accuracy of transmission line fault root cause classification can be achieved by using only contextual fault features such as time-of-day, month of the year, location (grid region), and climate and environmental conditions. By applying the characteristic criteria for each type of the most probable root causes, as discussed in Section 2, a classification procedure was developed that associates the accessible line fault information with the climatic and environmental conditions represented by rainfall regimes for different grid regions (presented in Sections 4 and 5). Table 4 presents the criteria used for this purpose.

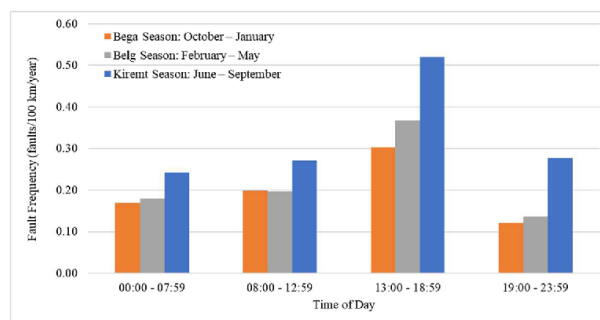


Fig. 14. Season and time dependent characterization of the unexplained fault frequency for the entire EEP network.

Table 4
Classification criteria to identify most probable causes of unexplained faults.

Major causes of unexplained faults	Classification criteria		
	Time of the day	Time of the year	Rainfall regime
Pollution	0:00 – 8:00	January – December	All Regimes
	21:00 – 23:00	October – February	Regime A
	21:00 – 23:00	October – May	Regime B
	21:00 – 23:00	June – September	Regime C
	21:00 – 23:00	December – February	Regime C
Lightning	17:00 – 23:00	June – September	Regime A and B
	17:00 – 23:00	March – May	Regime A and C
	17:00 – 23:00	October – November	Regime C
Fire	13:00 – 16:00	October – February	Regime A
	13:00 – 16:00	October – May	Regime B
	13:00 – 16:00	June – September	Regime C
External interferences	9:00 – 20:00	January – December	All Regimes

The application of the criteria can be best illustrated by the flowchart shown in Fig. 15. The entire dataset was in detail analyzed for consistency with these criteria and if a fault satisfied the conditions of a particular probable cause, then the fault was assigned to it. If a fault failed to satisfy the criteria for pollution, lightning or fire caused faults its cause was assigned to external interferences group. It turned out that among 4231 unexplained faults, lightning events were responsible for 787 (19 %) of them, pollution induced faults for 1135 (27 %), fire for 479 (11 %), and external interferences for 1830 (43 %). However, the external interference category also includes lightning and pollution events that had occurred outside of their characteristic trend areas. It is thus important to stress that lightning, pollution and fire induced

flashovers were responsible for a significant part of the unexplained outages within the EEP transmission system and that each of them was in one or another way associated with environmental and natural climatic phenomena [2,5,7].

6.2. Possible mitigation measures to minimize unexplained faults occurrence

In the following improvement and preventive measures are listed that can allow to minimize the occurrence of unexplained outages. Such approaches were not adequately reflected in older line designs, while they should seriously be considered in the design phases for newly

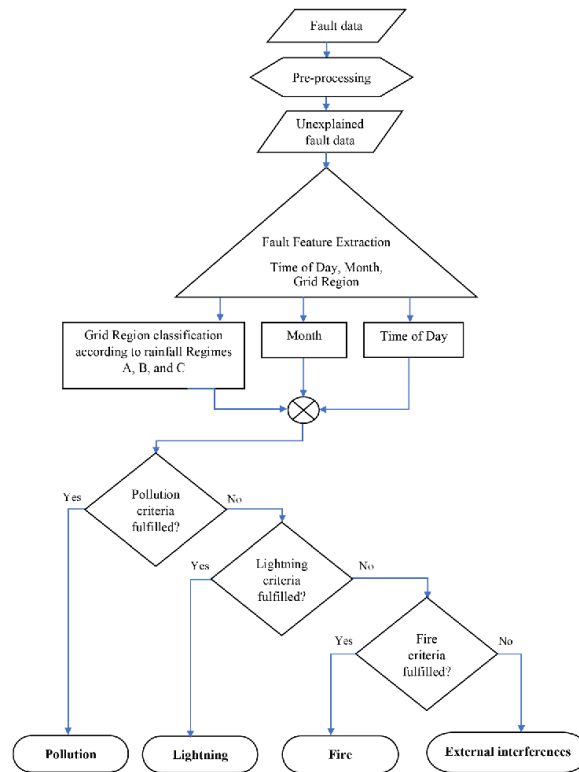


Fig. 15. Flowchart of the procedure used for classification of unexplained faults root causes.

planned transmission lines.

To reduce lightning related flashovers, it is necessary to enhance the protection measures by considering local lightning flash density, including tower footing resistance improvements. Installation of line surge arresters can provide an alternative solution to the improvement of tower footing resistance, especially when the latter become uneconomical and ineffective due to the soil type or rocky in mountainous terrain that the line crosses. When employing this solution, for efficient functioning of line surge arresters, at least one or two towers having adequate grounding and adjacent to the line sections with poor grounding also need to be equipped with line surge arresters. At the design stage, use of tower design types having lower tower surge impedance offers an advantage in reducing lightning related flashovers. For example, the cross-roped tower type design has lower tower surge impedance in comparison to its self-supporting counterparts [5,7,12,13,18].

In response to all types of pollution related flashovers on insulators, different techniques to reduce its effect by washing substation or line insulators, greasing (silicone grease) ceramic substations insulators, increasing the creepage distance of insulators, and replacement of hydrophilic insulators by hydrophobic ones can be implemented, depending on the economic and technical feasibility of selected measure. Bird guards can be used, or clearances increased to combat the problems related to bird streamers, and insulator pollution due to birds' excrement, as this also builds up and can lead to pollution related flashovers [1,2,5,13,18,21].

Many measures can be taken to reduce the influence of fire induced flashovers on the transmission lines. This includes good servitude and vegetation management. The combustible objects such as dry trees and grass, bushes and shrubs under line corridors must be cleared in time. Care must also be taken in line proximity during harvesting seasons in agricultural areas that produce an abundance of fine fuels for fire and special attention is required during sugar cane harvesting, which involves burning of the excess plant material. Moreover, developing and employing an early warning system for smart fire detection, location and monitoring, coupled with application of satellite remote sensing technology, can also help in reducing fire induced outages on transmission lines [5,7,13,18,19].

Finally, to reduce transmission line faults caused by external interferences, it is necessary to strengthen line inspection. All foreign and other floating objects that can collide with transmission lines and cause short circuit events should be removed from around their corridors. EEP should in addition reinforce own communication network and cooperate with concerned stakeholder and take technical measures to reduce damages caused by collisions of vehicles, trees, illegal construction activities in a close distance around power lines. Moreover, theft and vandalism of line components, such as removal of tower members and insulators contribute to a fair percentage of faults. EEP should therefore strengthen security and patrol most vulnerable lines, implement prevention measures, and crack down on illegal and criminal acts of stealing and damaging power transmission system infrastructures [7,13,18].

7. Study cases: analyses of poorly performing transmission lines

In this section a detailed description of the probable fault cause identification is presented for two transmission lines that experienced unacceptably high rates of unexplained outages between 2015 and 2022. The time of day and time of year analysis is used to examine records of each line faults and the most likely reasons for flashovers are established. Local meteorological and climatic information, through which the lines run, are combined with actual field experience.

7.1. Bahir Dar II–Alamata 230 kV line

The Bahir Dar II - Alamata 230 kV line was built in 1998 from Bahir

Dar, 348 km in northeast direction, to Alamata and it further extends 141 km north to Ashegoda wind farm. It provides the main link between the Northwest, North and Northeast grid regions of the EEP system. The line is situated in the tropical savanna and in semi-arid climate of the Northwest and North regions of Ethiopia. The insulator strings of the line are of glass type and their performance is susceptible to dew forming. 150 unexplained faults happened on it between 2015 and 2022, an average of 18.8 faults per year. Fig. 16 illustrates the average monthly meteorological parameters along the entire route of the line. It is exposed to high rainfall, above 200 mm in July and August, and high relative humidity of ~80 %. Light rains of 50 mm also occur in March and April, while the hot and dry season stretches from October to February.

As indicated in Fig. 17, this line has suffered of a high number of unexplained faults, 29 % of which mainly occur from late afternoon to early evening (17:00–20:00) and from midnight to the morning (21:00–8:00), especially during the months from June to September, having higher rainfall levels. In terms of time of the day, the highest outage frequency of 25 % is registered from 0:00–8:00 and with respect to time of the year 44 % of them take place from June to September. As rains with lightning density of about 21 flashes/km²/year mainly occur during late afternoon hours to midnight (17:00–23:00), between June and September, they can thus be considered as the main probable cause of these faults.

The line passes areas having a mixture of desert, agricultural and light industrial pollutants. A good correlation is found between the fault records and characteristic patterns of different types of pollution flashovers during periods from October to January and February to May, close to midnight (21:00–23:00) and between midnight and early morning hours (0:00–8:00). Moreover, bird steamer induced faults are also suspected to cause unexplained faults during June to September period from 0:00–8:00. It is therefore assumed that pollution flashovers cause the unexplained faults during the evening hours and at sunrise periods. During the October to May period, from 13:00 to 16:00, fire induced flashovers probably also cause unexplained faults. All other faults occurring from 9:00–12:00 throughout the year and the faults registered between 13:00–16:00 and 17:00–20:00 in seasons that are not typical for the major causes can be attributed as external interferences. Therefore, lightning caused faults are prevalent for this line, followed by pollution caused faults.

7.2. Shashemene–Alaba 132 kV line

The Shashemene - Alaba 132 kV line is 63 km long and situated in the tropical savanna and subtropical highland climate of the Southern region of Ethiopia. It has been in operation since 2000. During the period between 2015 and 2022 the line suffered 89 unexplained faults, an average of 11 faults per year. The monthly meteorological parameters along the entire route of this line are shown in Fig. 18. The area receives a rainfall intensity up to ~90 mm with relative humidity above 60 %, which increases from June to September. It also receives light rainfall, below 60 mm, from February to May. These conditions make the line exposed to frequent wetting of the insulators and susceptible to pollution flashover caused faults.

As presented in Fig. 19, a high frequency of unexplained line faults (58 %) occurs from the afternoon (13:00–16:00) up to early evening hours (17:00–20:00) and is evenly distributed throughout the year. While 18 % of the total faults happened from midnight to early morning (0:00–8:00), especially peaking by 11 % during the months from February to May during which 37 % of the total unexplained faults occurred.

The line passes through an agricultural area and insulator pollutants mainly originate from ploughing, crop spraying and soil fertilizing. The unexplained faults mainly occurring between October and January, from early evening up to early mornings hours, during the periods of increased humidity and dew formation, are likely caused by pollution

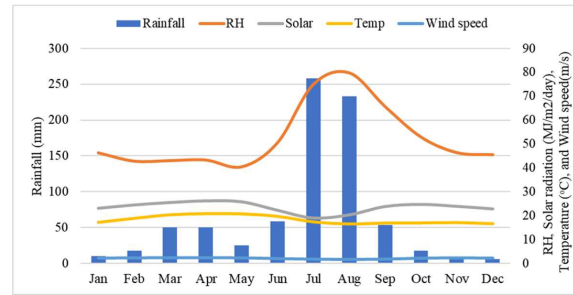


Fig. 16. Average monthly meteorological parameters along the entire route of Bahir Dar II–Alamata 230 kV line [32].

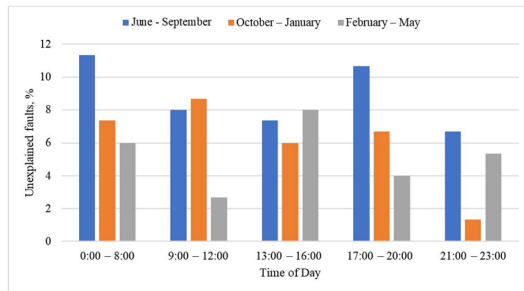


Fig. 17. Time-of-day and month (seasonal) appearance of unexplained faults on Bahir Dar II–Alamata 230 kV line.

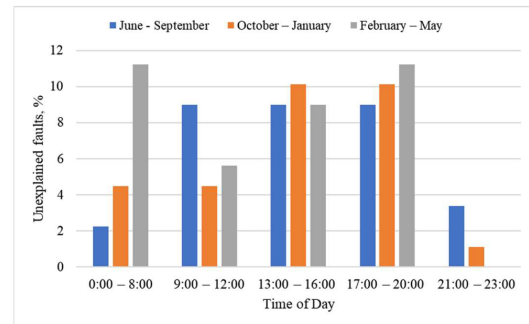


Fig. 19. Time-of-day and month (seasonal) characterization of the unexplained fault on the Shashemene–Alaba 132 kV line.

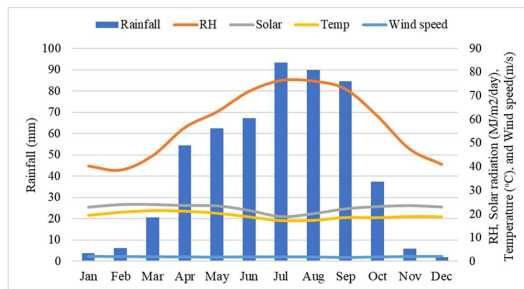


Fig. 18. Average monthly meteorological parameters along the entire route of the Shashemene–Alaba 132 kV line [32].

flashovers. Moreover, unexplained faults that occur between February and May from 0:00–8:00 are also likely to be caused by pollution flashovers and bird streamers.

The lightning intensity in the area is around 14 flashes/km²/year and hence lightning is mainly suspected as the likely cause of unexplained line faults happening from 17:00 to 23:00 during rainy season from June to September and in the late afternoons of April and May. The unexplained faults occurring during harvest and driest period from October to January, in the afternoon from 13:00–16:00, are probably due to fire induced flashovers. External interferences causes are typically responsible for unexplained faults occurring during daytime hours between 9:00 and 12:00 throughout the year and from 13:00–16:00 and 17:00–20:00 in the months that are not typical periods for pollution, lightning and fire caused outages. Thus, pollution caused faults are prevalent for this line, followed by lightning and fire caused faults

outages.

8. Conclusions

In this study, a total number of 8891 fault records that occurred on the Ethiopian transmission lines occurring between 2015 and 2022 are analyzed with the aim of identifying their main probable causes. It was found that 47 % of the faults were of unexplained origin, a rate highly exceeding the internationally acceptable outage limit. These faults were further analyzed with respect to their occurrence in grid regions, voltage levels, time of the day and time of the year and rainfall regimes for identifying their spatiotemporal characteristics and poorly performing lines. Results indicate the fault frequency variations with respect to spatiotemporal occurrence, voltage level and local climate.

A methodology is thereafter presented to truly identify, in retrospect, the major possible root causes of these faults. It is revealed that 27 % of the faults were identified as pollution related, 19 % were caused by lightning activity, 11 % were fire related, and 43 % caused by external object interferences. In addition, possible mitigation measures for avoiding them are also listed. This method of fault cause identification has practical benefits and influences the design, construction, and operational management of new and existing transmission lines. Finally, results of this work lay a base for further research on the identified major root causes of unexplained outages and on methods for automatic line fault identification and classification.

CRedit authorship contribution statement

Berhanu Z. Desta: Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Writing – original draft, Visualization.
Mengesha M. Wogari: Writing – review & editing, Supervision, Project

administration, Conceptualization, Funding acquisition, Resources. Stanislaw M. Gubanski: Writing – review & editing, Supervision, Resources, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

Acknowledgements

The authors wish to acknowledge the financial contribution made by the Swedish International Development Cooperation Agency (Sida) - Ethiopia Bilateral Program Contribution No: 51080124. We would like also to thank the Ethiopian Electric Power (EEP) for allowing and making the 8-year fault data available for this research purpose.

References

- [1] CIGRE Taskforce 33.04.01, Polluted insulators: a review of current knowledge, CIGRE technical publication 158, June 2000.
- [2] R. Macey, W. Vosloo, C. de Tonnell, *Environmental considerations: the practical guide to outdoor high voltage insulators*, eskom power series 3, Crown Publications, Johannesburg, 2004.
- [3] Ethiopian Electric Power, EEP operational and fault data from 2015 to 2022.
- [4] Sandhu, K.S., et al., A joint utility investigation of unexplained transmission line outages, EPRI publication EL-5735 Research Project 2335-1, May 1988.
- [5] L. Peter, R. Vajeth, Strategies for bating environmental influences on overhead lines to improve quality of supply, in: 2005 IEEE Power Engineering Society Inaugural Conference and Exposition in Africa, Durban, South Africa, 2005, pp. 80–87, <https://doi.org/10.1109/PESAFR.2005.1611790>.
- [6] CIGRE Working Group C4.303, Outdoor Insulation in Polluted conditions: Guidelines for Selection and dimensioning– Part 1: General principles and the a.c. Case, 361, CIGRE technical publication, 2008, June.
- [7] Hein Frederich Vosloo, The Need For and Contents of a Life Cycle Management Plan For Eskom Transmission Line Servitudes, Thesis, University of Johannesburg, Johannesburg, South Africa, 2009.
- [8] H.J.J. Bekker, D.A. Hoch, Analysis of factors contributing to unexplained transmission line faults on a high voltage transmission network, in: IEEE AFRICON. 6th African Conference in Africa, George, South Africa 2, 2002, pp. 655–660, <https://doi.org/10.1109/AFRCON.2002.1159988>.
- [9] U.J. Minnaar, F. Nicolls, C.T. Gaunt, Automating transmission-line fault root cause analysis, in: IEEE Transactions on Power Delivery 31, 2016, pp. 1692–1700, <https://doi.org/10.1109/TPWRD.2015.2503478>, Aug.
- [10] U.J. Minnaar, C.T. Gaunt, F. Nicolls, Characterization of power system events on South African transmission power lines, *Elec. Power Syst. Res.* 88 (2012) 25–32, <https://doi.org/10.1016/j.epsr.2012.01.015>.
- [11] J.T. Burnham, Bird streamer flashovers on FPL transmission lines, *IEEE Trans. Power Deliv.* 10 (1995) 970–977, <https://doi.org/10.1109/61.400832>.
- [12] J. He, X. Wang, Z. Yu, R. Zeng, Statistical analysis on lightning performance of transmission lines in several regions of China, *IEEE Trans. Power Deliv.* 30 (3) (2015) 1543–1551, <https://doi.org/10.1109/TPWRD.2014.2363122>, June.
- [13] Y. Hu, Analysis on operation faults of transmission line and countermeasures, *Gaodianya Jishu/High Volt. Eng.* 33 (3) (2007) 1–8.
- [14] M. Major, Investigation of Contamination Hashover As a Possible Cause For Unexplained Faults On the Montana Power Company's 500kV Transmission Lines, Thesis, Montana St. University, Bozeman, Montana, USA, 1993, November.
- [15] Kevin Kleinans, Investigation Into Possible Mechanisms of Light Pollution Hashover of 275kV Transmission Lines as a Cause of Unknown Outages, Thesis, University of Stellenbosch, Stellenbosch, South Africa, 2005, April.
- [16] D.R. Maehl, Investigation of Bird Induced Outages On Montana Power Company's 500kV Transmission lines, Thesis, Montana State University, Bozeman, Montana, USA, 1996.
- [17] IEC/TS 60815-1, Selection and dimensioning of high-voltage insulators intended for use in polluted conditions –Part 1: definitions, information and general principles, 2008.
- [18] B. Chen, Fault statistics and analysis of 220-kV and above transmission lines in a southern coastal provincial power grid of China, *IEEE Open Access J. Power Energy* 7 (2020) 122–129, <https://doi.org/10.1109/OAJPE.2020.2975665>.
- [19] A. Sukhmandan, D.A. Hoch, Fire induced flashovers of transmission lines: theoretical models, in: IEEE AFRICON. 6th African Conference in Africa, George, South Africa 2, 2002, pp. 617–622, <https://doi.org/10.1109/AFRCON.2002.1159981>, vol.
- [20] M. Łoboda, K. Lenarczyk, Correlation between recorded CG lightning discharges and shut-downs of selected HV overhead power transmission lines in Poland, in: 2014 International Conference on Lightning Protection (ICLP), Shanghai, China, 2014, pp. 167–171, <https://doi.org/10.1109/ICLP.2014.6973114>.
- [21] Francisco Moreira, Ricardo C. Martins, et al., Long-term management practices successfully reduce bird-related electrical faults in a transmission grid increasingly used by white storks for nesting, *J. Environ. Manage.* 327 (2023), <https://doi.org/10.1016/j.jenvman.2022.116897>.
- [22] Tena Gerardo Montoya, C. Ramiro Hernández, I. Jorge, T. Montoya, Failures in outdoor insulation caused by bird excrement, *Elec. Power Syst. Res.* 80 (6) (2010) 716–722, <https://doi.org/10.1016/j.epsr.2009.11.002>, ISSN 0378-7796.
- [23] P. Taklaja, R. Oidram, J. Niitsoo, I. Palu, Causes of indefinite faults in Estonian 110kV overhead power grid, *Oil Shale* 30 (2013) 225–243, <https://doi.org/10.3176/OIL.2013.2S.04>.
- [24] NMSA, Climatic and agroclimatic resources of Ethiopia. National meteorological services agency of Ethiopia, Meteorol. Res. Rep. Ser. 1 (1996) 1–137.
- [25] Abebe D., Future climate of Ethiopia from PRECIS regional climate model experimental design Ethiopia, presented climate strategies forum, November 2010.
- [26] Y. Seleshi, U. Zanke, Recent changes in rainfall and rainy days in Ethiopia, *Int. J. Climatol.* 24 (8) (2004) 973–983.
- [27] C. McSweeney, M. New and G. Lizcano, UNDP Climate change country profiles Ethiopia. <http://country-profiles.geog.ox.ac.uk/>, 2012 (accessed 10 May 2023).
- [28] B. Zedalem, M. Mamo, Assessment of external insulation problems related to pollution and climatic conditions in Ethiopia, *IEEE Electr. Insul. Magaz.* 36 (4) (2020) 36–46, <https://doi.org/10.1109/MEI.2020.9111098>, July–Aug.
- [29] National Meteorology Agency (NMA), 2010. Ground flash density map of Ethiopia, 1 March 2006 to 1 March 2010 (10km resolution).
- [30] Vaisala's national lightning detection network (NLDN) and global lightning detection network (GLD360). Lightning data from 2016 to 2022, Available at: <https://interactive-lightning-map.vaisala.com/>, 2022 (accessed 17 March 2023).
- [31] R. Herman, T. Gaunt, Probabilistic interpretation of customer interruption cost (CIC) applied to South African systems, in: 2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems, 2010, pp. 564–568, <https://doi.org/10.1109/PMAPS.2010.5528947>.
- [32] Climate Forecast System Reanalysis (CFSR), Global weather data. <https://globalweather.tamu.edu/> (accessed 12 April 2023).

Paper-II

Assessment of External Insulation Problems Related to Pollution and Climatic Conditions in Ethiopia

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Key words: outdoor insulation, pollution severity, Ethiopian power transmission system, insulator testing, climatic conditions of Ethiopia

This article assesses design practices as well as describes meteorological and environmental conditions that affect selection of outdoor insulators in Ethiopian transmission and distribution systems.

Introduction

Ethiopia is nowadays in urgent need of developing a modern power grid to meet the growing demand for reliable, cost-effective and environmentally friendly transmission and distribution of electric energy. The population growth, as well as development of various industries and agricultural and mining activities, increases pollution sources and yield new types of pollutants. Ensuring the safety and reliability of the network operation is thus among the top priorities for the local power companies. In addition, proper selection and dimensioning of outdoor insulation play a significant role in preventing or limiting the number of pollution induced flashovers on high voltage (HV) insulators in high voltage overhead lines, power generation plants and substations.

Presently in Ethiopia, the primary transmission lines operate at 400 kV, 230 kV, 132 kV and a 500 kV DC line is under construction for connection with Kenya. The national grid is divided into nine operational regions, including Addis Ababa, Central, Northern, North-Western, North-Eastern, Eastern, Southern, South Western, and Western regions [1]. Figure 1 shows the existing and planned transmission network of Ethiopia.

As flashovers of polluted high voltage insulators remain one of the major problems for the operation of Ethiopian power system, detailed research is necessary to assess the general and local environmental pollution conditions as well as meteorological information for accurately estimating site pollution severity levels to enable proper selection of insulators to meet the required pollution flashover performance. This is expected to help in developing a pollution severity map for the whole

country, which is crucial to enable in-depth statistical analysis of various pollution scenarios and flashover risk assessment.

This article presents the initial stage of the work undertaken for assessing environmental and climatic conditions as well as the policies adopted for insulator selection for the existing and planned transmission and substation projects. It also attempts to evaluate the existing maintenance strategies and plans and, finally, to estimate and classify regions according to the pollution type and the severity level. Such a baseline assessment has been done in close cooperation with Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU) companies to select candidate test sites characterized by increased risk for pollution effects and concentrating future research projects in areas of planned power network installations (AC and DC).

Climatic and Meteorological Conditions in Ethiopia

Information on the types of environmental conditions, such as source of pollution, deposition rates of soluble and insoluble contaminants and meteorological parameters, are needed to properly characterize insulator environment, and they vary broadly in Ethiopia. Parts of the Northern, North-Western, Central and Southern regions of the country are within the Ethiopian highland and mountains (Semien mountains) and have an altitude reaching 4500 m above sea level. These are the regions where most of the agricultural activities concentrate, and are relatively industrialized and populated with a large amount of carbon release and smoke from cars and households. The North-Eastern and parts of Eastern regions are in the Afar depression. This area of about 1200 km² is covered by salt deposits. It is a part of the Greater Rift Valley in East Africa with its lowest point at 162 m below sea level. Also, Danakil desert is in the North-Eastern region, where there are several saline lakes and salt mining activities are very common. The North-Western, Western and South-Western, Southern regions of Ethiopia are covered by vegetation, shrubs and forests with higher usage of fertilizer and chemical spray from the intensive agricultural and mining activities. Most of the Eastern

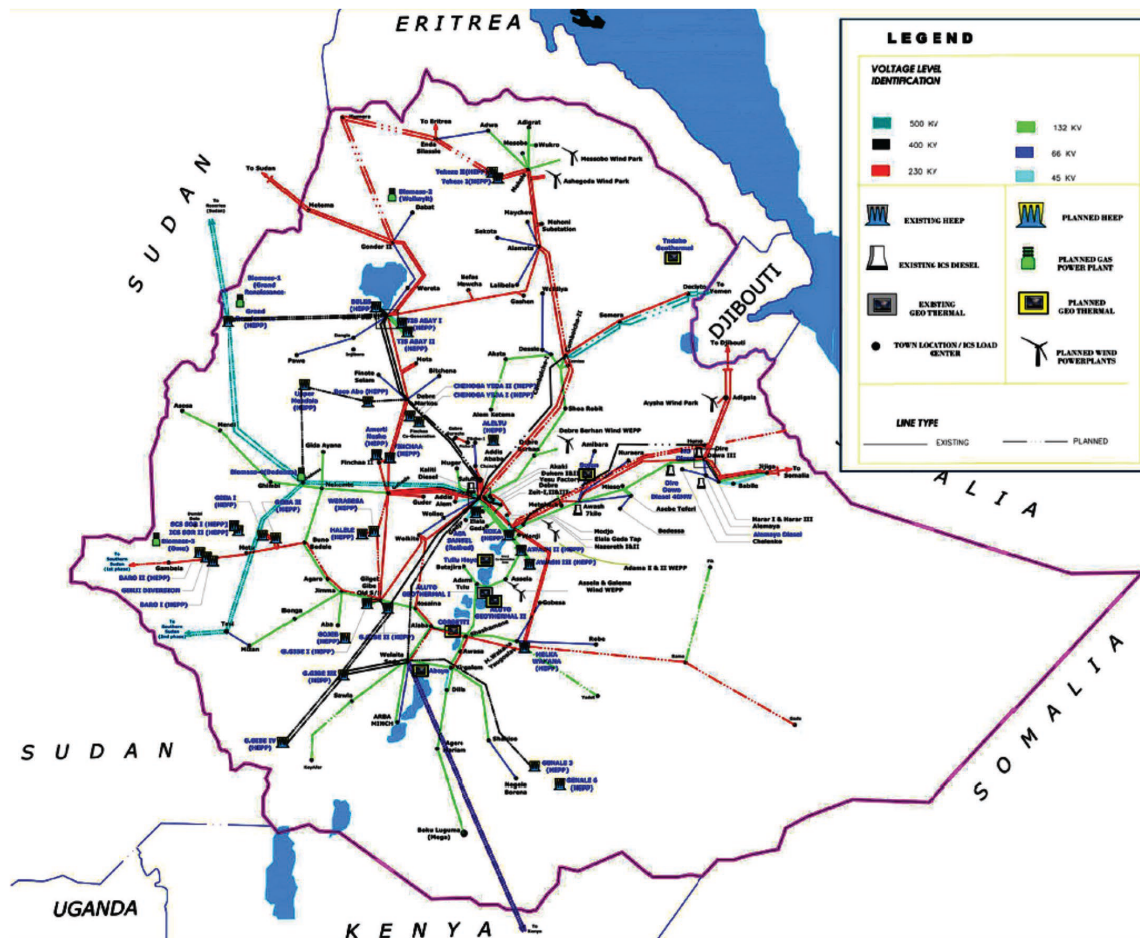


Figure 1. The existing and planned transmission network of Ethiopia (source: Ethiopian Electric Power (EEP) company [1]).

and South-Eastern regions are desert areas covered by grasslands with limited rainfall, very heavy and frequent sandstorms and salt fog sprays carried by wind from the Red Sea and the Arabian Sea.

As Ethiopia is situated near the equator, the climate is, in general, tropical and the weather is characterized by distinct wet and dry seasons. There are also dry hot desert areas around Semera and Ogaden with little rain. No real cold weather appears, although temperature drops sharply at night. Tropical or semi-desert steppe with a short rainy season, during which the rains are unpredictable and varying much from place to place, are found in the North-Eastern, Eastern and South-Eastern parts of Ethiopia. To provide some insight into the general climatic condition in Ethiopia, the meteorological parameters maps are shown in Figure 2(a) to (d). The meteorological information presented in the Figure are long-term annual average values (30 years), obtained from the Climate Forecast System Reanalysis (CFSR), which assimilates observations from ground stations

and observed estimates from multiple satellite, air balloon and aircraft observations. The data have a spatial resolution of approximately 38 km and are available since 1979 [2].

The altitude of installation and the population density have their own impact on the performance of insulators and on the type and source of pollutants. Figure 2(e) and (f) present respectively the altitude and population density for the entire country. The altitude information is extracted from a 30 m resolution Digital Elevation Model (DEM) data from the Shuttle Radar Topography Mission (<https://earthexplorer.usgs.gov/>) [3]. The population density data are collected from Global Gridded Population Database from the Center for International Earth Science Network (CIESIN) at Columbia University and International Center for Tropical Agriculture (CIAT) [4].

It can be seen in Figure 2(a) that the annual average temperature can be as low as 12°C in the Northwestern, Central, and parts of South-Western regions of the Ethiopian highlands and plateau, whereas it reaches up to 34°C in the lowlands of North-

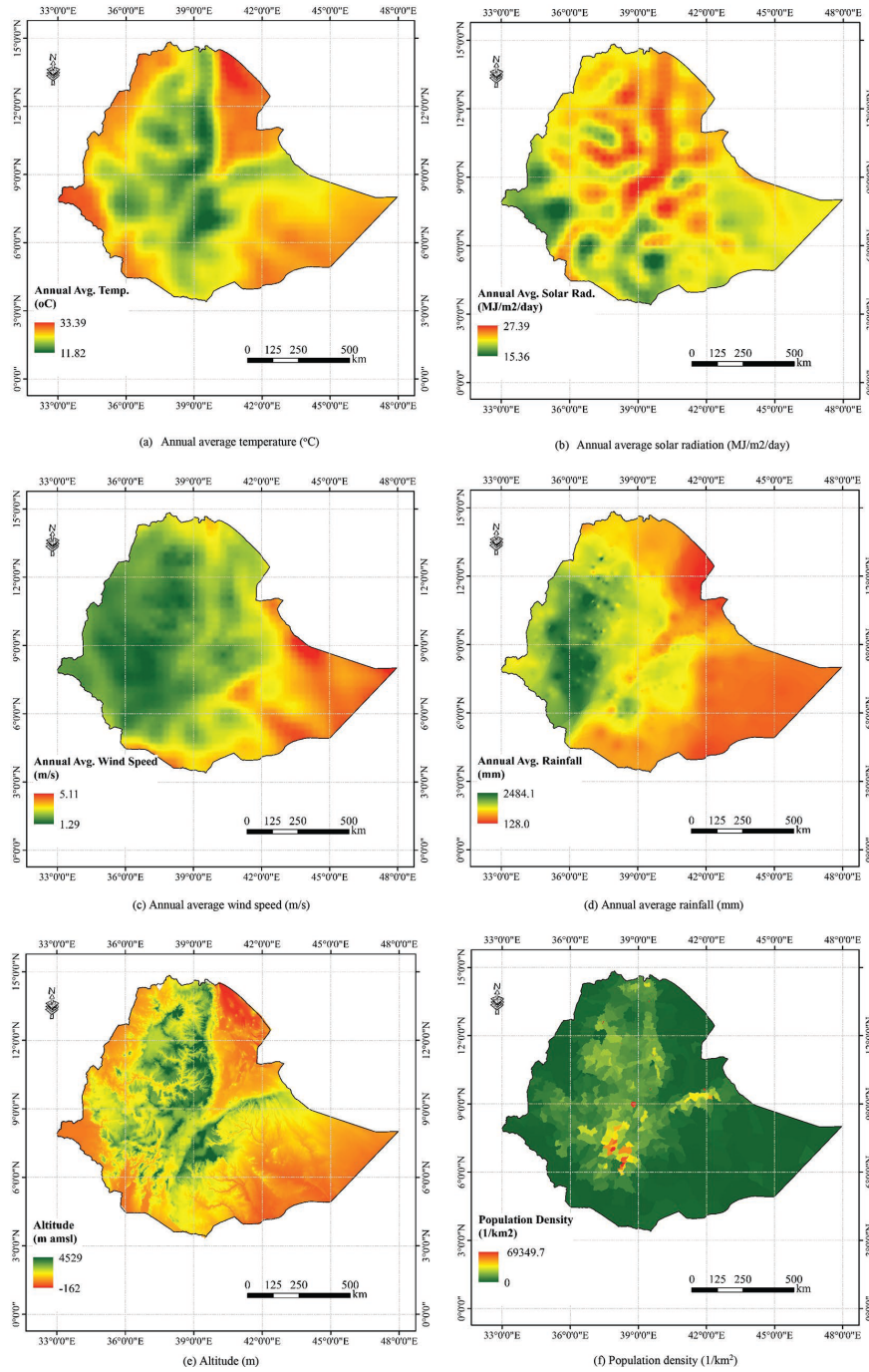


Figure 2. The general meteorological condition, altitude and population density in Ethiopia [2], [3], [4]. (a) Annual average temperature (°C). (b) Annual average solar radiation (MJ/m²/day). (c) Annual average wind speed (m/s). (d) Annual average rainfall (mm). (e) Altitude (m). (f) Population density (1/km²).

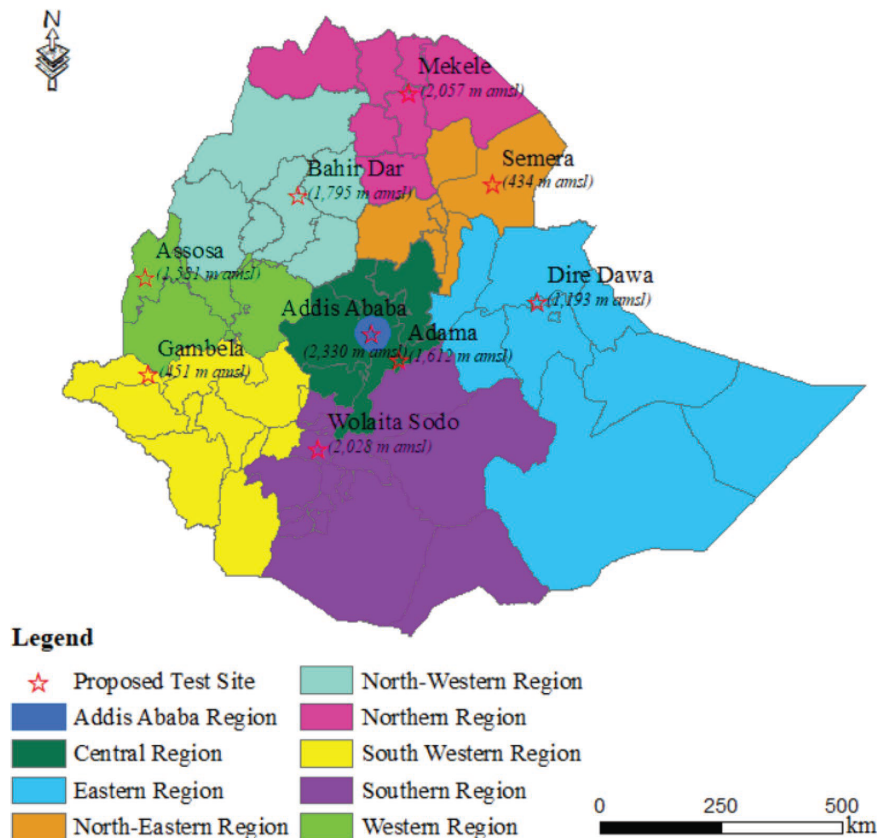


Figure 3. Locations of pollution test sites in Ethiopia.

Eastern (Semera) and East (Adama, Dire Dawa and Somali) regions. Gambella in the West regions of the country has the highest monthly maximum average temperature of above 30°C in February, March, April and June and lower temperatures in the other months.

The maximum annual average solar radiation varies between 27.4 MJ/m²/day and 15.4 MJ/m²/day, as shown in Figure 2(b). Central and North-Eastern regions in the Rift Valley have the highest monthly average solar radiation recorded in the months of March, April and May. The Western and Southern regions have relatively lower solar radiation.

The annual average wind speed is found to be lower around Northern, North-Western, Western and South-Western regions, with the minimum value of 1.3 m/s and higher values are recorded in the Eastern region (Dire Dawa and Somali region) with the maximum annual average value of 5.1 m/s, as shown in Figure 2(c). According to long-term studies in each region, the dominant wind direction is from the east (from the coastal areas of the Red Sea and the Gulf of Aden) toward the Western part of the country. The highest monthly maximum average wind speed in Dire Dawa is above 3 m/s and occurs during June, July

and August and it strongly influences accumulation of pollution on insulators installed in the area.

The annual average rainfall varies from about 128 mm in the arid area of North-Eastern (Danakil desert) and South-Eastern (Ogaden) regions to nearly 2500 mm in parts of North-Western region (Bahir Dar), Western region (Assosa) and South-Western region (Gambella). The other regions have relatively lower annual rainfall. In these areas, the rains do not occur at all during some years, causing droughts. Most of the rainy periods begin in early June and continue until the end of September. Hence, the natural washing of insulators is likely during these periods.

In Ethiopia, the climate varies mostly with altitude, and it is temperate on the plateau, the highlands, which comprise much of the country area, and hot and arid in the lowlands. As shown in Figure 2(e), Ethiopia has the lowest altitude at its North-Eastern part, reaching 162 m below sea level at Danakil Depression. The Ogaden area in Somali region and Gambella in the South-Western region also have very low altitude. In contrast, the Northern and parts of the North-Western region, where Ethiopian highlands and mountains are located, have relatively

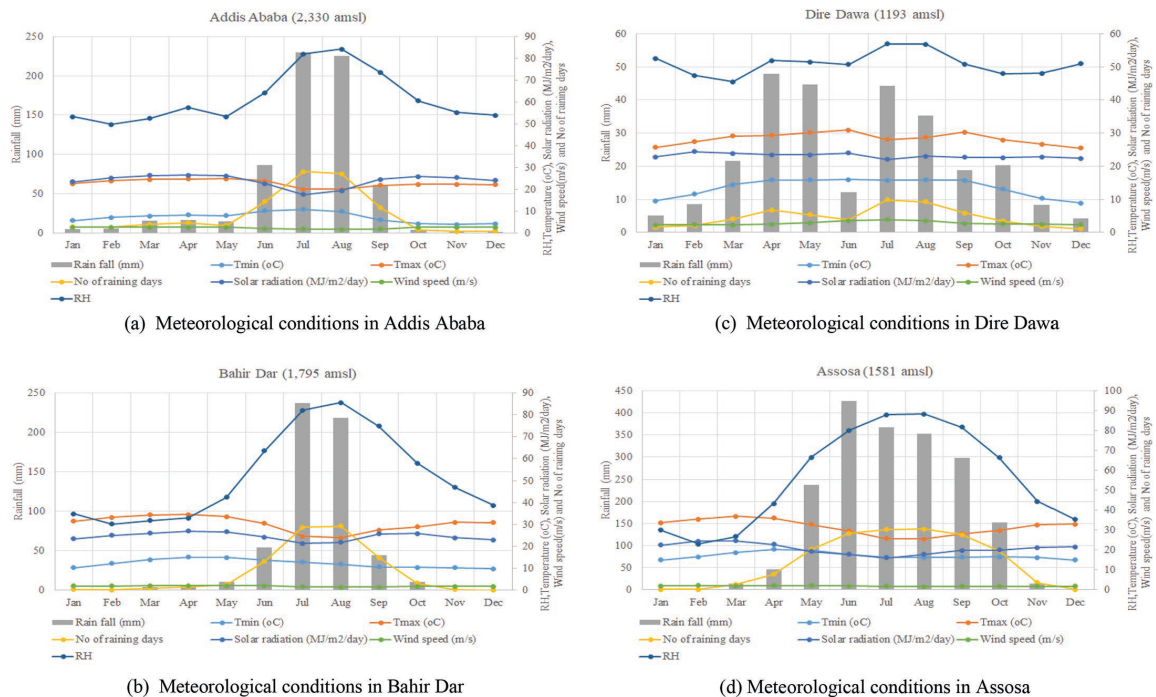


Figure 4. Examples of yearly variations (based on 30 years data) of meteorological parameters for the selected four test sites in Ethiopia. (source: Climate Forecast System Reanalysis (CFSR)) [2]. (a) Meteorological conditions in Addis Ababa. (b) Meteorological conditions in Bahir Dar. (c) Meteorological conditions in Dire Dawa. (d) Meteorological conditions in Assosa.

high altitudes with the maximum of 4500 m above sea level at Ras Dashen top.

With only about 20% of the population concentrated in urban areas, most Ethiopians live in scattered rural areas. As shown in Figure 2(f), the highest density is found in the highlands of the North, North-Western, Southern and Central regions of the country, particularly around the centrally located capital city of Addis Ababa. Areas of the North-Eastern, Far East and South-Eastern areas are sparsely populated.

Nine cities representing the vast variation of the climatic conditions are selected in each operational region of the Ethiopian power grid for continuation of pollution related research. The selection is based on considering the existence of transmission lines and substations that have the commercial and strategic importance, number and degree of importance to customers and connected load, voltage levels and climatic conditions. It is assumed, at this stage, that other locations of each region experience similar meteorological conditions. Figure 3 shows the test site locations within the nine operational regions of the Ethiopian national power grid.

Figure 4 illustrates variations of detailed meteorological conditions for Addis Ababa, Bahir Dar, Dire Dawa and Assosa regions, which are typical examples among the selected test sites to represent the variation of climatic conditions along transmission lines and at substations. The presented parameters include monthly average wind speed, rainfall, temperature (min

and max), altitude, average number of rainy days, relative humidity and intensity of solar radiation.

During the last few years, significant variations of the climatic condition as well as new development of large industrial and transport networks (cement, fertilizer, steel and iron factories), increased mining activities, and agricultural developments have contributed to the increase of pollution levels and appearance of different pollution mixtures that significantly affect the performance of existing outdoor insulators in service. If not considered early enough and carefully, the effect can escalate with time as well as affect the newly planned projects. It is also important to note that most of the existing transmission lines that connect the various regions of the country cross areas of different climatic and pollution conditions, in which the required insulator performance varies.

The classification of the operational regions of the Ethiopian transmission network, in terms of the general types of environments and types and pollution sources, is presented in Table 1. It is done by estimating the site pollution severity (SPS) class, according to IEC 60815-1:2008 [5].

The estimation of the pollution severity level has been done using the environmental and meteorological information in combination with the service experience and data on operational flashover incidents of insulators from lines and substations in-service on or close to the site and by considering qualitative indications for typical environments defined in [5].

Table 1. Types of environments and pollution in Ethiopian grid regions.

Region (representative site in the region)	General types of environments and types of pollution	Description of the environment/ region	Estimated site pollution severity (SPS) class
Addis Ababa (Addis Ababa)	Industrial, Type A (carbon, cement, gypsum, metallurgical, chemical substances and wastes, smoke from cars and households)	400 kV and 230 kV transmission lines (TL) and substations are in close proximity to an extended industrially developed area, typically with numerous man-made pollution sources producing carbon leftovers. It is the most densely populated region in Ethiopia. Since almost all TLs are connected to this region, it has very high strategic importance. Pollution originating from transport infrastructure and households is very high.	Heavy
Central (Adama)	Mixture of agricultural and industrial pollutants, Type A (carbon, sand, dust, cement, smoke from cars and households)	230 kV and 132 kV TLs and substations are in this region. It is in the Great Rift Valley region with many agricultural activities thus subjected to pollution from ploughing and crop spraying of fertilizers, products of burning and salts present in the soil; limited industrial pollution and regular rain washing. Sand and dust storms are common.	Medium
Northern (Mekelle)	Mixture of desert and light industrial pollutants, Type A (carbon, cement, gypsum, salty dust, chemical wastes, smoke from cars and households)	230 kV and 132 kV TLs pass through and are in close proximity to some industries and mining activities, which are sources of pollution. Mostly extended periods of dry conditions and desert area with salty and sandy soil. Dust storms are common. Subject to wind-borne salt particles from Afar depression region and Red Sea. Close to desert and open dry land and subjected for a long period (several weeks or months) of dry pollution accumulation.	Heavy
North-Western (Bahir Dar)	Mixture of agricultural and light industrial pollutants, Type A (ploughing, crop spraying, fertilizers, smoke from cars and households)	Double circuit 400 kV TL from Beles to Addis Ababa and double circuit 230 kV line to Sudan with very high commercial and strategic importance passes through the region. Substations are located in close proximity to many agricultural activities, thus subject to pollution from ploughing, crop spraying by chemicals and fertilizers, products of burning and bird droppings. Limited industrial pollutions from cement factories around Debre Markos and Dejen. Most of the lines are located close to highways with records of some vandalism activities.	Medium
North-Eastern (Semera)	Mixture of desert, coastal and light agricultural pollutants, Type B (saline lakes, sandy soils and salty dust storms, direct salt sprays)	230 kV TLs and planned 500 kV TL to Yemen with very high strategic importance. Substations are located in proximity to salt mining and agricultural activities. Sugar factory (light desert-industrial mixture). Subject to wind-borne salt particles and sandy soils with extended periods of dry conditions. Also directly subjected to salt sprays from the Red Sea and Gulf of Aden and dense saline fog and salted dew formation on insulator surfaces.	Very heavy
Eastern (Dire Dawa)	Mixture of desert, coastal and light industrial pollutants, Combination of Type A and Type B (sandy soils and salty dust storms, direct salt sprays)	230 kV TL to Djibouti. Substations are located in close proximity to cement factories. Very high economic and strategic importance, with the Ethiopia-Djibouti railway connection passing through. Heavy sandstorms and salted dews are common. Desert areas with fast accumulation of sand and salt, with regular moisture condensation and extended periods of dry conditions. May also be exposed to direct salt sprays from Red Sea, Gulf of Aden and Indian Ocean. High possibility of salted dew formation on insulator surfaces. Directly subjected to highly conductive contaminants or cement type dust of high density and frequent wetting by fog or drizzle.	Very heavy
Southern (Wolaita Sodo)	Agricultural, Type A (chemical wastes, fertilizers, ploughing)	500 kV HVDC converter station and TL to Kenya, 400 kV TL to Addis Ababa and 230 kV TL and substations are in this region with very high strategic importance. Most of the land is covered with forest and shrubs with regular monthly rain washing. Many agricultural and mining activities. Subjected to pollution from chemical wastes, ploughing or crop spraying.	Medium

(Continued)

Table 1 (Continued). Types of environments and pollution in Ethiopian grid regions.

Region (representative site in the region)	General types of environments and types of pollution	Description of the environment/ region	Estimated site pollution severity (SPS) class
South-Western (Gambela)	Agricultural, Type A (chemical wastes, fertilizers, ploughing, crop spraying)	Planned 500 kV TL extending from Dedessa substation to South Sudan and existing 230 kV TL and substation are in this region. Most of the land is covered with natural forest and shrubs. Many large farmlands and agricultural activities with regular rain washing. Subject to pollution due to ploughing, crop spraying with chemicals and fertilizers, products of burning, and bird droppings.	Medium
Western (As-sosa)	Agricultural, Type A (chemical wastes, fertilizers, ploughing, crop spraying)	This is the region where the Grand Ethiopian Renaissance Dam (GERD) hydropower plant is situated with the capacity of 6000 MW and a planned 500 kV double circuit line to Sudan will pass. 400 kV TL to Bahir Dar and 132 kV TL and substations are in the region. Very high economic and strategic importance to the country with many agricultural and mining activities. Most of the land is covered with forest and shrubs, with regular monthly rain washing. Subjected to contaminant from chemical wastes, ploughing or crop spraying. Prevailing wind not directly from these pollution sources.	Light

Measurements of parameters like equivalent salt deposit density (ESDD), non-soluble deposit density (NSDD) or any other site-assessment have so far not been performed and their lack has its own impact on the accuracy of the presented estimates, which have to be further verified by performing, in the future, an extensive measurement program.

According to the general types of environment and climatic conditions assessed, five regions of different types of pollutions have been identified. These include agricultural pollution, industrial pollution, mixture between desert and coastal pollution, mixture between agricultural and industrial pollution, and finally mixture between desert and industrial pollution. The map of the estimated site pollution severity (SPS) classes of the grid regions is shown in Figure 5.

Policies and Practices of Power Companies Regarding Present and Future Insulator Selection

It is evident that the national and power company's policies and the economic situation dictate how the selection of insulator types and materials proceeds. This, in turn, affects the choice of insulator profile, which is mainly based on the type of environment. The environmental and system constraints also affect the choice of material type [6]. The Ethiopian Electric Power (EEP) company, the only power company in the country, owned by the government, is responsible for designing, specifying, construction and supervision of all transmission lines and substations in Ethiopia. The purpose of this section is to assess the company's approach and practices for selecting and dimensioning outdoor insulators. These include examining the environmental conditions considered in the selection process and evaluating the procedures for insulator monitoring and maintenance. As per the information collected and analyzed, most of the existing lines and substations in the Ethiopian power grid use glass, por-

celain and recently, in a limited manner, composite insulators. In general, glass insulators are the dominant insulator and most of the faults observed are associated with them.

The major limitation identified in this assessment is that currently the company lacks consistent guidelines that consider specific application requirements and environmental conditions where the insulators are to be used. For most of the new projects, insulator selection and dimensioning have been undertaken without a detailed study of the service experience from the existing lines and substations. Field measurements of site pollution severity at test stations located in the same geographical area or similar environmental conditions are not performed and used as input data for the designing and selection process. Only estimates of site pollution severity are used and the system requirements and economic reasons dominate the selection of insulator material and type.

If the choice is principally guided by economic factors, without properly considering environmental conditions and the service experience, an acceptable balance between initial investment, maintenance costs and replacement costs is not achieved. This approach is relatively simple and cheap but possibly yields over- or under-dimensioned solutions. Neither clearly defined test method description nor acceptance criteria for evaluating insulator suitability have been found in project documentations. The documents do not report on any service experience records or any test field measurements aiming to estimate site pollution severity. The usual trend is to assume site pollution severity class as a worst case (either heavy or very heavy) and applying the corresponding minimum unified specific creepage distance (USCD) rule from international standards [5] [7] [8], which ultimately leads to a less economical solution due to over design of insulators. Probably, cost and time constraints do not allow for a thorough site assessment. This is a serious limitation, which forces the company to accept designs based on limited information, but nevertheless, on sound assumptions. This is a situation that should, as far as possible, be avoided as it may

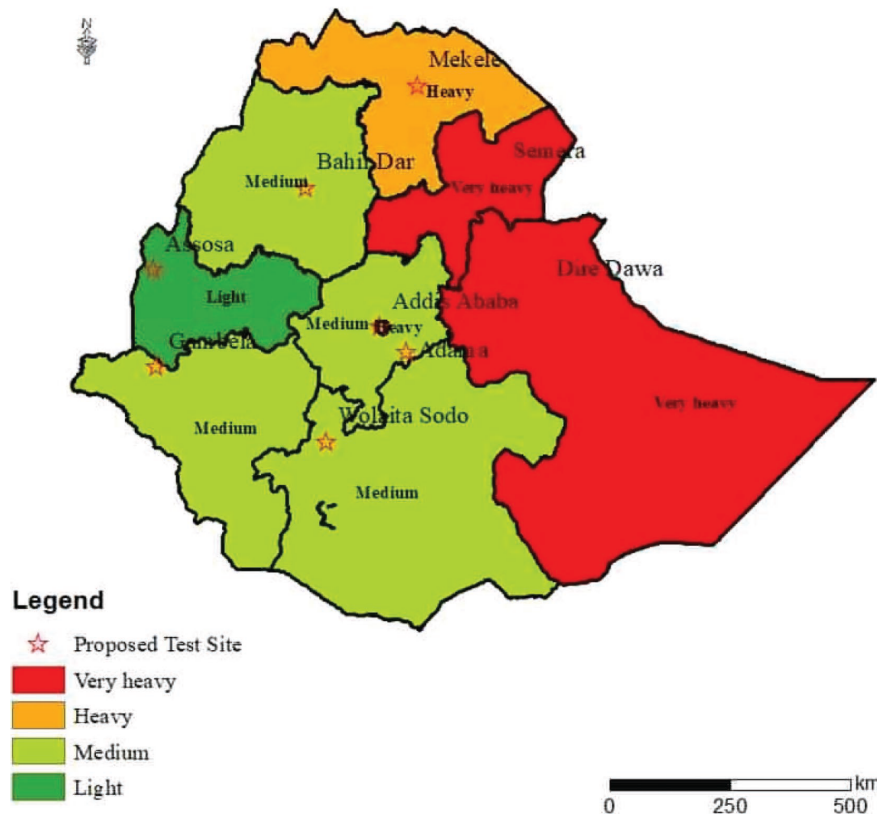


Figure 5. Estimated distribution of site pollution severity (SPS) classes of Ethiopian grid regions.

lead to increased maintenance costs and is, in longer terms, neither economical nor reliable [9].

Moreover, in most of the EEP projects, there is a trend to use the same type and size of insulators for the entire route of a line, even if the line crosses different geographical and environmental conditions. Failure to apply important corrections, especially for altitude, were found to be the main reason for a poor performance of external insulators in many parts of the country. Such incidents are especially common where the lines cross the Ethiopian highlands and plateaus of the Northern and North-Western regions, where altitudes exceed 2000 m above sea level and significantly vary.

Yet another issue identified as a limitation within the power company operational practices is unable to make use of clearly identified insulator pollution monitoring techniques. This is considered to be a serious problem in terms of securing reliability in power system operations. In addition, the company lacks a scheduled maintenance plan and palliative practices to achieve the required insulator performance throughout the expected lifetime. EEP should thus elaborate such measures to prevent outdoor insulators from failing too early, based on detailed studies of the environments as well as the economic and logistic feasibility.

Insulation Problems Met in Practice and Fault Performance Records

As per the general information collected from technical experts of Ethiopian system operator, insulator flashovers seem to be one of the main causes of the observed failures, and the incorrect dimensioning, not considering the complicated and dynamic interaction with the environment, is believed to be the main reason. A variety of data from service experience or laboratory tests may be used to select insulators. Service experience is useful, but it should be kept in mind that it may be based on pollution performance of lines with over-designed insulation [6]. One of the challenges faced during this study, was the lack of well-organized data and detailed fault records. A usual practice is to record earth faults and transient earth faults in substation logbooks without specifying real cause of these events that brings a difficulty in distinguishing if they originate from pollution flashovers or for other reasons, for example lightning flashes. In an attempt to find a pattern in the monthly records of transient earth faults with meteorological variation and environmental conditions, Figure 6 presents a summary of the records from 400 kV, 230 kV and 132 kV transmission lines

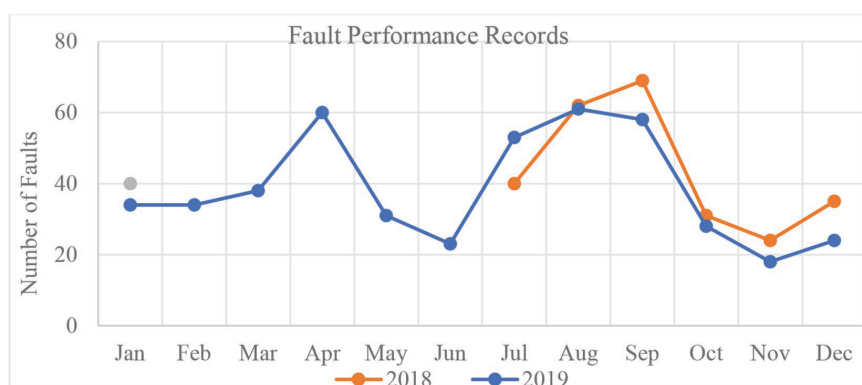


Figure 6. Earth fault/transient earth faults records on HV transmission lines in Ethiopian power grid.

of Ethiopian power grid during the period from July 2018 to January 2020 [10].

By examining the number of transient earth faults occurring in each month and comparing the pattern for each year, it can be observed that the number of faults follow the seasonal variations of the meteorological parameters, thus transient earth faults occurred during dry periods and seasonal winds with salt spray and dust storms (approx. during 8 months between October 2018 to May 2019), are assumed to be dominantly caused by pollution induced flashovers. This constitutes around 58% of the total earth faults recorded throughout the year. It thus is estimated that the high voltage transmission system suffers from about 270 faults due to pollution induced flashovers each year. This estimate should, however, be further verified by research activities using fault cause identification methods.

The main reason for unexpected and repeated insulator failures is the usage of the same type and size of insulators throughout the entire route of the transmission lines crossing different climatic conditions, which is the case for almost all the critical lines of the Ethiopian grid. In addition to improper selection of insulators that do not fit local conditions, a substantial number of failures also occurs due to the gradual change of climatic and meteorological conditions as well as of the increasing number of large industrial and agricultural projects. This has a strong impact on the appearance of new pollution types and accumulation patterns. The problems escalate when monitoring and maintenance measures are not applied in time.

Typical examples are failures of glass and porcelain suspension insulators in the Northern and North-Eastern desert areas, around Mekelle and Semera, where the insulators are exposed to a mixture of industrial and desert borne pollutants. Accumulation of salt particles carried by winds from saline lakes in Danakil desert might also be the cause for repeated insulator failure in these areas. Similar incidents are also reported from the Eastern region around Dire Dawa and Jijiga where dust storms and direct salt sprays from the Red Sea, Indian Ocean and Gulf of Aden are frequent. Prolonged dry periods with little or no rain, and hence with very low probability for natural cleaning, cause a rapid build-up of pollution on insulator surface in both these regions. Figure 7 shows an example effect of a massive dust storm that extended from Djibouti and hit Dire Dawa and Jijiga areas on May 18, 2019. Dust storms periodically reaching Ethiopia from Sahara Desert occur in the months of March and April in the Northern region and parts of the North-Western region around Gondor and Bahir Dar. Other examples are incidents occurring on glass insulated lines, like 132 kV line from Adama to Awash, 230 kV line around Gehedo, Semera and on 400 kV line from Debre Markos to Sululta (especially on tower number 342 around Muketuri) and on 400 kV line from Bahir Dar to Grand Ethiopian Renaissance Dam (GERD).

Pollution related problems are not limited to only transmission lines and substations. There are also reported failures on distribution level insulators, up to 33 kV, which are mostly as-



Figure 7. Effect of dust storms in Dire Dawa (a and b) and Jijiga (c), May 2019.



Figure 8. Examples of insulators damaged by pollution flashover events.

sociated with local sources of contaminants, altitude variations, poor quality of insulator materials and manufacturing process, especially those manufactured locally.

Figure 8 shows examples of insulators (132 kV cap and pin porcelain and 230 kV long rod composite) damaged by pollution flashovers at Adama and Hurso substations in the Central and Eastern regions of the Ethiopian power grid.

Conclusions

This article summarizes information of climatic and environmental conditions in Ethiopia and classifies them into five

different categories in terms of pollution types and sources by estimating the site pollution severity class of nine operational regions in the Ethiopian power grid. This classification has been used as a base for selection of candidate test sites for detailed research work that aims to determine a more accurate pollution severity map of the entire country.

The article also presents a critical analysis of the Ethiopian grid operator's (EEP) approach to the selection and dimensioning of insulators for HV transmission lines and substations. The company has so far neither systematically used practices based on service experience from the existing insulators nor used site pollution level measurements and laboratory tests. No evidence

of such practices have been found in documentations of new projects, other than estimation of worst-case scenarios as the input for insulation design practices.

It is evident that EEP never applied consistent and standard HV insulator selection and dimensioning approaches for its pervious, ongoing and upcoming projects. The increasing number of faults and unplanned outages the system suffers due to unpredictable, frequent and early failure of its insulators are the manifestations of such poor insulator design and selection trends. This is a serious problem in terms of both the initial costs that often yield over-dimensioning of applied insulation and towers as well as the increased maintenance costs.

The company should, as soon as possible, include in its design team experts that are able to address the challenges related to pollution performance of outdoor insulation. For now, this issue might not be given enough attention due to a relatively small number of outages, but this assessment shows that there are enough indications that pollution related flashovers will escalate in the coming years and they may affect the overall operation of the Ethiopian power system and hence the country's growth and economy. It is, therefore, recommended that actions targeting development of a precise pollution severity map of Ethiopia should start before it is too late.

References

- [1] Ethiopian Power System Expansion Master Plan Study, "Transmission Planning Report", Volume 4, September 2014.
- [2] Climate data source: <https://globalweather.tamu.edu>
- [3] Altitude data source: <https://earthexplorer.usgs.gov>
- [4] Population density: <http://sedac.ciesin.columbia.edu/data/collection/gpw-v4>
- [5] IEC/TS 60815-1, "Selection and dimensioning of high-voltage insulators intended for use in polluted conditions –Part 1: Definitions, information and general principles", 2008.
- [6] CIGRE Working Group C4.303, "Outdoor insulation in polluted conditions: Guidelines for selection and dimensioning – Part 1: General principles and the a.c. case", CIGRE technical publication 361, June 2008.
- [7] IEC/TS 60815-2, "Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 2: Ceramic and glass insulators for a.c. systems", 2008.
- [8] IEC/TS 60815-3, "Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 3: Polymer insulators for a.c. systems", 2008.
- [9] CIGRE Task Force 33.04.01: "Polluted insulators: a review of current knowledge", CIGRE technical publication 158, June 2000.
- [10] Operation history from July 2018 to January 2020 collected from the national grid Load Dispatch Center (LDC).



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Paper-III

Article

Investigation on Pollution-Induced Flashovers of In-Service Insulators in Ethiopian Power Transmission Lines

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Abstract: Power transmission lines in Ethiopia are experiencing an alarmingly high frequency of unexplained outages triggered by environmental factors, which significantly undermine the reliability of the country's power system. This paper presents investigations aiming to identify those among the unexplained fault records that have been caused by pollution induced flashovers. An identification method is developed, which associates the contextual fault features, such as information about the characteristics of the fault, fault location, and time of day, as well as month of its occurrence with local meteorological/climatic and environmental conditions. A total number of 4231 unexplained faults, recorded between 2015 and 2022, were analyzed. Among them, 1045 faults (24.7%) were identified as being most likely caused by pollution induced flashovers. The entire network suffered from more than 130 pollution-induced flashovers annually with a frequency of about 0.8 faults/100 km/year. The fault frequency strongly differed among the grid regions, being highest in the Northeast and lowest in the Southwest region. Moreover, the performed analyses also concentrated on the evaluation of the pollution performance of various insulator types employed in the network. The results indicate that porcelain insulators have the highest pollution-induced flashover intensity of 1.47 faults/year/1000 units, followed by silicone rubber polymeric composite insulators and glass insulators with the respective intensities of 1.21 and 0.83 faults/year/1000 units. These results indicate that despite the high expectations towards the pollution performance of silicone rubber polymeric insulators, their use in the Ethiopian climatic and environmental conditions appears to be unsatisfactory.

Keywords: Ethiopian power transmission system; unexplained outages; pollution flashover; outdoor insulators; silicone rubber polymeric insulators; site pollution severity



Citation: Desta, B.Z.; Wogari, M.M.; Gubanski, S.M. Investigation on Pollution-Induced Flashovers of In-Service Insulators in Ethiopian Power Transmission Lines. *Energies* **2024**, *17*, 2007. <https://doi.org/10.3390/en17092007>

Academic Editor: Gang Liu

Received: 10 February 2024

Revised: 14 March 2024

Accepted: 21 March 2024

Published: 24 April 2024



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1. Introduction

Overhead transmission lines of Ethiopian national grid are subject to a variety of environmental factors that influence their performance, including lightning, pollution, and various climatic conditions. Inadequate design and maintenance in response to environmental influences can lead to a deterioration in power system reliability, resulting in significant financial consequences [1,2]. Therefore, conducting an in-depth analysis of transmission line faults is crucial, as it aids in identifying the primary causes of line outages and devising preventive measures.

The 132, 230, and 400 kV HVAC lines owned and managed by the Ethiopian Electric Power company (EEP) spans a total length of 16,875 km, as of 2022 [3]. The insulation of these lines is based on standard porcelain and glass cap-and-pin insulators strings as well as on long-rod polymeric composite insulators made of silicone rubber. A high number

of outages caused by external factors have occurred on these lines, mainly in the form of single line-to-ground faults.

Our previous study [4] has shown that out of the total of 8891 unplanned interruptions that occurred between 2015 and 2022, 4231 (47%) were of unexplained origin. This fault intensity significantly compromises the reliability of the system. Each such incident results in the frequent operation of circuit breakers and induces transients into the network, leading to the premature wear of the system components, power delivery stops, and resulting financial losses [5–8]. This situation calls for the need to identify the root causes of these faults and for implementing suitable corrective measures.

The EEP transmission network covers various climatic regions and is thus subject to varying environmental conditions, which are thought to be the main factors affecting the line performance. These include various rainfall patterns, lightning intensity, pollution accretion severity, fire occurrence, and others. Lines that are adequately designed for a specific region may not fit well with the other region conditions, where different fault mechanisms dominate [1,9,10]. The pollution type and its severity also vary across the regions. Unfortunately, the understanding and information about pollution-induced faults on insulators is very limited within EEP. It is not listed in the EEP transmission line fault-cause categories and not considered as a possible cause for outages occurring in its transmission systems. Until now, EEP has not had any regular procedure for monitoring pollution severity that could provide information for proper selection and testing of line insulation. Thus, the site pollution severity is often not adequately considered, which consequently results in the inappropriate choice of insulator type and size and yields poor pollution flashover performance of insulators in service [1,11,12].

This work focuses on detailed analyses of the unexplained faults to identify pollution-induced flashovers (PFO) and investigate their geographical and temporal distribution in the Ethiopian power grid. The aim is to identify the regions (location) which are the hotspots for this type of outage, as well as to find the lines that suffer from them the most. Moreover, this work attempts to evaluate the performance of various insulator types installed in the network in terms of their trip-out intensity. This knowledge will further impact the EEP's policy in selection and dimensioning of outdoor insulation for new transmission lines. Additionally, it will enable the establishment of suitable monitoring, maintenance, and inspection procedures for existing lines [12–15].

2. Method for Identifying Pollution Induced Line Faults

It is not always straightforward to identify line faults resulting from pollution flashovers. However, specific contextual characteristic patterns exist to aid in their identification [2,13,14,16,17]. To identify them from the records of unexplained faults, the verification procedure used in this work focused on identifying patterns that could indicate or agree with the recognized characteristic features of pollution-induced faults. These include contextual fault details such as the time and season of occurrence and geographical location of the fault, in addition to climatic and environmental conditions of the affected region [2,9,15–17]. Moreover, information extracted from the voltage and current records during the fault, like the fault duration, success of reclosure events, and operational history, can provide valuable insights [2,15–18].

2.1. Characteristic Patterns and Conditions of Pollution Flashovers

2.1.1. Time-of-Day of Fault Occurrence

For the fault data to align with those expected for pre-deposited pollution and wetting-induced flashover (referred to as a type A pollution flashover process) [11], the fault incidents should be predominantly concentrated between the hours of midnight and the early morning, extending up to 08:00, coinciding with the likelihood of light rain, dew, or mist formation [2,5,9,19]. As nighttime humidity rises, instances of pollution flashovers become more frequent, reaching their highest intensity just before sunrise, around 06:00. Notably, such faults are virtually absent during daytime hours [2,5,9,20]. On the other

hand, bird streamer-related flashovers, a particular case of type B pollution (instantaneous pollution flashover) [11], typically exhibit two peaks linked to the bird's digestive cycle. One peak occurs early in the evening, around 22:00, while the other is observed in the morning at 06:00 [2,6,19]. Studies conducted in Florida, Estonia, and South Africa have reported similar patterns of these faults [2,7,13,19].

2.1.2. Seasonal Patterns of Fault Occurrence

Regarding fault occurrences in connection with the time of year, the majority of pollution-induced outages happen during hot and drier periods, attributed to condensation and moisture absorption during cooler nights. Additionally, these outages are prevalent during seasonal transitions when fog and light rains occur after the hot and dry season [1,5,11,12]. Bird streamer faults exhibit a seasonal pattern linked to the presence of birds or their feeding habits, with their frequency tending to rise during spring [2,6,13,19].

2.1.3. Geographical Location of Faults

The geographical distribution of faults can also aid in determining their underlying causes [14,15,18]. In this context, pollution-induced faults are expected to occur within regions having sources of salty dust from desert and semi-arid areas, as well as pollution from industrial and intensive agricultural activities, busy roadways, and proximity to coastal areas [1,5,11,12,20]. Moreover, in locations supporting birdlife with ample water and food resources, bird streamer faults may also take place [6,7,19,21,22]. Therefore, knowing the geographic position of a fault is instrumental in determining its cause [1,2,11,14].

2.1.4. Climatic and Meteorological Conditions

Several research investigations have indicated the influence of meteorological factors like temperature, rainfall, wind direction and speed, and relative humidity in facilitating the accumulation of pollutants on the surface of insulators and their wetting [1,2,11,13,14]. In this regard, main rainy/wet seasons are characterized by the highest number of days in a month with heavy precipitation (greater than 10 mm). Frequent heavy rainfall washes insulators and reduces the chance of pollution accumulation. In contrast, periods with light rains (rainfall between 1 mm and 10 mm) can contribute to wetting the pollution layer and facilitate flashovers. During dry seasons with a longer number of consecutive days without rain (more than 5–10 days without rain), the accretion of pollutants on the surface of the insulator is high [1,5,13,23].

Moreover, warm day-time temperatures greater than 5 °C are assumed to be favorable for pollution accumulation. Strong winds also contribute to the uneven accumulation of pollutants on insulator surfaces. Elevated humidity levels and/or morning dew, coupled with strong sea winds, establish optimal conditions for rapid accumulation of pollution layers and increase the flashover risk [1,5,13,23].

This study involved determining the geographic coordinates of every transmission line tower across the entire network of Ethiopia. Using ArcGIS 10.5 software, meteorological parameters were assigned to them, and an average of these parameters for all the towers was thereafter computed to denote the meteorological conditions along the entire line under consideration. For very long lines, the average was estimated for shorter sections between substations.

2.1.5. Contextual Characteristics of Line Faults

Voltage and current magnitudes during the fault, the involved phases, duration of the fault, success of reclosure, and other protection data help to suggest the probable reasons behind the fault's origin [6,7,16,17,24]. The fault features extracted from the fault voltage and current waveforms are easily affected by the pre-fault operating state of the system, and there is no direct link between their characteristics and external causes. On the other hand, other contextual fault characteristics, such as time stamps (season, day/night, month, hour), geographic location, meteorological and environmental data, and other information

related to service experience are directly relevant to various external line-fault causes such as lightning, pollution, fire, wind, etc. [16,17]. The pollution flashover fault should usually appear as a transient single line to ground fault with a high rate of successful reclosure. Moreover, it should rather occur under normal operating conditions with steady-state voltages and currents, which ensures that it is not preceded by any lightning or switching overvoltage event or by a drop/distortion of the voltage or increase in the current. The faulted phase voltage should not immediately drop to zero after the fault starts, and the fault current should be low, as the fault resistance is usually high (not solid/metallic short circuiting) [6,7,24].

This set of characteristic patterns and other conditions described above form the basis for classification of grid region and formulating the criteria for assigning the reason of unexplained faults to the pollution flashover category.

2.2. Classification of Grid Regions

The interaction between the meteorological and environmental conditions of Ethiopia, in terms of pollution accumulation, wetting, and natural cleaning ability is used to derive a classification of grid regions. Identifying the season in each grid region that exhibit similar patterns in accumulating a high level of pollution on the insulator surface, conducive for critical wetting and favorable for self-cleaning and an overall reduction in pollution accumulation, is the base for the classification. This facilitates the classification of the country's territory into distinct groups of grid regions and offers a convenient structure for examination of unexplained faults in more detail. Accordingly, the grid management regions of the EEP are classified into four grid region groups. The North, Northwest, Addis Ababa, and Central grid regions of EEP are classified as Group 1 (G1), the West and Southwest regions are classified as Group 2 (G2), the South region is classified as Group 3 (G3), and the East and Northeast regions are classified as Group 4 (G4). Figure 1 shows the geographical location of these grid regions with the indicated annual average rainfall of the Ethiopian territory.

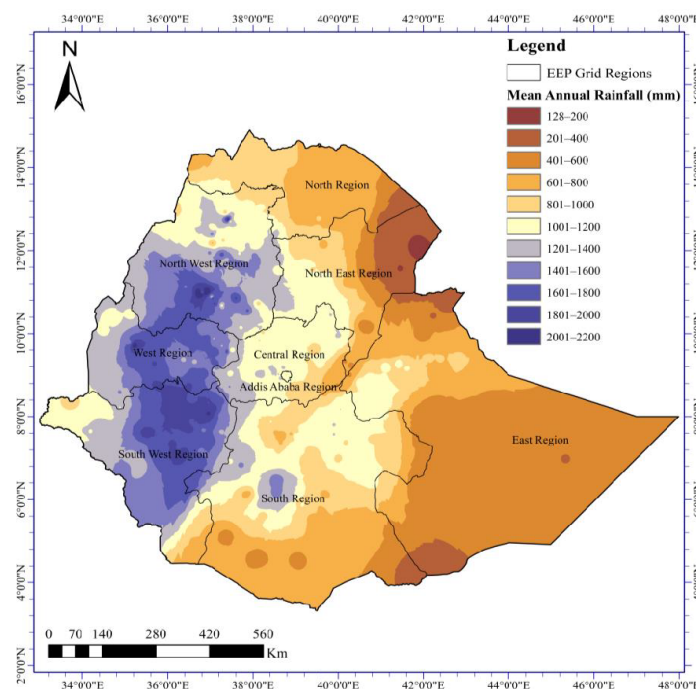


Figure 1. Map of annual average rainfall of Ethiopia showing the grid regions of EEP.

The climatic and meteorological information do not provide any information on the pollution severity. They can, however, indicate when the weather is favorable for the accumulation of pollutants on insulator strings and critical for wetting of the pollutants [1,13]. Given that Ethiopia's climate is predominantly tropical, its weather conditions exhibit distinct wet and dry seasons, each characterized by varying levels of rainfall and temperature patterns [25–27]. Thus, to have an insight into the meteorological conditions representing the different Groups, four representative sites are considered to evaluate the weather and environmental conditions that are suitable for the appearance of pollution flashovers. It can be assumed that different areas in each Group encounter comparable regional meteorological/climatic conditions as their respective representatives [1]. Figure 2 depicts the variations in specific meteorological conditions for Group 1 (Addis Ababa), Group 2 (Assosa), Group 3 (Gode) and Group 4 (Semera). A detail description of climatic and meteorological information in Ethiopia and respective analyses of the conditions for pollution accretion in each grid region, including their estimated site pollution severity class, can be found in our previous works [4,10].

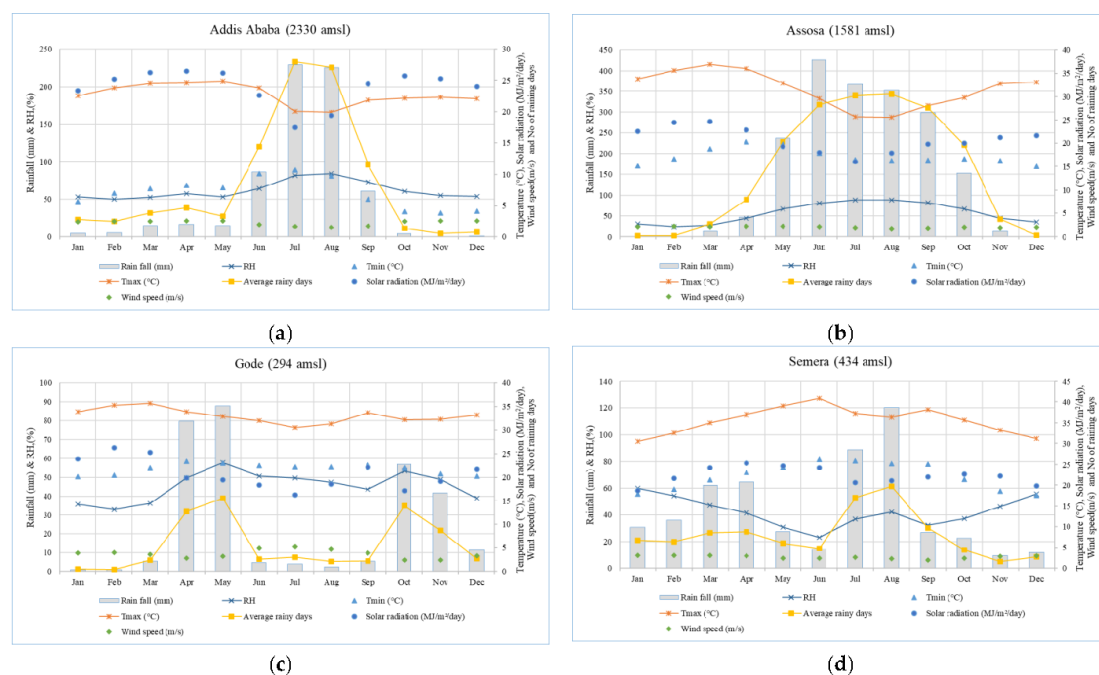


Figure 2. Illustrations of annual variations in meteorological parameters (derived from 30 years of data [28]) for four representative sites in Ethiopia. (a) Addis Ababa; (b) Assosa; (c) Gode; (d) Semera.

The descriptions of the environmental and meteorological conditions of each group are as follows:

Group 1 comprises the North, Northwest, Addis Ababa, and Central grid regions of EEP. They cover a large geographic area, and the major sources of pollution in these regions come from highways, construction sites, transportation, natural dust from local soils, and industrial as well as agricultural activities. These regions are characterized as having a mixture of desert, industrial, and agricultural environments with mainly type A pollution, and their estimated site pollution severity (SPS) class is medium to heavy, according to IEC 60815-1:2008 [10,11].

The meteorological conditions for Group 1 areas, as shown in Figure 2a, are predominantly dry from October to February of the next year, while the period from March to

May is a short rainy season. The average monthly rainfall is about 6.4 mm during these periods and pollution accumulation on insulators is expected to be relatively high. Periods with less than 20 mm rain begin at the end of March and continue to the end of May, and periods with less than 10 mm rain begin at the end of September and continue to the end of March the following year. Average rainfall from June to September (the main rainy season) is about 170 mm. Hence, the pollution layer accumulated on insulator surfaces is washed away during this period. On average, there are 20 rainy days from June to September in this group. The monthly average relative humidity in this group is above 55% throughout the year and above 77% in July and August. The monthly average maximum temperature within the group during the low-rain and hot season is about 27 °C and decreases to 24 °C in the other seasons. The prevailing wind direction during the dry period is from the east and the average wind speed of the group ranges from 1.7 to 2.7 m/s.

Thus, for regions in this group, the atmospheric accumulation and wetting of pollution on the insulator surface, and consequently the flashover risk, are expected to be significantly higher from October to February of the next year and from March to May, and lower between June and September.

Group 2 comprises the Southwest and West grid region of EEP, stretching from the southwest through to the west of Ethiopia. The major sources of pollution in these regions are from agricultural and mining activities and are mainly of type A with the estimated site pollution severity (SPS) class of light to medium [10,11].

As shown in Figure 2b, the period spanning from October to February of the next year is mainly dry. The average monthly rainfall during this period is 6.7 mm. Moreover, periods with less than 20 mm rain are in March and November, whereas periods with less than 10 mm rain begin in December and continue to the end of February. During the primary rainy season from March to September, the monthly average rainfall reaches 200 mm and secures natural washing of insulator surfaces.

The group has an average relative humidity of above 65% from May to October and the monthly average maximum temperature in the low rain and hot season is less than 34 °C and decreases to 31 °C in the other periods. The dominant wind direction during the dry period is southeast with an average wind speed from 1.8 to 2.3 m/s. Therefore, for regions in this group, the climatic and meteorological conditions from October to February of the next year allow for the accumulation and wetting of pollution on insulator surfaces. Thus, the flashover risk is expected to be significantly higher during this period than from March to September.

Group 3 comprises the South grid region of EEP and covers the south and southeast part of Ethiopia. The major sources of pollution are mainly dust from semi-arid areas, highways, construction sites, mining, industrial, and agricultural sources. The regions are characterized as having mixture of agricultural and industrial types of environments [10], with type A pollution accumulation and have an estimated site pollution severity (SPS) class of medium to heavy [11].

As shown in Figure 2c, the main dry season in regions of Group 3 is from June to September and from December to February of the next year, while from October to November there is a short rainfall season. During the former periods, the average monthly rainfall is low, respectively, 17 mm and less than 10 mm. During March to May (the main rainy season), the weather is moist, and the average rainy days and average monthly rainfall reach 10 days and 44 mm. The natural washing of insulators by rain increases in this period.

Regions in this group have an average relative humidity of above 50% from April to October, which can humidify the pollution on the insulators. The monthly average maximum temperature of the region in the main dry and short rainfall season is about 31 °C and increases to 33.5 °C in the main rainy season. The prevailing wind direction during the dry period is from the southeast, with the average wind speed of the region ranging from 2 to 3.5 m/s. Consequently, for regions in this group, the pollution flashover

risk is expected to be significantly higher from June to September and October to February of the next year and lower from March to May.

Group 4 includes the East and Northeast regions of EEP covering the eastern part of the country. They receive very little or no rainfall at any time of the year [24–26]. The major sources of pollution in these regions are from highway transportation, salty soils, sandy dust storms from the desert, and direct salt sprays originating from the coastal area, as well as from agricultural and mining activities. The regions are characterized by a mixture of desert, coastal, and agricultural types of environments with a combination of type A and type B pollutions [10]. The estimated site pollution severity (SPS) class in the regions is heavy to very heavy [11].

As shown in Figure 2d, the periods from October to February of the next year and from March to May are the main dry seasons. During these periods, the average monthly rainfall is low, around 27 mm. Moreover, less than 20 mm rain periods are during January and June, and less than 10 mm rain periods begin in November and December. During June to September (the main rainy season), the weather is moist, but the rainfall is usually light. Most of the rainy days are continuous drizzle or scattered rains, and the average monthly rainfall reaches 45 mm. Hence, the washing effect during this period is minimal.

This group has a low average relative humidity of 46% throughout the year, and it only exceeds 50% in the months of December and January. The monthly average maximum temperature of the group during the main dry season is less than 31 °C and increases to 34 °C in the other seasons. The dominant wind direction during the dry period is from the east, with the average speed ranging from 2.2 to 3.5 m/s.

Therefore, for regions in this group, the climatic and meteorological conditions occurring at any time of the year are considered as favorable for pollution accumulation and wetting, and the expected risk for flashovers seems to be high throughout the year. As some areas within the group might also encounter direct salt sprays originating from the Red Sea and the Gulf of Aden, there is a high likelihood of dew with salt content forming on insulator surfaces, and rapid pollution accumulation and increased flashover risk are characteristic of them.

2.3. Criteria for Evaluating Unexplained Fault Data

As indicated in [16,17], a high accuracy in classifying the root causes of transmission line faults can be attained by exclusively utilizing contextual fault features. Information about the characteristics of the fault, the time of day and month of the year the fault occurred, fault location, and the climatic/meteorological and environmental conditions (represented by the grid region Groups) are used to develop the criteria to classify the fault origin. It is believed that the criteria outlined in Table 1 below represent the necessary and sufficient conditions expected to be fulfilled by faults related to pollution-initiated flashovers.

Table 1. Criteria used to identify pollution caused unexplained faults.

Conditions	Time of the Day	Month of the Year	Grid Region Classification (Groups)
Condition 1	19:00–8:00	October–February	Group 1, Group 2, Group 3, and Group 4
Condition 2	19:00–8:00	March–May	Group 1 and Group 4
Condition 3	19:00–8:00	June–September	Group 3 and Group 4

The implementation of these criteria can best be demonstrated through the flowchart depicted in Figure 3. The criteria and the procedure described in the flowchart serve as a general guideline for evaluating the roots of unexplained faults. The first decision block checks whether an unexplained fault fulfils the characteristics criteria outlined in Section 2.1.5. If the unexplained fault does not satisfy this criterion, then this fault is not considered as pollution caused and categorized as “Not Consistent with PFO”. Otherwise, the process continues, and information on the fault location (Grid Region), month, and

time of its appearance is extracted. The subsequent decision blocks in the flow chart use the criteria presented in Sections 2.1 and 2.2 as well as in Table 1.

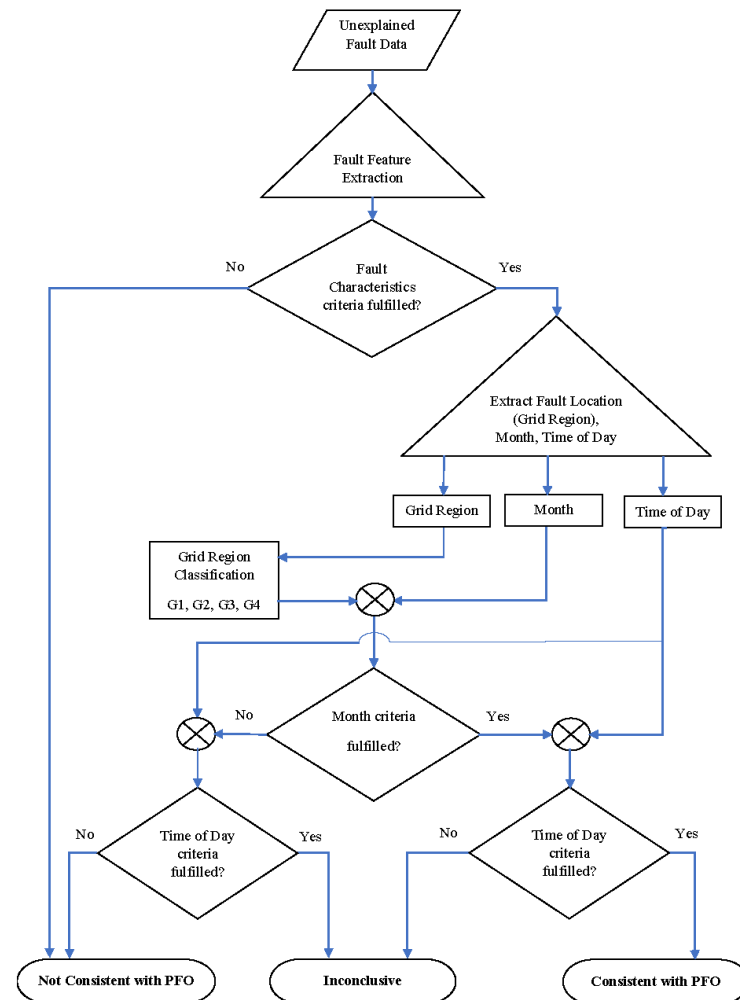


Figure 3. Procedure for application of criteria for identifying pollution flashover-induced faults.

In the following steps, after assigning the right grid region group to the fault, it is tested for the month and time-of-the-day criteria. If the conditions are fulfilled, then the fault is categorized as “Consistent with PFO”. If only one of the criteria is fulfilled, then it becomes difficult to assign it as PFO because other possible environmentally induced causes of unexplained fault may also exhibit similar characteristics. So, such cases are “Inconclusive” and need further investigations to assign their possible causes. Moreover, if it fails to fulfill both criteria, then it is not considered as pollution-induced flashover and hence assigned as “Not Consistent with PFO”.

3. Statistics of Spatiotemporal Distribution of Pollution-Induced Flashover Faults

The entire dataset of unexplained outages was evaluated for consistency with the criteria outlined in Section 2.3. A total of 4231 unexplained faults were examined, and it appeared that 1045 (24.7%) faults were found to be Consistent with PFO, and 2222

(52.5%) events were assigned as Inconclusive, out of which 1649 (39%) did not meet the time-of-the-day criterion and 573 (13.5%) did not meet the month criterion. The remaining 964 (22.8%) were found to be Not Consistent with PFO and could be attributed to other causes occurring in the daytime and early evening hours [9,29]. However, the Inconclusive category might also include PFO incidents that took place outside of their typical characteristic trends [2,19,30].

This result reveals that pollution-induced flashovers contributed for a substantial portion of the unexplained interruptions in services observed within the EEP transmission network. The result was studied further to demonstrate statistical distributions of the flashovers over the years, time of year, time of day, and across grid regions and voltage levels. The rate of occurrences of faults for individual transmission lines were also calculated to evaluate their performance and the results are discussed in the following subsections.

3.1. Geographical Distribution of Pollution-Induced Flashovers across EEP Grid Regions

The distribution of pollution-induced faults in each grid region of EEP between 2015 and 2022 is presented in Figure 4. Among these regions, the Northeast region suffered 290 (27.8%) faults, the highest frequency of interruptions with 3.1 faults/100 km/year, followed by the Northwest region which endured 155 (14.8%) faults and 1.1 faults/100 km/year. The Addis Ababa, East, Central and South grid regions also experienced a higher number of interruptions during this period with more than 100 faults and 0.55 faults/100 km/year each. The Southwest region suffered 23 (2.2%) faults, the lowest number of incidents with 0.2 faults/100 km/year.

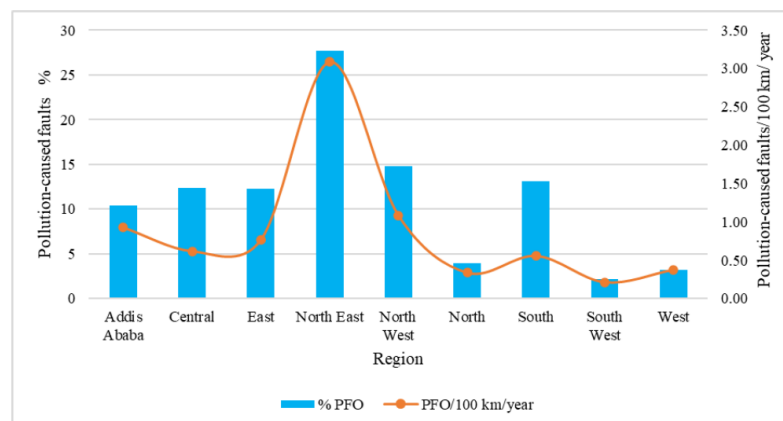


Figure 4. Distribution of pollution-induced flashover faults across EEP grid regions from 2015–2022.

Furthermore, to facilitate comparisons and analyze the geographical distribution of pollution-induced faults, the centroids of each transmission line circuit were utilized to allocate a geographical position to each incident and to estimate the prevalence of PFO faults in terms of faults per unit length and unit time. For each circuit, the number of faults per 100 km of transmission line per year was calculated. These data were then incorporated into the GIS database, and centroids were determined for each circuit using ArcGIS software to generate a national-level map illustrating spatial trends. Figure 5 shows the transmission grid in Ethiopia (132–400 kV) as of 2022 (indicated by grey lines), alongside the average number of pollution-induced faults recorded per 100 km of line per year for each circuit. This representation is shown using circles with radii that vary proportionally [4].

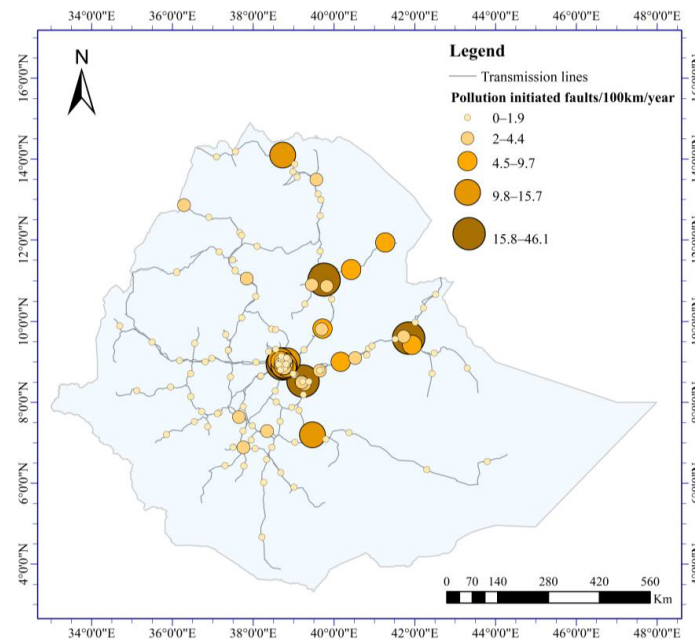


Figure 5. Geographical distribution of pollution induced faults across Ethiopia from 2015–2022.

Pollution flashover faults were found in 152 circuits, with an average of 3.0 faults per 100 km per year. In terms of geographical variations, the majority of these circuits were concentrated in the Northeast, Eastern, and Central part of Ethiopia as shown in Figure 5.

Typically, standard requirements for high-voltage transmission lines permit the occurrence of 1–2 unexplained faults per 100 miles (equivalent to 0.62–1.24 unexplained faults per 100 km per year) [6,13]. This range of acceptable numbers depends on the line's significance and location. In most European nations, a rate of approximately one flashover per 150 km of line per year (equivalent to 0.67 faults per 100 km per year) is generally considered acceptable [7]. In this respect, the Ethiopian (132–400 kV) power grid experiences an unacceptably higher frequency of disturbances that are related to line insulator flashovers. It is found that the transmission lines suffered during the years 2015 to 2022 from more than 130 pollution-related faults per year, resulting in a fault frequency of 0.81/100 km/year. This is an unacceptably high rate of outages and evidently indicates that pollution-induced problems appear more often than presumed by the EEP. Instances of fault frequencies for underperforming EEP's 132, 230, and 400 kV lines from 2015 to 2022 are listed in Table 2.

The distribution of pollution-induced fault frequency for the primary-voltage-level lines is illustrated in Figure 6. When the frequency of faults is evaluated separately, 132 kV lines suffered the highest fault frequency at 0.98 faults/100 km/year, and the faults experienced by 230 kV lines amounts to 0.75 faults/100 km/year. These poor performances are in accordance with the service experiences reported by EEP experts. Almost half of the 132 and 230 kV lines were built prior to 2005, and their underperformance could, in addition to the environmental and climatic factors, be attributed to the aging of the line infrastructure. In contrast, 400 kV lines display a lower fault frequency of about 0.57/100 km/year.

Table 2. Pollution-induced fault frequencies of specific EEP 132, 230, and 400 kV lines between 2015 and 2022.

Transmission Lines	Grid Region	Line Length (km)	Number of Towers	In-Service Year	System Voltage (kV)	Type of Insulator Material	Number of Insulator Strings	Total Pollution-Induced Faults	Number of Faults per 100 km per Year
Combolcha II—Semera	North East	174.8	391	2011	230	Polymeric composite	1275	78	5.6
Combolcha II—Legetaffo	North East and Addis Ababa	276.3	608	2012	230	Polymeric composite	2106	53	2.4
Bahir Dar II—Debre Markos	North West	193.8	427	2011	400	Glass	2562	46	3.0
Bahir Dar II—Alamata	North West and North East	344.5	792	1998	230	Glass	2544	33	1.2
Combolcha I—Akista	North East	82.0	191	2006	132	Polymeric composite	669	28	4.3
Semera—Dicheto	North East	65.9	131	2017	230	Polymeric composite	414	27	6.8
Debere Berhan—Showarobit	North East	57.5	206	1985	132	Porcelain	636	27	5.9
Debre Markos—Sululta	Central and North West	432.0	464	2011	400	Glass	5568	26	0.8
Alamata—Combolcha II	North East	170.5	362	2010	230	Polymeric composite	1200	25	1.8

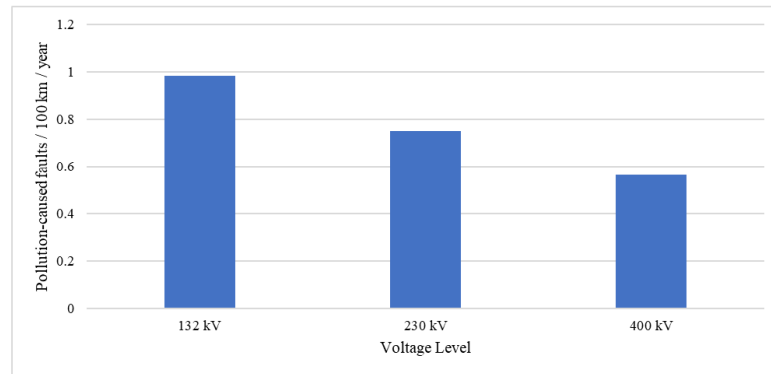


Figure 6. Frequency of pollution-induced faults for 132 kV, 230 kV, and 400 kV lines.

3.2. Time-of-Day and Seasonal Examination of Pollution-Induced Faults

Scrutiny of the identified pollution-induced faults revealed that yearly trends in their appearance varied from one year to another—it had an increasing trend, peaking in 2018, as shown in Figure 7. Since 2019, it has become constant due to pollution saturation (an equilibrium condition between the pollution deposit rate and insulator cleaning rate) [1]. The reason for the increasing trend could be attributed to changes in environmental and meteorological conditions, issues related to the selection and dimensioning of insulators, infrastructure aging, and ineffective maintenance procedures. Further study is required to elucidate the reason for this trend and develop strategies to mitigate future fault occurrences.

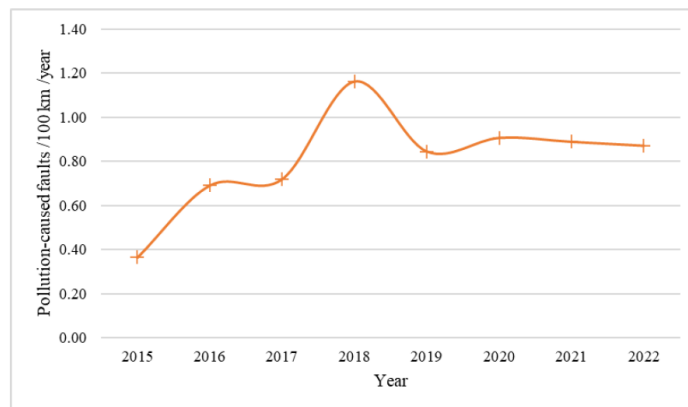


Figure 7. Annual variation in pollution-induced faults in Ethiopian power grid.

The time-of-the-day curve of pollution induced faults (PFO) is shown in Figure 8. It exhibits a pattern characterized by three peaks. The number of faults rises quickly after sunset between 19:00–20:00, and after showing a decrease, it again rises around midnight, mainly due to pollution wetting that can be associated with light precipitation, dew formation, and moisture adsorption during the night. At around 06:00 in the early morning, there is again a rapid increase in the fault number, likely due to a combination of wetting and bird steamers, the latter usually occurring during the spring season in areas populated by large birds. Thereafter, the number of faults drops close to zero and remains at this level practically for the whole day. This pattern has a good correlation with the

patterns for bird streamer and pollution-caused faults in Florida and in South Africa, as shown in Figure 8.

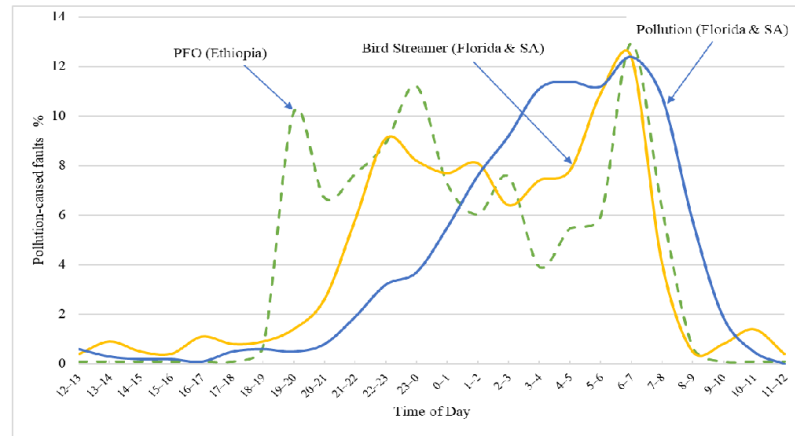


Figure 8. Pollution-induced faults within the Ethiopian network, in comparison with the typical time-of-day fault profiles attributed to pollution and bird streamers observed in Florida, USA, and South Africa [2,19].

The seasonal pattern of fault incidence is depicted in Figure 9, exhibiting a maximum fault during the dry months of October to February and March to May, peaking in December and April. A relatively lower number of faults occur from May to September, except for August, which falls during the main rainy season in most parts of Ethiopia. The seasonal trend of fault occurrence follows the rainfall patterns in the country.

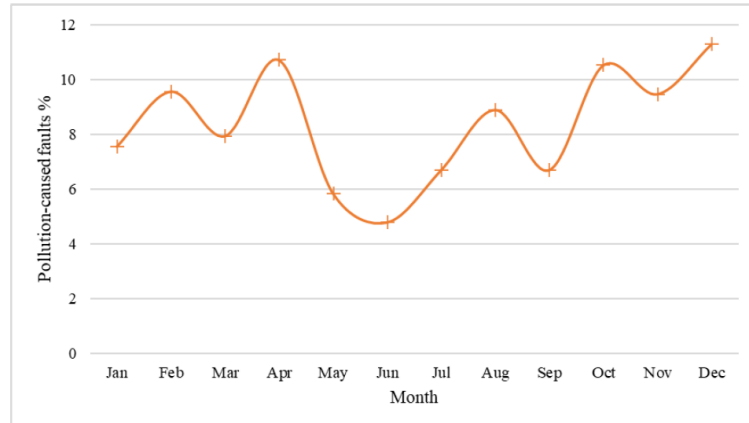


Figure 9. Seasonal trend of pollution-induced flashover faults in the Ethiopian power network.

4. Analysis of Pollution-Induced Flashover Faults by Type of In-Service Insulator

Pollution flashover performance of insulators has observable trends when examined from the viewpoint of its type (cap-and-pin strings or long rod), waveform of energization (i.e., AC or DC), and its material (glass, porcelain or polymeric) [1,11,12]. In this section, the identified pollution-induced faults were further analyzed to investigate how the different materials of in-service-used insulator arrangements impact on the intensity of pollution-induced flashover faults. For this analysis, the number of faults that occurred on a specific

line is allocated to the specific insulator type of the line. The analysis was performed in terms of pollution flashovers intensity, involving the number of pollution flashovers allocated to a certain insulator type (porcelain and glass cap-and-pin strings or silicone rubber polymeric composite long rods) for a given period and system voltage and the number of insulator strings assembled from these insulators normalized for 1000 units [24].

The analysis result indicates that, out of the total 1045 pollution-induced faults, 77 (7.3%) occurred on porcelain strings, 542 (51.9%) on glass strings, and the remaining 426 (40.8%) occurred on polymeric composite long rods. Most of the faults occurred on glass and polymeric insulators which, respectively, represent 61% and 34% of the total insulators installed in the system, while porcelain insulators strings represent only 5%. Figure 10 compares the pollution flashover intensity for each voltage level and for insulator types, covering eight consecutive years from 2015 to 2022. For 132 kV lines, the intensity of pollution-induced flashovers was highest on strings assembled from porcelain cap-and-pin insulators, with the intensity of 1.79 faults/year/1000 units, followed by glass insulator strings with 1.10 faults/year/1000 units and polymeric long rod insulator, which suffered the least number of faults with less than 0.93 faults/year/1000 units. For 230 kV lines, the intensity of pollution-induced flashovers was highest on strings of polymeric composite insulators with the intensity of 1.36 faults/year/1000 units and followed by glass insulator strings with 0.93 faults/year/1000 units. Here, porcelain insulators had the lowest intensity of faults with less than 0.26 faults/year/1000 units. In 400 kV lines, glass insulator strings are exclusively used and experienced the fault intensity of 0.47 faults/year/1000 units.

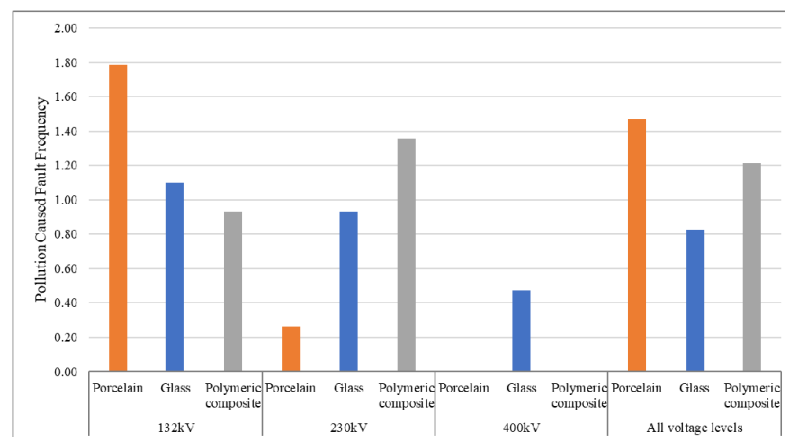


Figure 10. Distribution of PFO intensity by type of insulator (2015 to 2022).

For the three voltage levels, porcelain insulator strings had the highest pollution-induced flashover intensity of 1.47 faults/year/1000 units, followed by polymeric composite long rod insulators with an intensity of 1.21 faults/year/1000 units and glass insulator strings with the lowest fault intensity of 0.83 faults/year/1000 units. The percentage distributions of individual insulator types and a comparison to the intensities of pollution-induced flashovers for all voltage levels are summarized in Table 3.

As already indicated, the combined intensity of pollution flashovers was highest on strings assembled from ceramic (porcelain and glass) insulators, mainly due to their hydrophilic surface properties. Moreover, the other reason which additionally contributes to the poor pollution performance of these insulators can be attributed to aging, as these lines were built 30–40 years ago. Various environmental stresses erode and degrade their end fittings and surfaces. These include exposure to high-temperature variations during long, dry periods and vandalism. This conclusion is also supported by the reported service experience.

Table 3. Distribution of PFO intensity by type of insulator for 132 kV, 230 kV, and 400 kV system voltage (2015 to 2022).

Voltage Level	Type of Insulator					
	Porcelain		Glass		Polymeric Composite	
	Percent of Insulator Strings	Pollution Flashover Intensity (%)	Percent of Insulator Strings	Pollution Flashover Intensity (%)	Percent of Insulator Long Rods	Pollution Flashover Intensity (%)
132 kV	10	46.8	59.2	28.8	30.8	24.4
230 kV	2.7	10.3	38.6	36.5	58.7	53.2
400 kV	0	0	100	100	0	0
All voltage levels	4.9	41.9	61.2	23.6	33.9	34.5

High-temperature-vulcanized (HTV) silicone rubber (SR) polymeric insulators installed on 132 and 230 kV lines also suffered from a significant number of pollution-induced flashovers, even though these insulators are relatively newly installed in the system. Despite these types of composite insulators being generally known to have superior pollution performance due to their hydrophobic properties, their performance in the Ethiopian climatic and environmental conditions appears to be not so satisfactory.

Polymeric composite insulators were introduced into the EEP network in 2008, specifically on 132 and 230 kV lines. To assess their impact on improving pollution flashover performance of the network, the total number of pollution-induced flashovers on these lines was compared. This involved comparing older lines, insulated with glass or porcelain before 2008, with newer lines insulated by silicone composite insulators. Analysis of data from 2015 to 2022 revealed 869 pollution-induced flashovers on 132 and 230 kV lines. Among these, 426 faults were observed on lines insulated with silicone composite insulators, while the remaining 443 faults occurred on lines insulated with glass or porcelain. This suggests that the use of SR polymeric insulators for 132 and 230 kV lines did not significantly improve the pollution flashover performance of the network. Moreover, there is concern that their performance may deteriorate as they approach 30–40 years of service, like the older glass or porcelain-insulated lines.

Many factors can contribute to this effect. One of them may be traced to improper practices or policies during the design and dimensioning stage of the line design. Usually, the climatic and environmental stresses to which the insulators will be subjected during operation are not properly taken into consideration. It especially refers to not considering or incorrectly assuming site pollution severity (SPS values) for line locations. In addition, the pollution level in some line locations might appreciably change (mainly increase) since the initial assumptions were made, which results in difficulty in selecting and dimensioning the appropriate insulator type and size that best fit the local climatic and environmental conditions and possibly yields under- or over-dimensioned insulation [10].

Another factor that should be considered is the exposure of silicone rubber composite insulators to intense UV radiation and high temperature during dry and hot periods from October to May in most parts of Ethiopia. This results in the formation of micro-cracks and surface degradation of the rubber and severely reduces the hydrophobic property of the insulator's surface and contributes to the collection of more pollution than the smooth surface does. Polymeric insulators are also more vulnerable to biological growths in the humid subtropical highland climatic conditions of Ethiopia, which may further reduce their hydrophobic properties. Such service induced changes in the housing material properties compromise the hydrophobicity and resistance to tracking, which lead to greatly degraded pollution flashover performance and premature failure [1,11,12].

Moreover, the quality of materials and production processes which affect the overall behavior of the insulator is also an important factor one should consider [1]. This can also be one of the reasons for the poor performance of polymeric insulators in the Ethiopian power network. During construction of new lines and maintenance of existing ones, the

laboratory tests to verify the electrical properties of candidate insulators do not usually include pollution flashover performance tests. Even if such a test were to be carried out, there is no reference pollution monitoring activity or pollution severity map for the country to select the proper pollution parameters such as ESDD and NSDD and to set up the adequate test environment. The documentation for respective projects lacks clear descriptions of test methods or acceptance criteria for assessing insulator suitability. Moreover, these documents do not include any reports on service experience records or field measurements aimed at estimating site pollution severity [10]. This results in using under or over dimensioned insulators with lower quality, which is uneconomical for EEP and has a huge impact on their overall performance during operation.

These days, there is a significant increase in replacing porcelain and glass insulator sets with polymeric composite types on towers where a line suffers a high rate of outages due to unexplained outages (possibly PFO). But this again is carried out without detailed study of the root causes and assessment of the environmental pollution severity level. The trend is to simply use the same insulator type and parameters which were used for other lines in projects that have different environmental conditions and pollution severity levels. This yields large investments, which might not solve the problem and can yield a large financial loss.

In general, this poor performance of in-service insulator appears to be the result of the policies and procedures of the EEP concerning the selection and dimensioning of present and future insulators, which lack consistent guidelines that take into consideration the particular application needs and environmental factors in which the insulators will be deployed.

We therefore recommend that EEP improves its practice towards selection and dimensioning of outdoor insulators by defining guidelines for monitoring, maintenance, and inspection procedures for new and existing lines. One of the major uncertainties when selecting outdoor insulators can be linked with estimation of the actual values of the pollution severity level of installation sites. Field monitoring of pollution severity at critical line locations and establishing test stations for carrying intensive measurement campaigns is a prerequisite for improving the present state. Ultimately, creating a comprehensive pollution severity map covering the entire country can provide invaluable information for optimal insulator selection. Moreover, pollution performance tests and acceptance criteria should be included as requirements in the purchase specifications for outdoor insulators.

In addition, EEP should implement scheduled maintenance plans and palliative practices to compensate for the design failures, thereby reducing maintenance costs and mitigating premature failures of outdoor insulators. These plans should be based on detailed evaluations of environmental factors, alongside considerations of technical, economic, and logistical viability. Potential maintenance and preventative strategies to mitigate pollution flashover-caused outages include washing substation and line insulators, using creepage extenders, replacing hydrophilic insulators with hydrophobic alternatives, and application of RTV silicone coatings. The selection of these measures should depend upon their economic and technical feasibility [1,2,12,14].

5. Case Studies: Analyses of Underperforming Lines

This section provides case studies for two transmission lines that encountered unacceptably high rates of pollution-caused outages from 2015 to 2022. This can be considered as verification of the results obtained by the above presented method. Local climatic and meteorological data along the lines' routes, coupled with historical field experience are used to assess their consistency with the typical conditions conducive to pollution-induced flashovers.

5.1. Combolcha II—Semera—Dicheto 230 kV Line

The Combolcha II—Semera—Dicheto 230 kV line stretches 241 km from Combolcha II substation through Semera to the Dicheto substation in the northeast part of Ethiopia,

which has a desert and semi-arid climatic conditions, characterized by having limited rainfall throughout the year. It is near the Danakil desert and Red Sea and is exposed to direct salt sprays, salty dusts, and salty fog carried by strong winds. It also is exposed to mining contamination from the desert and saline lakes in the region and is thus subject to a combination of type A and type B pollutants. The line is insulated with long-rod HTV silicone rubber composite insulators and is known from service experience to have poor performance. A total of 105 pollution-induced flashovers were identified on this line from 2015 to the end of 2022, an average of 13.1 faults per year. Figure 11 shows the monthly average meteorological parameters across the entire length of the line. The line receives an average rainfall of less than 48 mm from March to August. The yearly average values of relative humidity (above 42%), temperature (above 27 °C), and windspeed (2.5 m/s) fit the conditions for pollution accumulation and wetting.

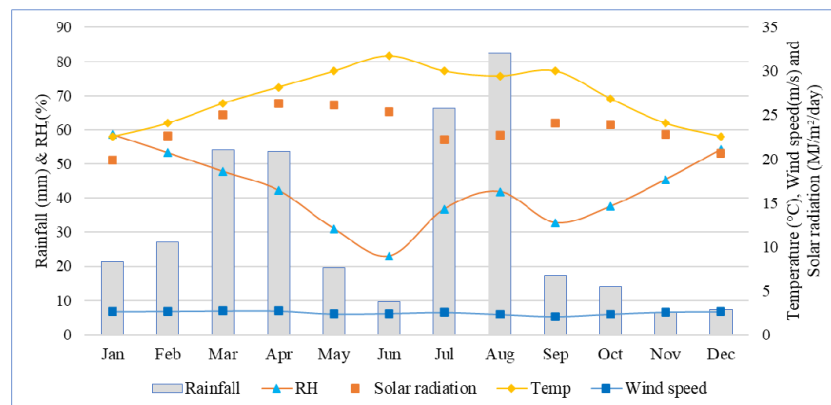


Figure 11. Monthly average meteorological parameters across the entire length of the Combolcha II—Semera—Dicheto 230 kV line [28].

Figures 12 and 13 indicate that the pollution-induced faults mainly occurred on the line during the night from 19:00 to early morning (5:00–6:00), peaking at midnight (23:00–1:00) and especially in April and August. This is the rainy season in the region, having relatively low rainfall levels, when insulator surfaces are wetted by light precipitation during the evening hours and dew formation at sunrise.

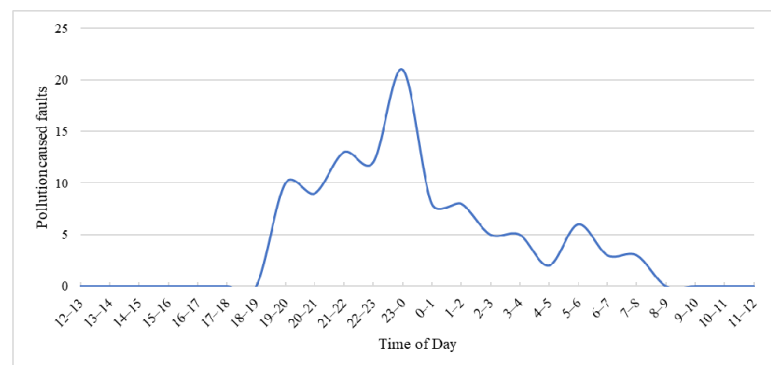


Figure 12. Daily distribution of pollution-induced faults of the Combolcha II—Semera—Dicheto 230 kV line.

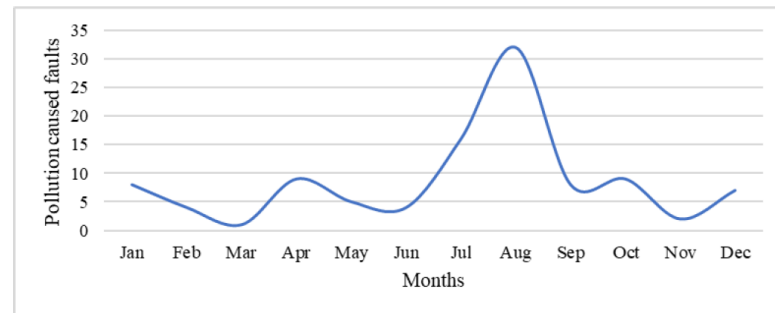


Figure 13. Monthly distribution of pollution-induced faults of the Combolcha II—Semera—Dicheto 230 kV line.

Both forms of pollution flashover mechanisms, namely type A and type B, are highly likely to occur on this line. The region is not a favorable place for large birds to live due to its climate, thus bird streamer-caused faults seem unlikely to occur.

The presented data show a good correlation between the temporal distributions of the identified pollution-induced faults and the climatic conditions. Moreover, the reason for the greatly degraded pollution performance of the silicone rubber composite insulators installed on the line can be attributed to their exposure to sandstorms (the local desert sand contains calcium and sodium salts) as well as intense UV radiation and high temperatures, which contribute to the formation of micro-cracks and drastically reduced the hydrophobicity on insulator surfaces.

5.2. Bahir Dar II—Debre Markos—Sululta 400 kV Line

The Bahir Dar II—Debre Markos—Sululta 400 kV line spans 410 km, extending from the northwestern highlands of Ethiopia to Addis Ababa, crossing subtropical highland and tropical savanna climatic conditions. The environmental conditions along the route of the line are characterized by a mixture of desert, industrial, and agricultural pollutants. The main sources of pollution in the area are from transportation, construction, quarry sites, naturally occurring dust from local soils, cement factories, and agricultural activities such as ploughing, fertilizers, crop spraying, and harvesting. The line is insulated with glass-cap and pin strings. The line is known for having a high number of unexplained outages, and the performed analysis identified a total of 72 pollution induced faults on it for the period between 2015 to 2022, an average of 9 faults per year. Figure 14 shows the monthly average meteorological parameters across the entire length of the line. The line receives an average rainfall of about 270 mm from June to September and an average relative humidity above 58%, temperature above 17 °C and windspeed 1.8 m/s for the whole year.

The time-of-the-day curve depicted in Figure 15 reveals that most of these faults occurred close to midnight, from 22:00 to 23:00, and early in the morning, between 6:00 to 7:00. Figure 16 indicates that the majority of faults occurred between November and February, attributed to dew formation on the glass insulator surface, and from March to May (due to light precipitation), respectively, corresponding to the dry and light rainfall seasons in the area. Most faults were concentrated during spring ploughing, winter crop harvesting, and burning. The bird streamer mechanism may contribute to the faults occurring in October and November, during the autumn season. The described conditions are consistent with type A and type B pollution-flashover mechanisms.

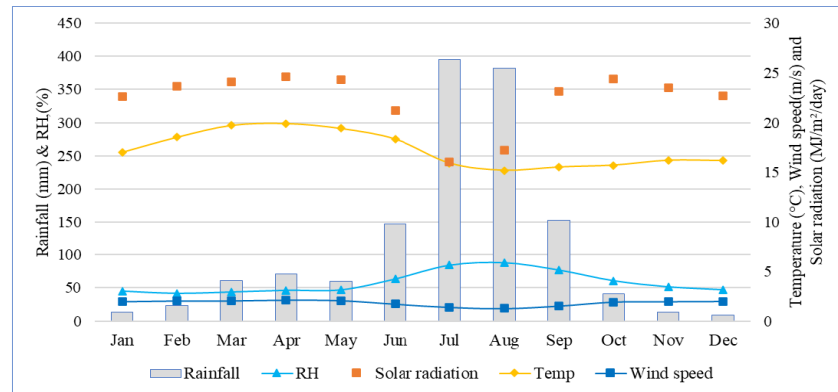


Figure 14. Monthly average meteorological parameters across the entire length of the Bahir Dar II—Debre Markos—Sululta 400 kV line [28].

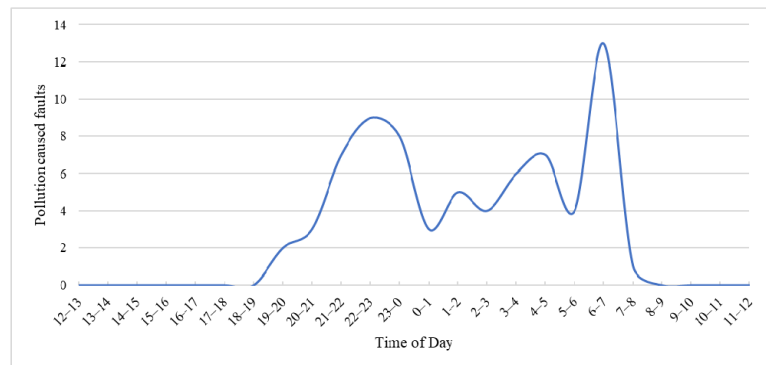


Figure 15. Daily distribution of pollution-induced faults of the Bahir Dar II—Debre Markos—Sululta 400 kV line.

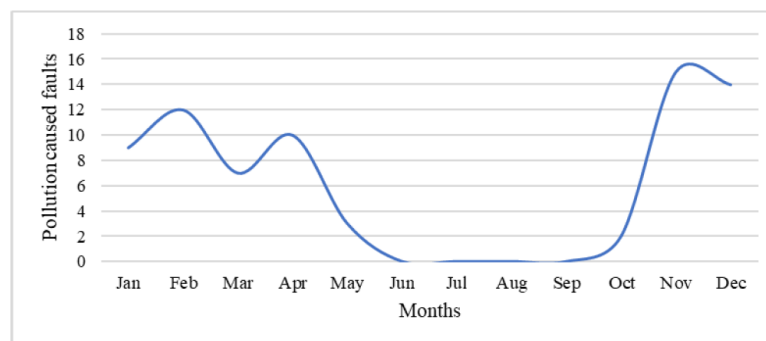


Figure 16. Monthly distribution of pollution-induced faults of the Bahir Dar II—Debre Markos—Sululta 400 kV line.

Moreover, the reduction in flashover voltage (above 10%), because of the lowered air density by high altitude (~2000 m) and nearly constant temperature along the route of the line, could also contribute to the increased outage rate [1]. Therefore, there is a good

correlation between the meteorological pattern, environmental conditions, reported service experiences, and the identified pollution-induced faults.

6. Conclusions

Unexplained fault records from Ethiopian transmission lines, which took place between 2015 to 2022, were analyzed with the aim of identifying among them the faults caused by pollution induced flashovers. This was achieved by developing a method considering information about the characteristics of the fault, the time of day and time of the year (month) the fault occurred, the location of the fault, and the climatic/meteorological and environmental conditions at the fault location.

The results have indicated that the lines excessively suffer from pollution-induced outages that embrace a significant part of all interruptions in the Ethiopian power system. Their frequency appears much higher compared to the international acceptable outage rates. The Ethiopian Electric Power company should therefore intensify work on minimizing these outages and ensuring the highest possible reliability of its power transmission lines.

Moreover, the analyses concerning the type of insulators installed at the lines of all the voltage levels indicate that the pollution performance of silicone rubber composite long-rod insulators appeared to not be as good as one could expect based on the available literature data on this subject. This clearly indicates that proper selection and dimensioning of the composite insulator in Ethiopia remain problematic and should be based on paying more attention to the local climatic and environmental conditions. Further detailed work is also required to evaluate the severity of these conditions as an input for the development of the pollution map for the whole country, which will become a starting point to further tackle the problem and to assist design practices for present and future insulator selection.

Author Contributions: Conceptualization, B.Z.D., M.M.W. and S.M.G.; methodology, B.Z.D.; formal analysis, B.Z.D. and S.M.G.; investigation, B.Z.D.; resources, M.M.W. and S.M.G.; data curation, B.Z.D.; writing—original draft preparation, B.Z.D.; writing—review and editing, M.M.W. and S.M.G.; visualization, B.Z.D.; supervision, M.M.W. and S.M.G.; project administration, M.M.W.; funding acquisition, M.M.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Swedish International Development Cooperation Agency (Sida)—Ethiopia Bilateral Program, contribution number 51080124.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

Acknowledgments: The authors gratefully acknowledge the financial contribution made by the Swedish International Development Cooperation Agency (Sida)—Ethiopia Bilateral Program and the support provided to our research activities by the Department of Electrical Engineering of Chalmers University of Technology and its dedicated staff. We would like also to thank the Ethiopian Electric Power company for providing access to the 8-year fault data in its power network.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. CIGRE Taskforce 33.04.01. *Polluted Insulators: A Review of Current Knowledge*; CIGRE Technical Publication 158; CIGRE: Paris, France, 2000.
2. Macey, R.; Vosloo, W.; de Tourreil, C. Environmental considerations. In *The Practical Guide to Outdoor High Voltage Insulators*; Eskom Power Series; Crown Publications: Johannesburg, South Africa, 2004; Volume 3.
3. Ethiopian Electric Power. EEP Operational and Fault Data from 2015 to 2022.
4. Berhanu, Z.D.; Mengesha, M.W.; Stanislaw, M.G. Analyses of Unexplained Faults in Transmission Lines in the Power Grid of Ethiopia. *Electr. Power Syst. Res.* **2024**, *231*, 110293. [[CrossRef](#)]
5. Major, M. Investigation of Contamination Flashover as a Possible Cause for Unexplained Faults on the Montana Power Company's 500 kV Transmission Lines. Master's Thesis, Montana St. University, Bozeman, MT, USA, November 1993.

6. Maehl, D.R. Investigation of Bird Induced Outages on Montana Power Company's 500 kV Transmission Lines. Master's Thesis, Montana State University, Bozeman, MT, USA, 1996.
7. Taklaja, P.; Oidram, R.; Niitsoo, J.; Palu, I. Causes of indefinite faults in Estonian 110 kV overhead power grid. *Oil Shale* **2013**, *30*, 225–243. [\[CrossRef\]](#)
8. Herman, R.; Gaunt, T. Probabilistic interpretation of customer interruption cost (CIC) applied to South African systems. In Proceedings of the 2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems, Singapore, 14–17 June 2010; pp. 564–568. [\[CrossRef\]](#)
9. Bekker, H.J.J.; Hoch, D.A. Analysis of factors contributing to unexplained transmission line faults on a high voltage transmission network. In Proceedings of the IEEE AFRICON—6th Africon Conference in Africa, George, South Africa, 2–4 October 2002; Volume 2, pp. 655–660. [\[CrossRef\]](#)
10. Zelalem, B.; Mamo, M. Assessment of external insulation problems related to pollution and climatic conditions in Ethiopia. *IEEE Electr. Insul. Mag.* **2020**, *6*, 36–46. [\[CrossRef\]](#)
11. IEC/TS 60815-1; Selection and Dimensioning of High-Voltage Insulators Intended for Use in Polluted Conditions—Part 1: Definitions, Information and General Principles. International Electrotechnical Commission: Geneva, Switzerland, 2008.
12. CIGRE Working Group C4.303. *Outdoor Insulation in Polluted Conditions: Guidelines for Selection and Dimensioning—Part 1: General Principles and the a.c. Case*; CIGRE Technical Publication 361; CIGRE: Paris, France, 2008.
13. Sandhu, K.S. *A Joint Utility Investigation of Unexplained Transmission Line Outages*; EPRI Publication EL-5735 Research Project 2335-1; Sierra Pacific Power Company: Reno, NV, USA; National Rural Electric Cooperative Association: Arlington, VA, USA; Electric Power Research Institute: Washington, DC, USA, 1988.
14. Peter, L.; Vajeth, R. Strategies for bating environmental influences on overhead lines to improve quality of supply. In Proceedings of the 2005 IEEE Power Engineering Society Inaugural Conference and Exposition in Africa, Durban, South Africa, 11–15 July 2005; pp. 80–87. [\[CrossRef\]](#)
15. Vosloo, H.F. The Need for and Contents of a Life Cycle Management Plan for Eskom Transmission Line Servitudes. Master's Thesis, University of Johannesburg, Johannesburg, South Africa, 2009.
16. Minnaar, U.J.; Nicolls, F.; Gaunt, C.T. Automating Transmission-Line Fault Root Cause Analysis. *IEEE Trans. Power Deliv.* **2016**, *31*, 1692–1700. [\[CrossRef\]](#)
17. Jian, S.; Peng, X.; Yuan, H.; Lai, C.S.; Lai, L.L. Transmission Line Fault-Cause Identification Based on Hierarchical Multiview Feature Selection. *Appl. Sci.* **2021**, *11*, 7804. [\[CrossRef\]](#)
18. Minnaar, U.J.; Gaunt, C.T.; Nicolls, F. Characterisation of power system events on South African transmission power lines. *Electr. Power Syst. Res.* **2012**, *88*, 25–32. [\[CrossRef\]](#)
19. Burnham, J.T. Bird streamer flashovers on FPL transmission lines. *IEEE Trans. Power Deliv.* **1995**, *10*, 970–977. [\[CrossRef\]](#)
20. Kleinhans, K. Investigation into Possible Mechanisms of Light Pollution Flashover of 275 kV Transmission Lines as a Cause of Unknown Outages. Master's Thesis, University of Stellenbosch, Stellenbosch, South Africa, April 2005.
21. Moreira, F.; Martins, R.C.; Aguilar, F.F.; Canhoto, A.; Martins, J.; Moreira, J.; Bernardino, J. Long-term management practices successfully reduce bird-related electrical faults in a transmission grid increasingly used by white storks for nesting. *J. Environ. Manag.* **2023**, *327*, 116897. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Tena, G.M.; Hernández, R.; Montoya, J.I. Failures in outdoor insulation caused by bird excrement. *Electr. Power Syst. Res.* **2010**, *80*, 716–722. [\[CrossRef\]](#)
23. Wesley, R.; Garcia, S. Using Environmental Parameters to Create Pollution Maps for Power Utilities: Experience in Brazil. In Proceedings of the INMR World Congress 2022, Berlin, Germany, 16–19 October 2022.
24. Sklenicka, V. *Investigating Unexplained Reclosures on Power Grid*; INMR: Kelowna, BC, Canada, 2023. Available online: <https://www.inmr.com/analyzing-unexplained-reclosures/> (accessed on 21 October 2023).
25. Abebe, D. Future Climate of Ethiopia from PRECIS Regional Climate Model Experimental Design Ethiopia. Presented Climate Strategies Forum, November 2010. Available online: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/applied-science/precis/precis_experimental_design_dawit.pdf (accessed on 18 April 2022).
26. Seleshi, Y.; Zanke, U. Recent changes in rainfall and rainy days in Ethiopia. *Int. J. Climatol.* **2004**, *24*, 973–983. [\[CrossRef\]](#)
27. McSweeney, C.; New, M.; Lizcano, G. UNDP Climate Change Country Profiles Ethiopia. 2012. Available online: <http://country-profiles.geog.ox.ac.uk/> (accessed on 10 May 2023).
28. Climate Forecast System Reanalysis (CFSR). Global Weather Data. Available online: <https://globalweather.tamu.edu/> (accessed on 12 April 2023).
29. Chen, B. Fault statistics and analysis of 220-kV and above transmission lines in a southern coastal provincial power grid of China. *IEEE Open Access J. Power Energy* **2020**, *7*, 122–129. [\[CrossRef\]](#)
30. Hu, Y. Analysis on operation faults of transmission line and countermeasures. *Gaodiyuan Jishu/High Volt. Eng.* **2007**, *33*, 1–8.

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Appendix B: Results of statistical analysis of unexplained faults on EEP transmission lines (2015–2022).

Table A – 1 Frequency of unexplained faults per 100 km per year on 132 kV lines across EEP grid regions during the years 2015–2022.

Grid Regions	2015	2016	2017	2018	2019	2020	2021	2022	Faults/100 km/year
Addis Ababa	10.504	16.614	22.667	18.296	14.435	11.918	20.142	13.260	15.980
Central	2.176	4.018	4.047	3.828	4.047	4.703	6.234	6.453	4.438
East	0.308	0.924	1.470	2.022	2.713	4.792	5.245	1.989	2.433
North-East	1.926	8.341	3.707	3.012	1.854	4.634	4.634	11.353	4.933
North-West	0.000	1.727	0.000	0.000	0.000	0.843	6.746	0.843	1.270
North	0.000	0.949	0.474	1.230	0.410	2.871	2.871	0.000	1.101
South	3.350	5.022	3.597	6.040	4.411	6.990	5.429	1.900	4.593
South-West	3.685	2.073	3.168	4.753	1.358	1.132	1.132	1.584	2.361
West	2.242	4.485	3.622	2.886	2.611	2.611	3.435	3.435	3.166

Table A – 2 Frequency of unexplained faults per 100 km per year on 230 kV lines across EEP grid regions during the years 2015–2022.

Grid Regions	2015	2016	2017	2018	2019	2020	2021	2022	Faults/100 km/year
Addis Ababa	2.924	3.055	3.014	4.520	2.825	2.769	3.693	1.846	3.081
Central	1.670	1.156	1.805	1.891	2.321	1.719	1.891	1.547	1.750
East	0.091	0.534	1.468	1.201	1.068	1.802	1.802	0.934	1.113
North-East	1.861	3.350	4.476	10.444	5.968	5.636	2.818	7.128	5.210
North-West	1.156	3.372	4.431	7.995	4.913	5.298	5.587	5.009	4.720
North	1.235	0.920	1.911	1.752	2.156	2.561	2.156	0.943	1.704
South	0.324	1.618	3.882	8.412	3.882	3.235	1.941	2.912	3.276
South-West	1.341	1.955	4.527	1.029	1.646	1.955	0.514	1.441	1.801
West	4.141	3.365	5.177	2.330	3.106	3.365	7.506	4.659	4.206

Table A – 3 Frequency of unexplained faults per 100 km per year on 400 kV lines across EEP grid regions during the years 2015–2022.

Grid Regions	2015	2016	2017	2018	2019	2020	2021	2022	Faults/100 km/year
Addis Ababa	0.505	1.974	0.980	1.176	0.392	1.765	0.588	0.196	0.947
Central	0.347	0.347	0.676	0.902	0.129	0.387	0.902	1.289	0.622
East	NA	NA	NA	NA	NA	NA	NA	NA	NA
North-East	NA	NA	NA	NA	NA	NA	NA	NA	NA
North-West	0.516	1.805	2.966	2.450	2.966	5.029	7.737	7.092	3.820
North	NA	NA	NA	NA	NA	NA	NA	NA	NA
South	0.505	0.678	0.508	1.695	0.847	0.967	0.967	1.406	0.947
South-West	0.000	8.333	1.667	5.000	1.667	6.667	1.667	3.333	3.542
West	NA	NA	0.000	0.000	0.000	0.050	0.150	0.000	0.033

Table A – 4 Fault frequency per 100 km per year in different rainfall regimes evaluated for 132, 230 and 400kV lines (faults/100 km/year).

132 kV	2015	2016	2017	2018	2019	2020	2021	2022	Mean	Std Dev
Rainfall Regime A	3.224	6.575	6.281	5.559	4.922	5.894	7.960	6.350	5.846	1.214
Rainfall Regime B	2.706	3.359	3.242	3.422	2.037	1.941	2.950	2.562	2.777	0.505
Rainfall Regime C	3.350	5.022	3.597	6.040	4.411	6.990	5.429	1.900	4.593	1.435

230kV	2015	2016	2017	2018	2019	2020	2021	2022	Mean	Std Dev
Rainfall Regime A	1.296	1.326	2.169	2.898	2.387	2.533	2.230	1.871	2.089	0.497
Rainfall Regime B	1.781	2.796	4.590	4.257	3.297	3.631	3.839	3.505	3.462	0.773
Rainfall Regime C	0.324	1.618	3.882	8.412	3.882	3.235	1.941	2.912	3.276	2.121

400kV	2015	2016	2017	2018	2019	2020	2021	2022	Mean	Std Dev
Rainfall Regime A	0.411	1.182	0.868	1.011	0.233	0.933	0.778	0.855	0.784	0.276
Rainfall Regime B	0.498	2.274	1.086	0.777	0.848	1.554	2.260	2.013	1.414	0.624
Rainfall Regime C	0.505	0.678	0.508	1.695	0.847	0.967	0.967	1.406	0.947	0.371

Table A – 5 Season and time dependent characterization of the unexplained fault frequency evaluated for 132, 230 and 400kV lines (faults/100 km/year).

400 kV	Time of the day							
Seasons	00:00 - 07:59		08:00 - 12:59		13:00 - 18:59		19:00 - 23:59	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Bega: October – January	0.1077	0.0768	0.0960	0.0503	0.2268	0.1510	0.0568	0.0471
Belg: February – May	0.0742	0.0578	0.0400	0.0594	0.1388	0.1085	0.0678	0.0431
Kiremt: June – September	0.0586	0.0179	0.0600	0.0599	0.1073	0.0619	0.0943	0.0705

230 kV	Time of the day							
Seasons	00:00 - 07:59		08:00 - 12:59		13:00 - 18:59		19:00 - 23:59	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Bega: October – January	0.1818	0.0604	0.1271	0.0892	0.1990	0.0746	0.1288	0.0679
Belg: February – May	0.1258	0.0820	0.1086	0.0746	0.2907	0.1283	0.1308	0.0890
Kiremt: June – September	0.2683	0.1099	0.1716	0.0314	0.4625	0.0946	0.3544	0.1090

132 kV	Time of the day							
Seasons	00:00 - 07:59		08:00 - 12:59		13:00 - 18:59		19:00 - 23:59	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Bega: October – January	0.1922	0.0813	0.3584	0.0951	0.4872	0.1739	0.1557	0.0451
Belg: February – May	0.3270	0.1861	0.4336	0.2321	0.6518	0.2858	0.1954	0.1098
Kiremt: June – September	0.3479	0.1284	0.5445	0.1574	0.8880	0.1694	0.3065	0.0908

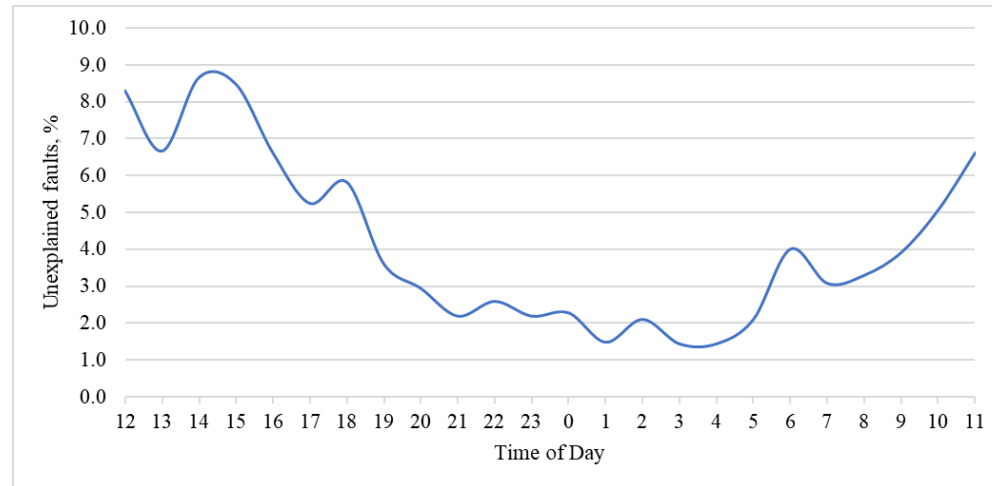


Figure A – 1: The time-of-day trend of unexplained faults in EEP 132 kV network.

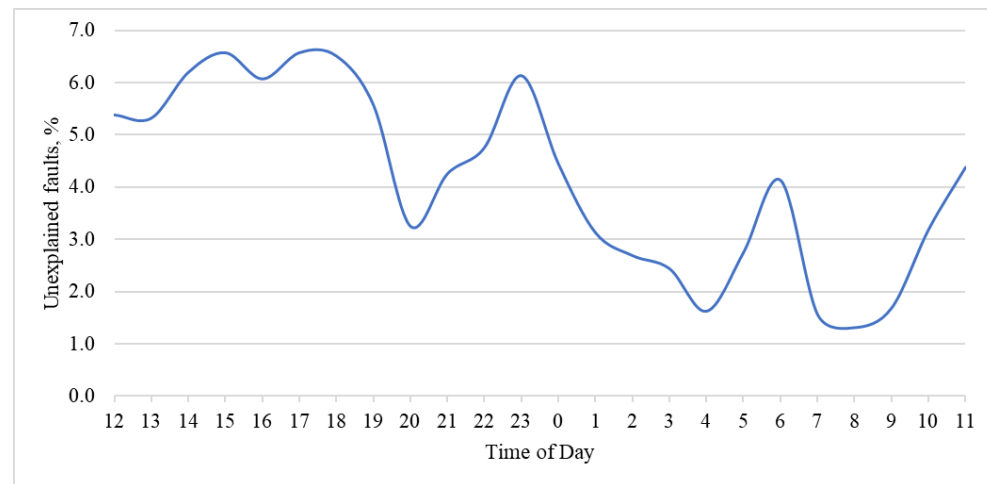


Figure A – 2: The time-of-day trend of unexplained faults in EEP 230 kV network.

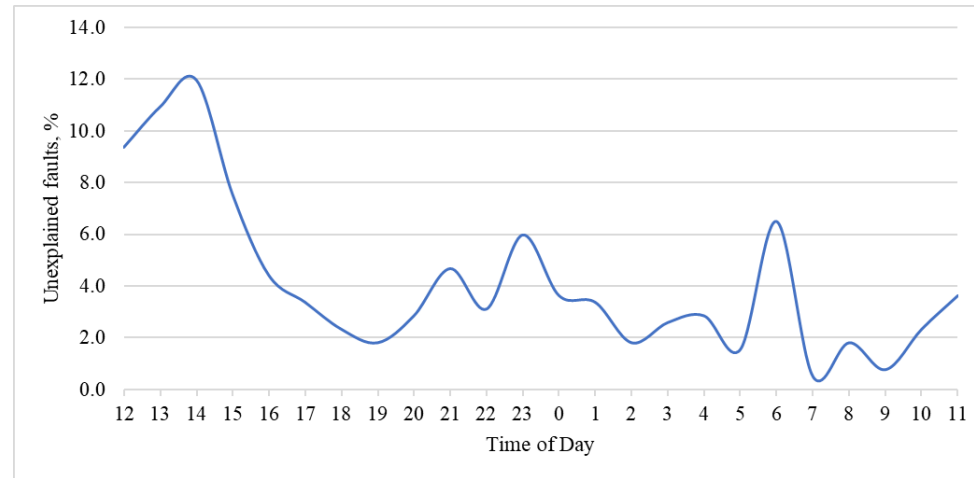


Figure A – 3: The time-of-day trend of unexplained faults in EEP 400kV network.

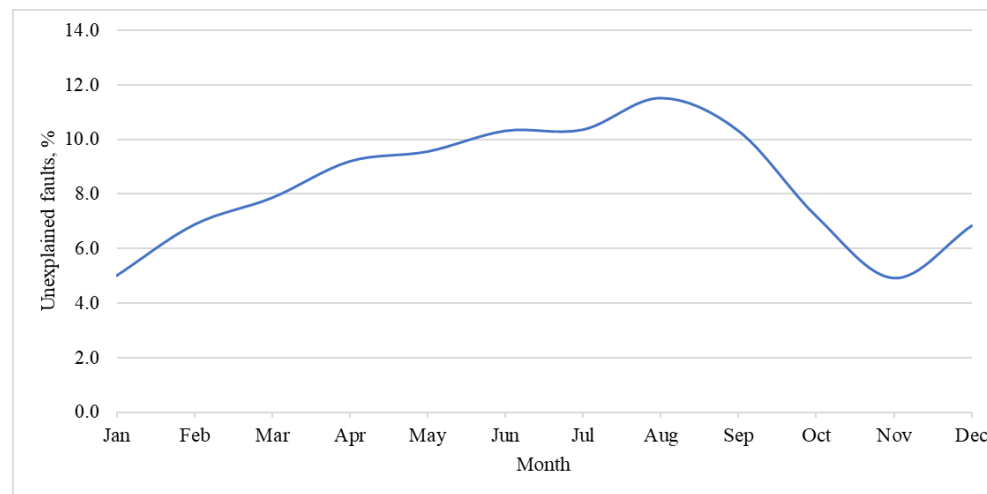


Figure A – 4: Annual trend of unexplained faults in EEP 132 kV network.

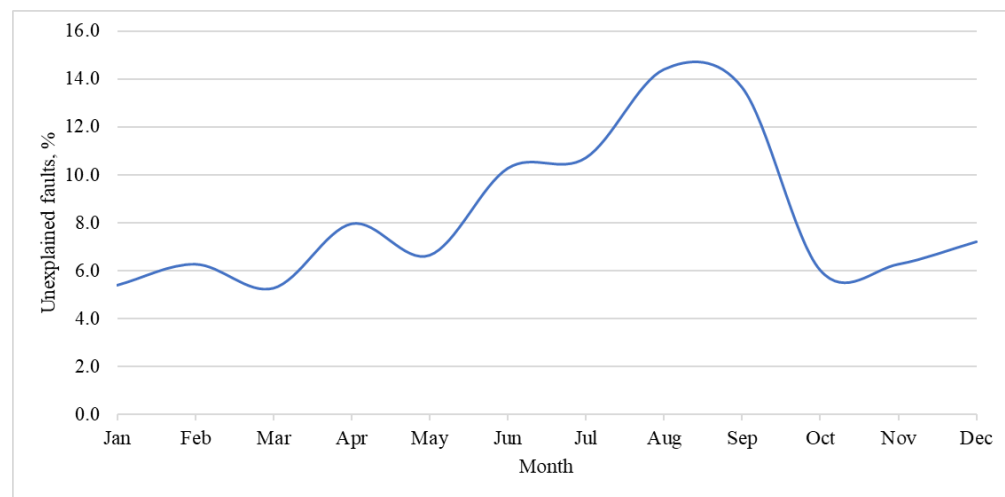


Figure A – 5: Annual trend of unexplained faults in EEP 230 kV network.

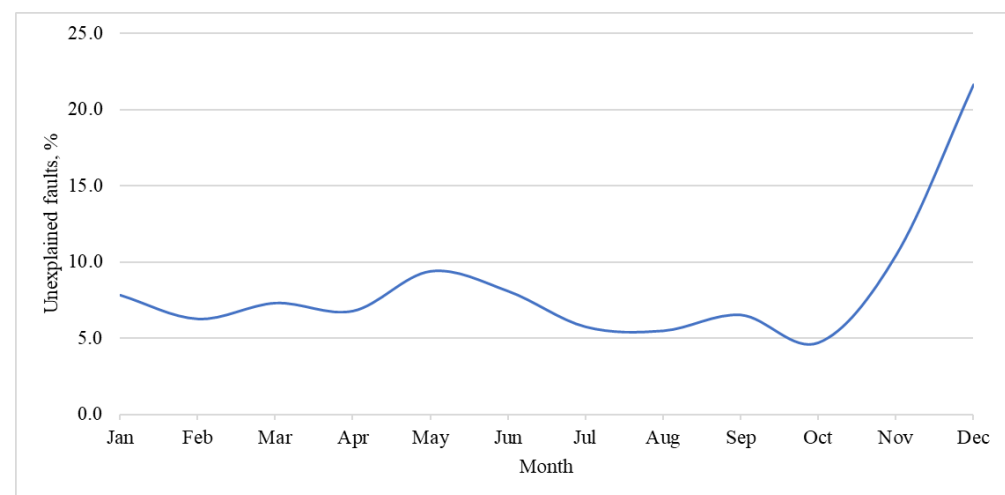


Figure A – 6: Annual trend of unexplained faults in EEP 400 kV network.

Appendix C: Results of statistical analysis of pollution-induced flashovers on EEP transmission lines (2015-2022).

Table A – 6 Frequency of pollution-induced Flashovers on 132 kV lines across EEP grid regions.

Grid Regions	2015	2016	2017	2018	2019	2020	2021	2022	PFO/100km/year
Addis Ababa	1.364	3.170	1.722	1.696	2.543	0.848	2.543	2.035	1.990
Central	0.000	0.316	0.823	1.411	0.941	0.941	1.764	1.411	0.951
East	0.360	0.180	0.368	1.378	1.085	1.447	1.989	0.723	0.941
North-East	1.209	4.354	1.935	2.177	1.451	3.870	1.451	6.047	2.812
North-West	0.000	0.000	0.000	0.000	0.000	0.000	3.373	0.000	0.422
North	0.000	0.000	0.000	0.820	0.000	0.000	0.000	0.000	0.103
South	0.350	1.154	0.196	1.174	0.587	0.978	1.109	0.196	0.718
South-West	0.667	0.222	0.222	0.667	0.000	0.000	0.222	0.000	0.250
West	0.517	0.345	0.172	0.275	0.550	0.275	0.412	0.550	0.387

Table A – 7 Frequency of pollution-induced flashovers on 230 kV lines across EEP grid regions.

Grid Regions	2015	2016	2017	2018	2019	2020	2021	2022	PFO/100km/year
Addis Ababa	0.000	0.220	0.404	0.202	0.606	0.198	0.593	0.000	0.278
Central	0.000	0.394	0.359	0.718	0.646	0.790	0.215	0.574	0.462
East	0.246	0.502	0.549	0.640	0.366	1.097	0.823	0.457	0.585
North-East	0.994	2.414	3.117	6.883	4.415	4.026	1.428	2.597	3.234
North-West	0.298	0.298	0.893	1.687	1.489	0.992	0.992	0.595	0.906
North	0.123	0.319	0.479	0.907	0.378	0.605	0.000	0.227	0.380
South	0.000	0.000	1.170	1.170	0.502	0.502	0.836	0.836	0.627
South-West	0.336	0.336	0.515	0.000	0.103	0.103	0.206	0.000	0.200
West	0.703	0.000	0.703	0.000	0.234	0.000	0.938	0.234	0.352

Table A – 8 Frequency of pollution-induced flashovers on 400 kV lines across EEP grid regions.

Grid Regions	2015	2016	2017	2018	2019	2020	2021	2022	PFO/100km/year
Addis Ababa	0.000	0.370	0.630	0.000	0.000	0.210	0.210	0.000	0.178
Central	0.000	0.270	0.517	0.517	0.259	0.259	0.517	1.293	0.454
East	NA	NA	NA	NA	NA	NA	NA	NA	NA
North-East	NA	NA	NA	NA	NA	NA	NA	NA	NA
North-West	0.144	0.144	1.299	1.299	1.443	1.299	1.877	3.753	1.407
North	NA	NA	NA	NA	NA	NA	NA	NA	NA
South	0.505	0.000	0.000	0.527	0.176	0.263	0.351	0.351	0.272
South-West	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
West	NA	NA	NA	NA	NA	NA	NA	NA	NA

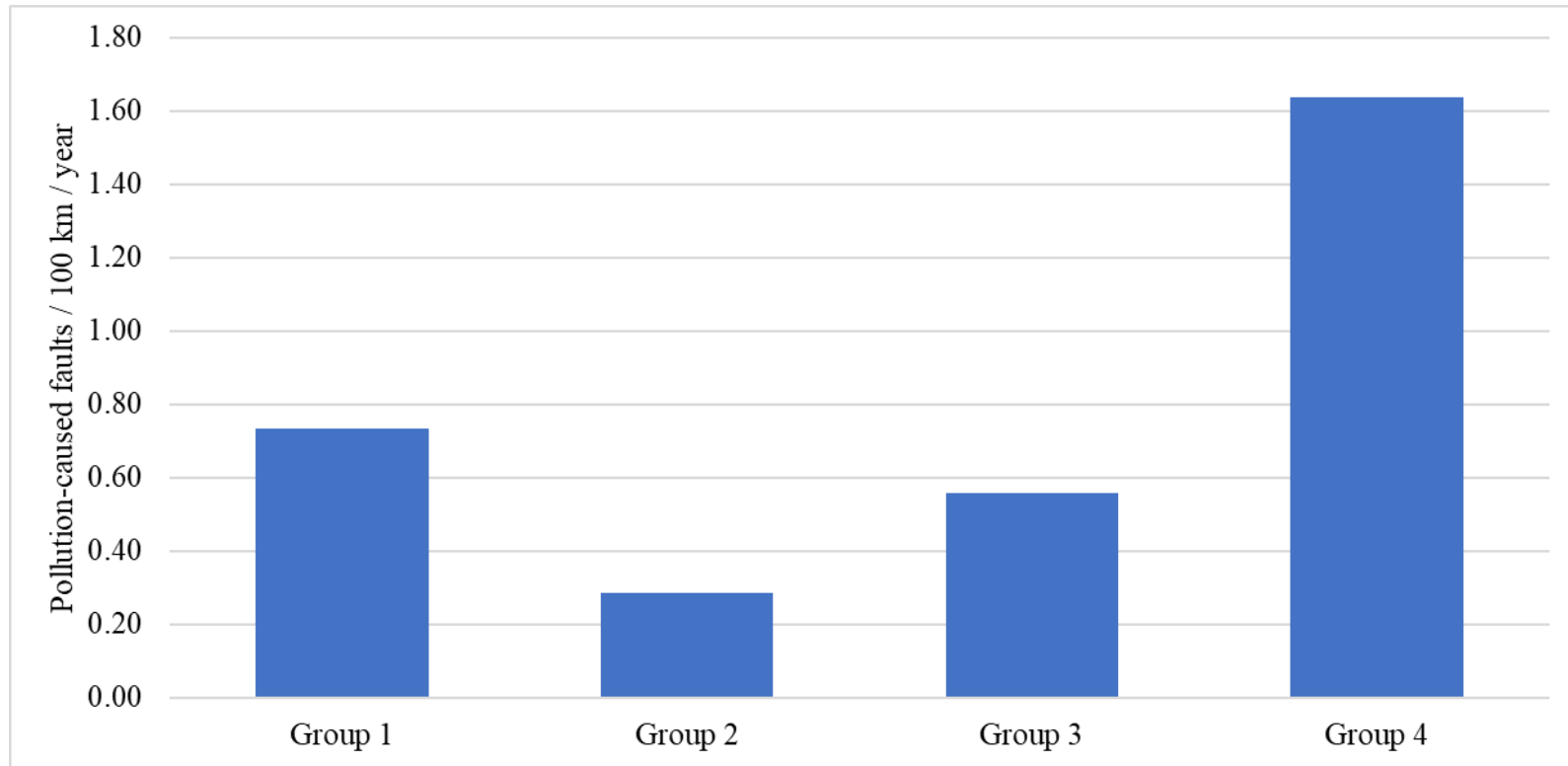


Figure A – 7: Distribution of pollution-induced flashover fault frequency across grid region classification groups from 2015 to 2022.

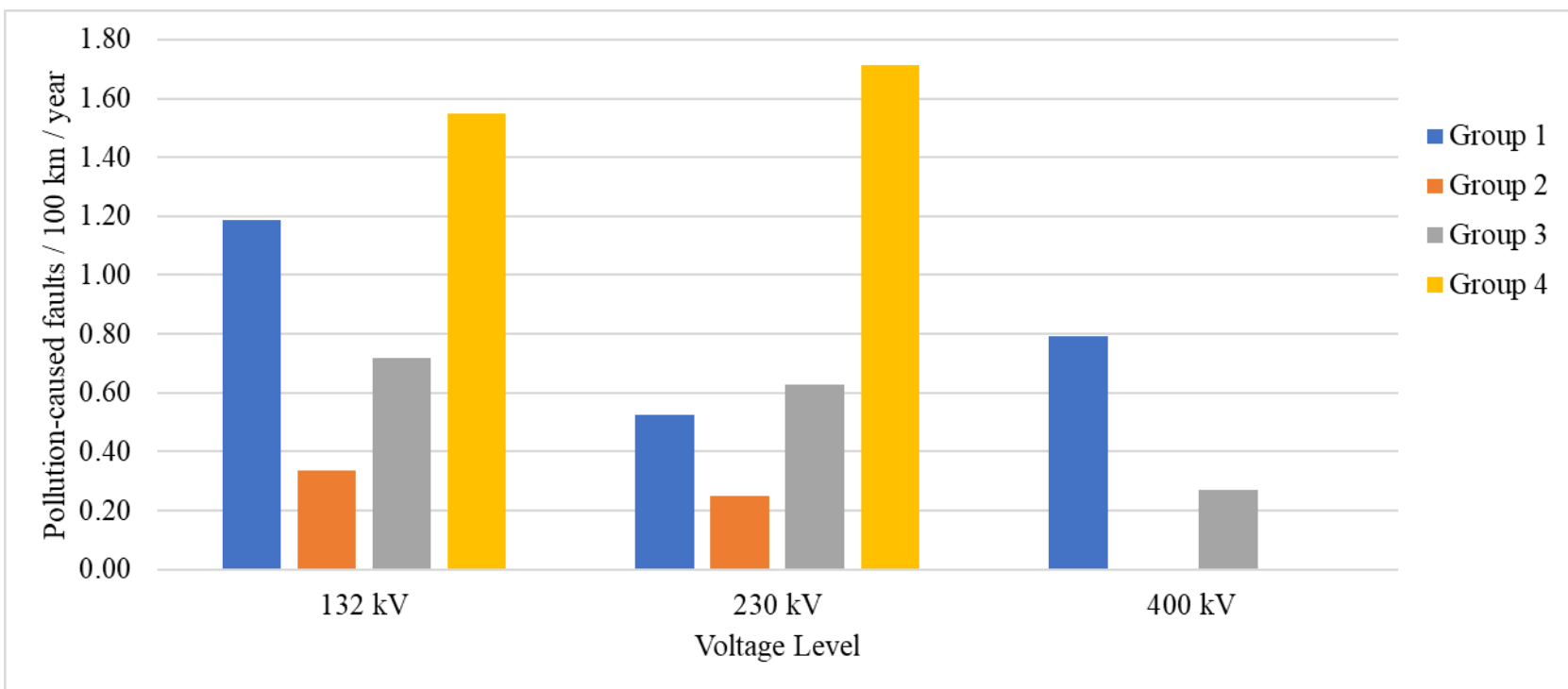


Figure A – 8: Frequency pollution flashover faults according to grid region classification group and voltage levels.

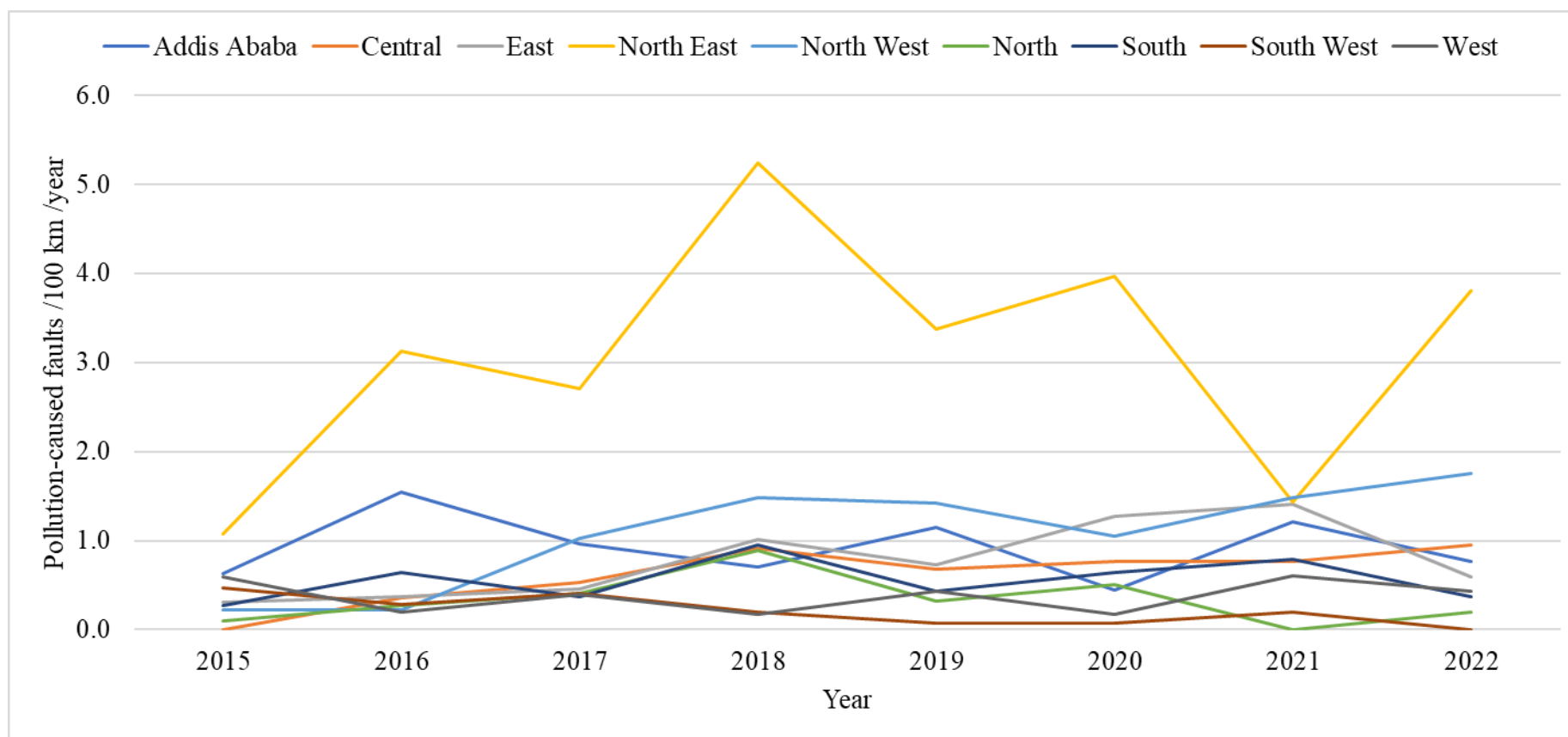


Figure A – 9: Annual distribution of PFO faults per 100 km of lines during the period 2015-2022 in EEP grid management regions.

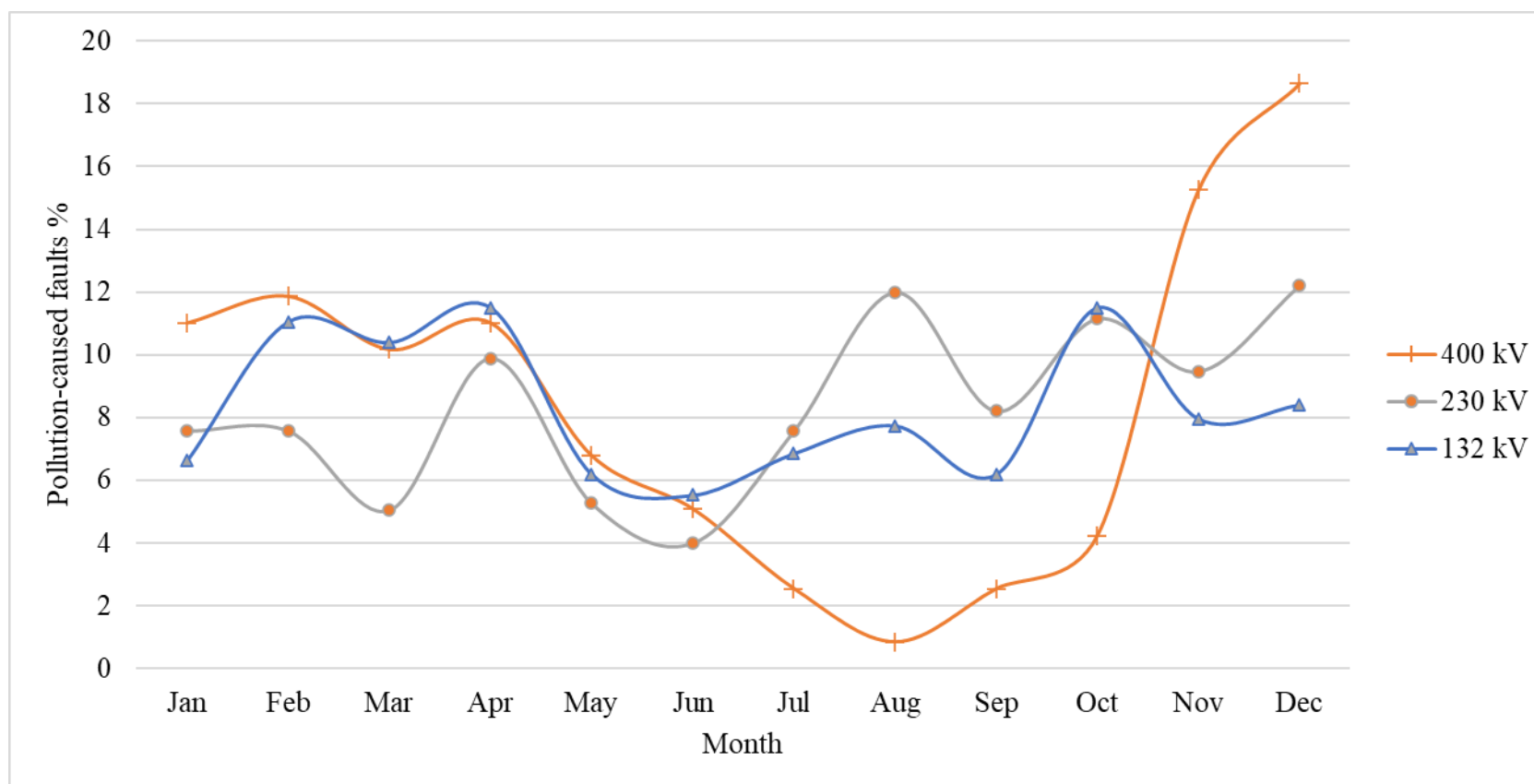
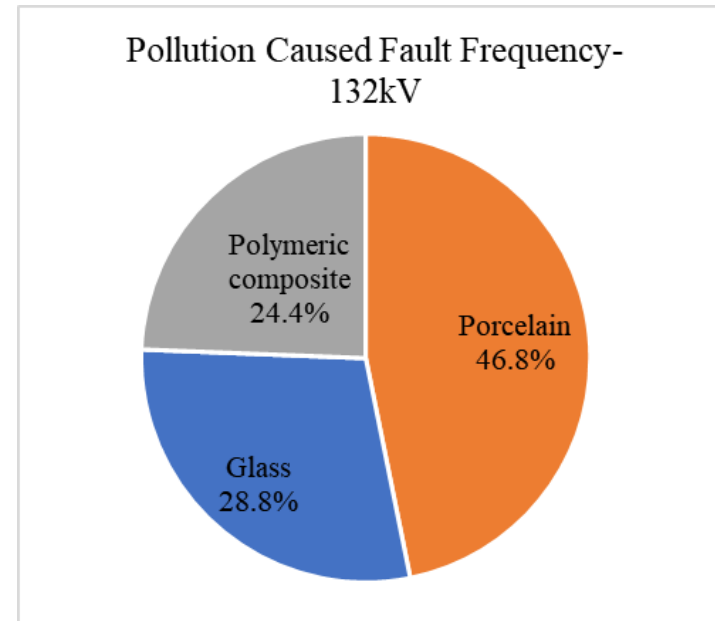
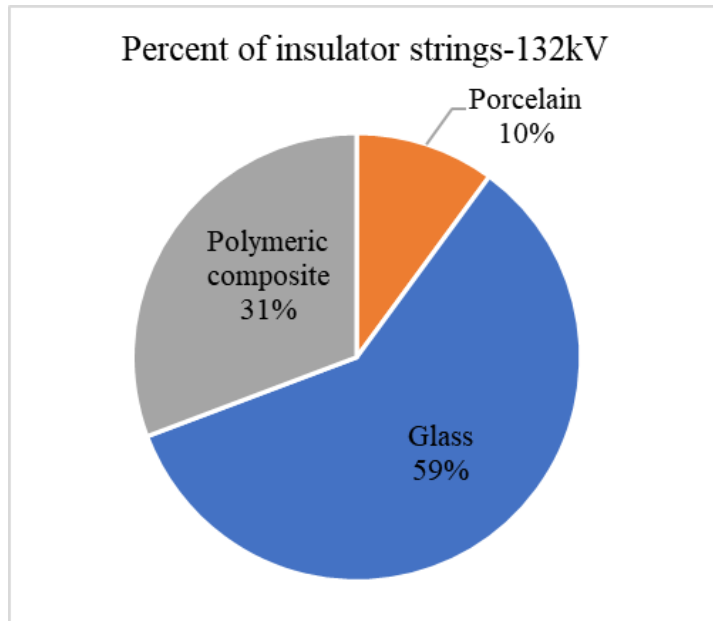
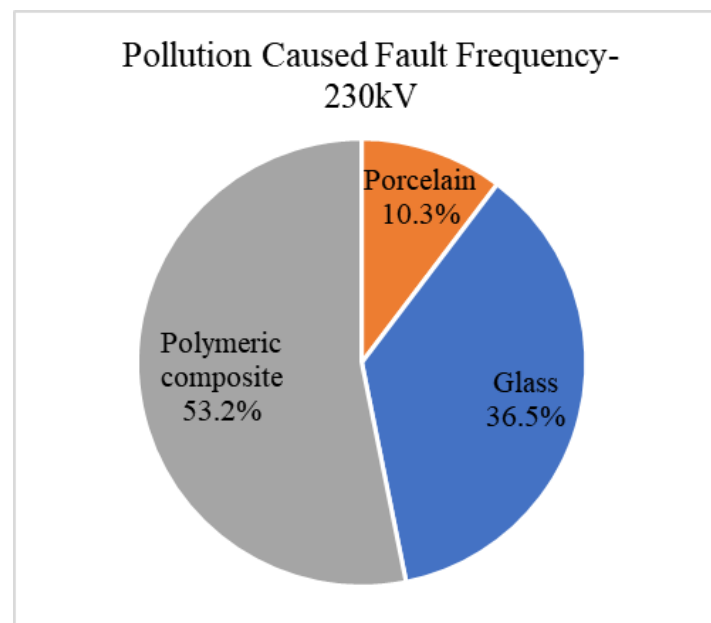
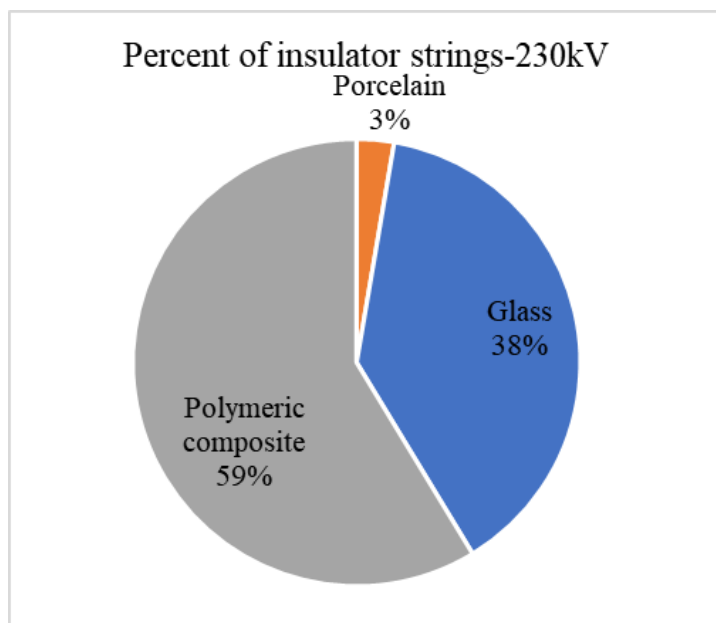


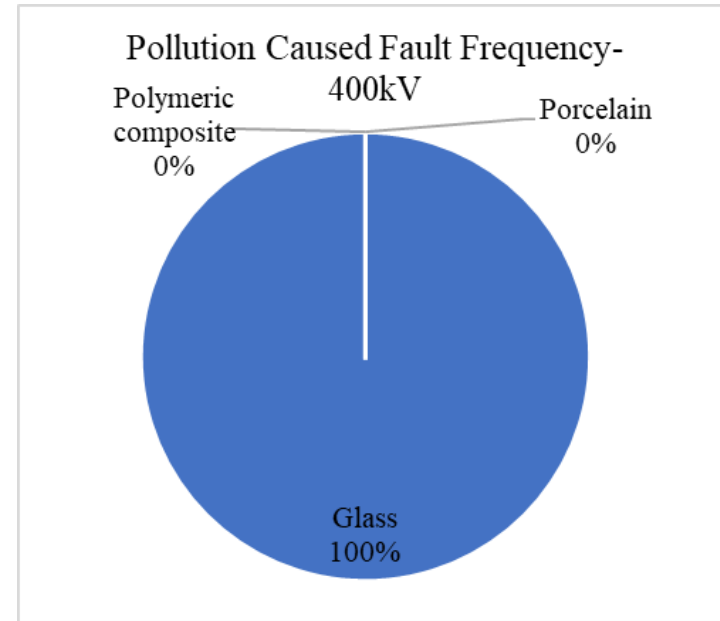
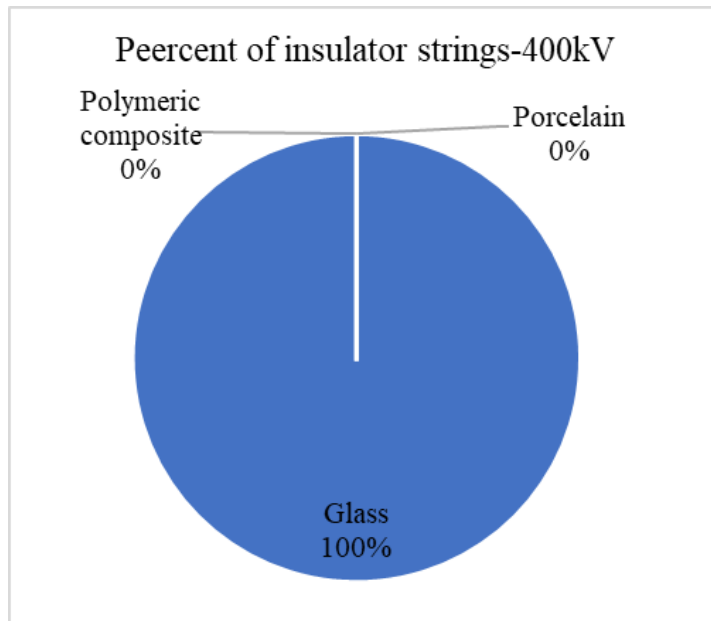
Figure A – 10: Seasonal trend of pollution-induced flashover faults in the Ethiopian power network for all voltage levels.



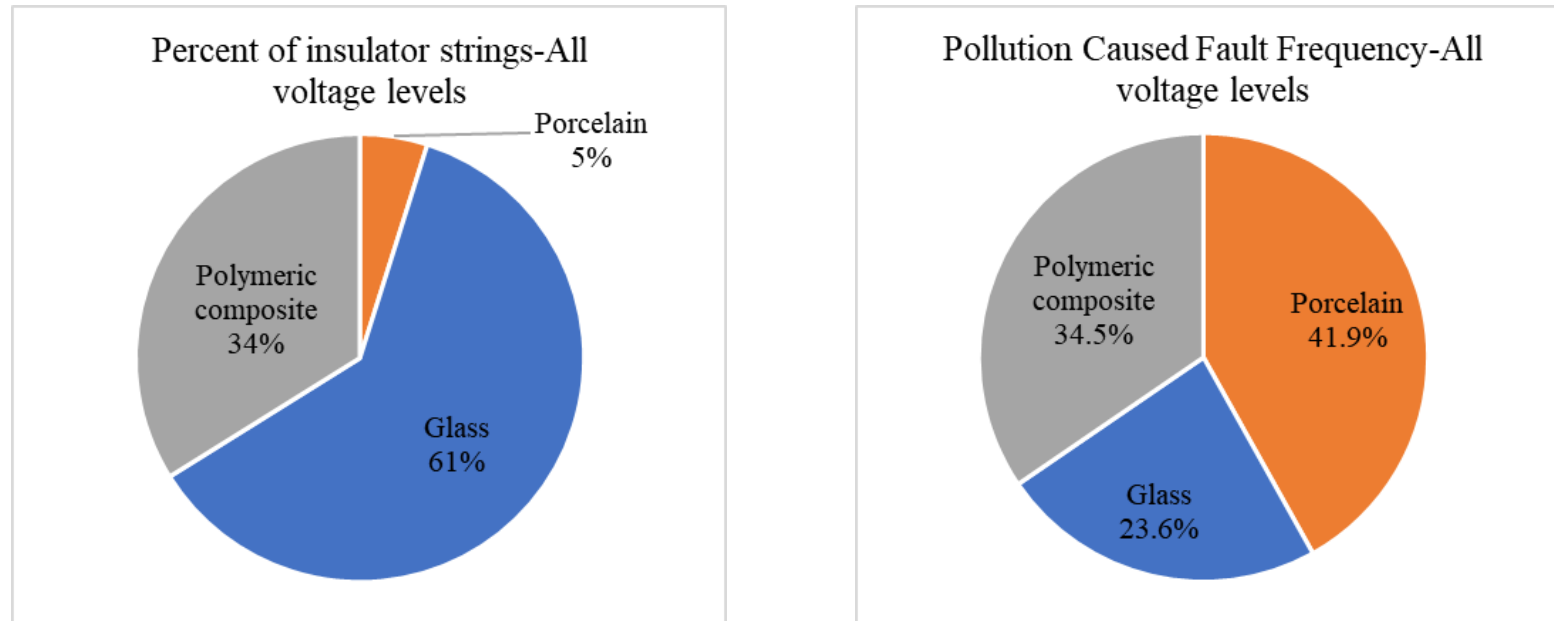
(a) Distribution of PFO intensity by type of insulator for 132 kV system voltage.



(b) Distribution of PFO intensity by type of insulator for 230 kV system voltage.



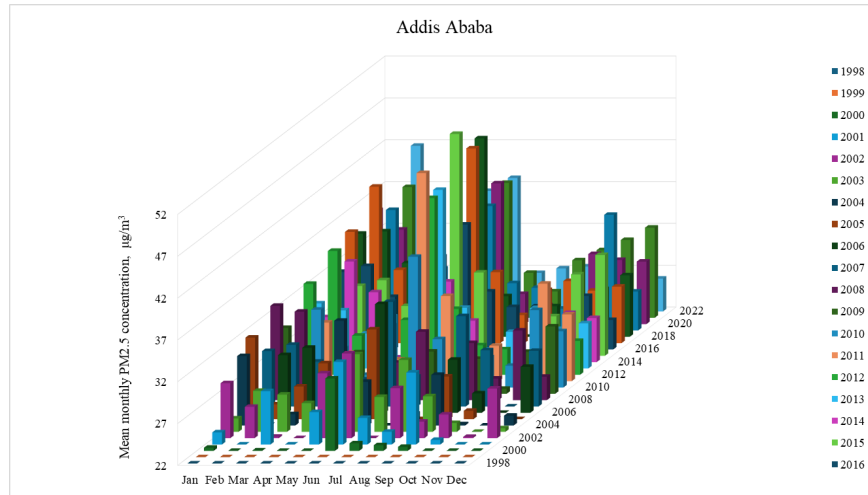
(c) Distribution of PFO intensity by type of insulator for 400 kV system voltage.



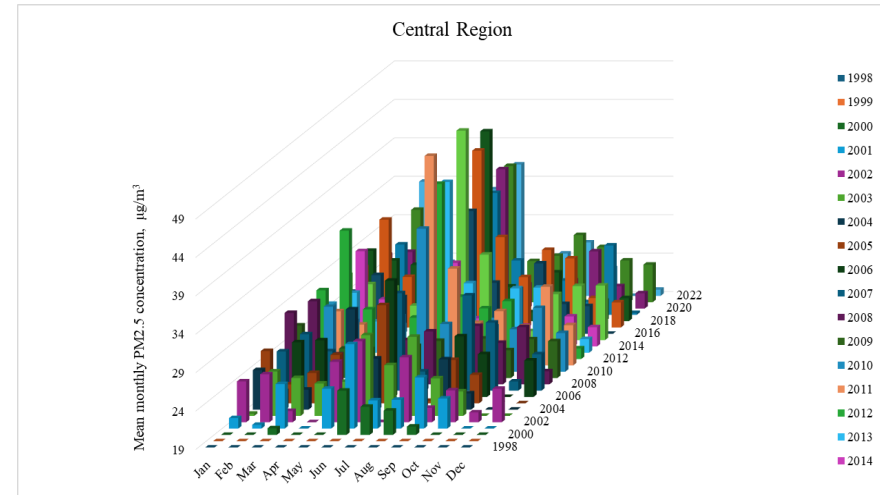
(d) Total percentage distribution of PFO intensity by type of insulator (2015 to 2022).

Figure A – 11: The percent distribution of individual insulator string types and comparison of percentage distributions of pollution flashovers intensities related to insulator string types for all voltage levels.

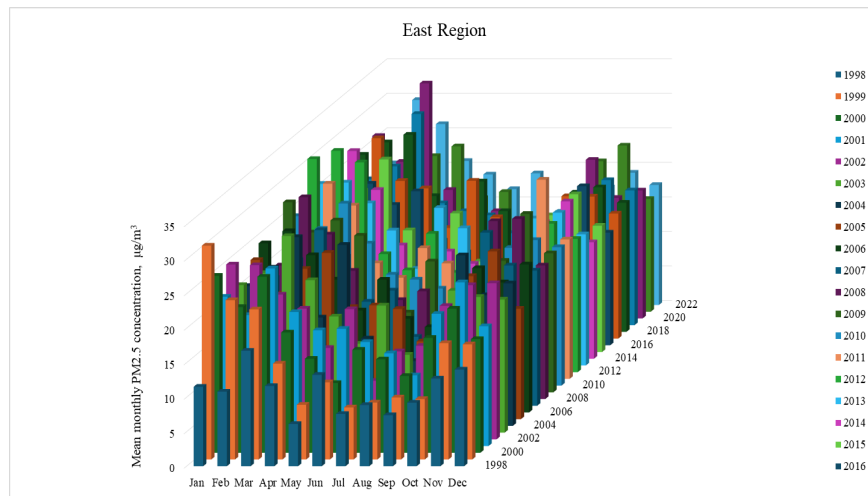
Appendix D: Temporal patterns of PM2.5 density for years 1998-2022.



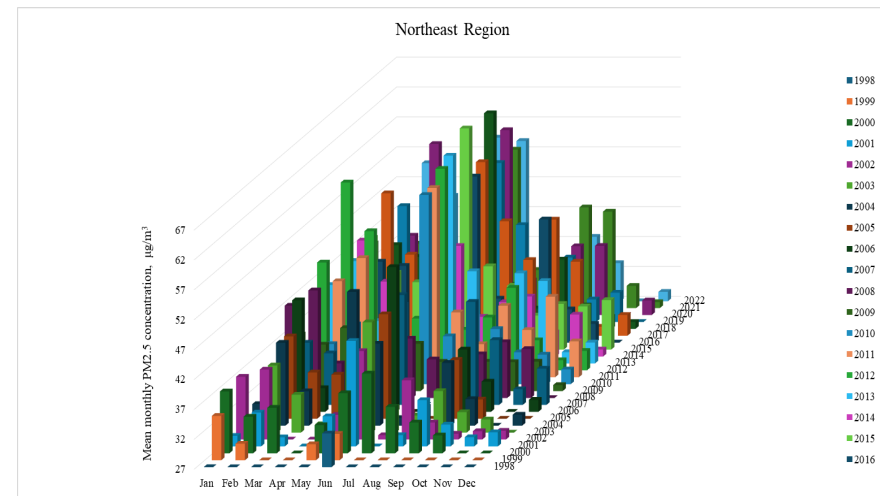
(a)



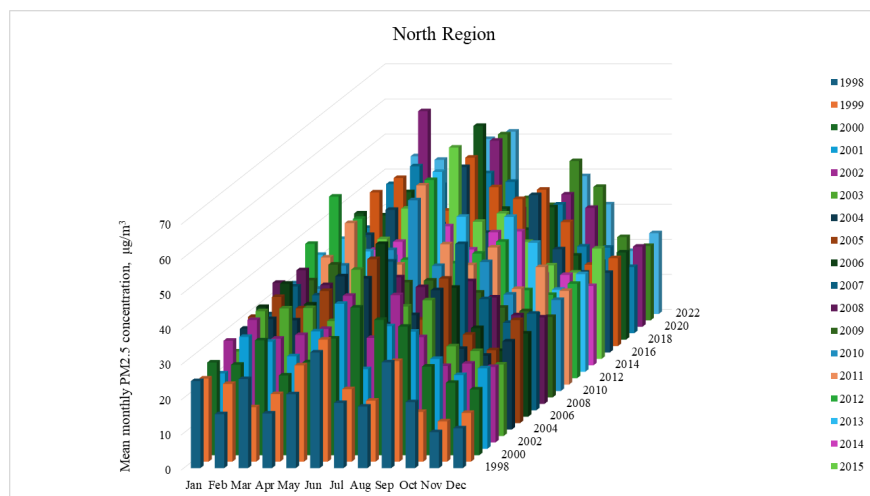
(b)



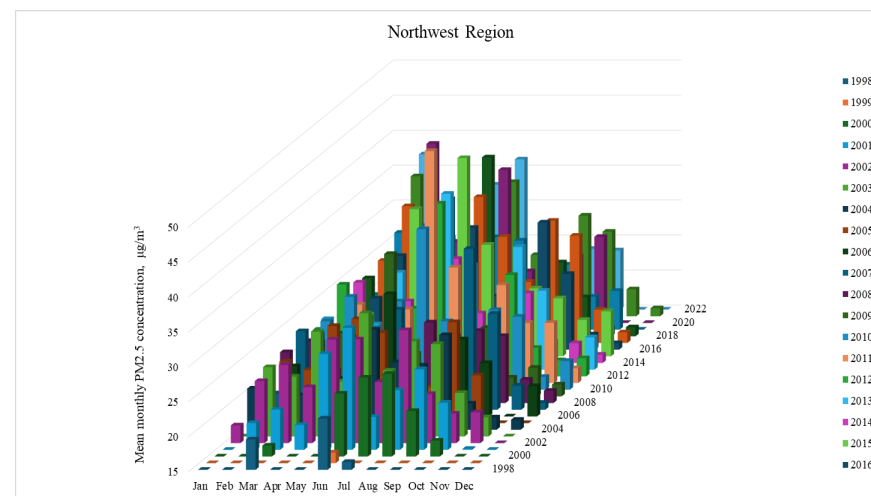
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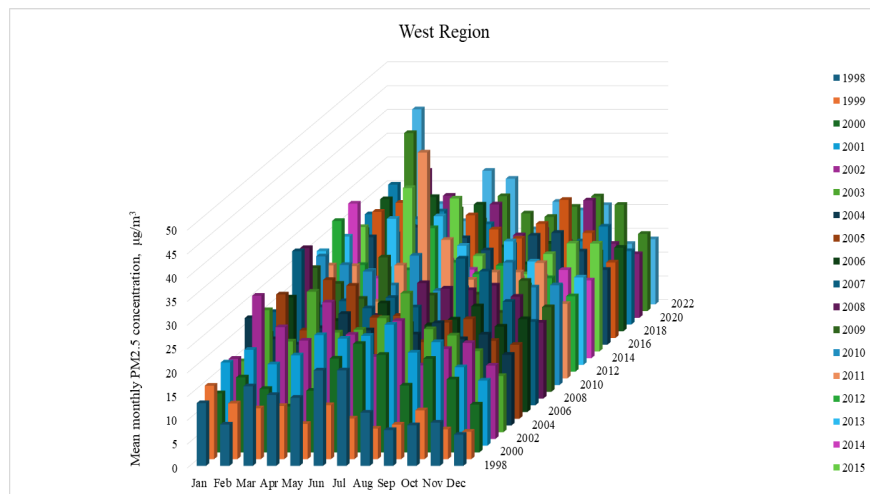
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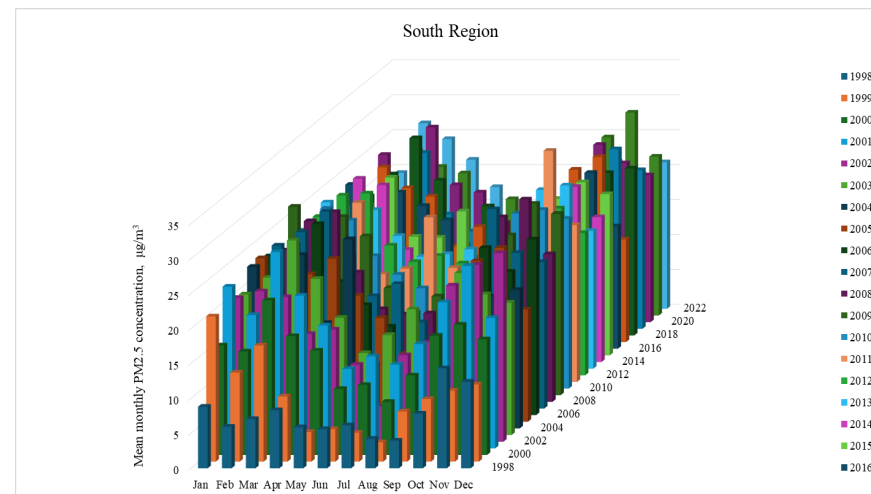
(e)



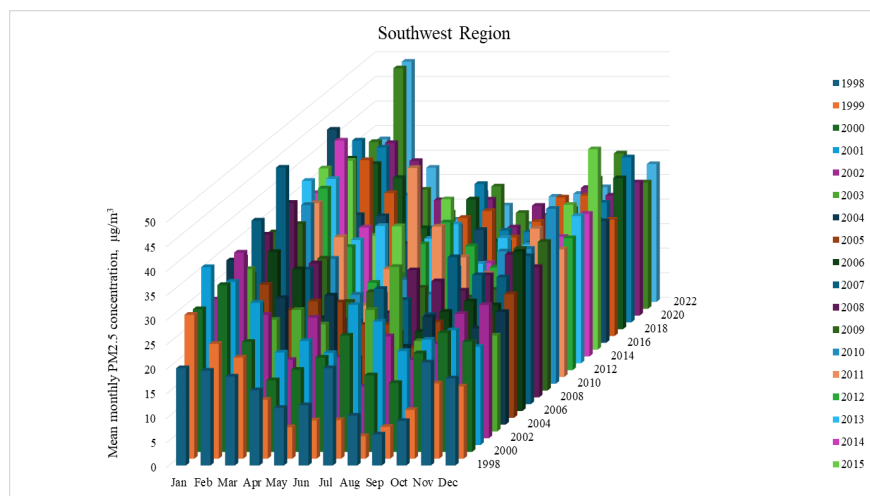
(f)



(g)



(h)



(i)

Figure A – 12: Temporal patterns of PM_{2.5} density across EEP grid region for years 1998-2022.

Appendix E: SPS estimation

Table A – 9 Detailed results of the SPS estimation.

Selected sites for SPS Estimation	Grid Region	Voltage [kV]	Type of Insulator material	Faults/100 km/year	Altitude [m]	Number of Insulators	Mean PM _{2.5} [ug/m ³]	Pollution Induced Fault per year	MTBF Actual	Annual rainy days	Annual dry days	Estimated number of pollution critical wetting events per year	Pollution type	General types of environments	NSDD/ESDD ratio	Examples of typical environments	Estimated SPS class	ESDD	NSDD	ESDD from IST	Corrected ESDD	Final average ESDD	SPS	SPS Class
SP1	West	500	Porcelain	na	1267	1000	20.30	na	6	194	171	37	type A	Agricultural	2	E1	Very light	0.006	0.012	0.018	0.018	0.012	0.006	Light
SP2	West	500	Glass	0.00	1193	9252	18.52	0.00	6.00	155	210	77	type A	Agricultural	2	E2	Light	0.015	0.030	0.014	0.025	0.020	0.011	Light
SP3	West	500	Glass	0.00	1221	9168	18.52	0.00	6.00	155	210	77	type A	Agricultural	2	E2	Light	0.015	0.030	0.014	0.025	0.020	0.011	Light
SP4	West	500	Porcelain	na	539	1000	21.55	na	8	139	226	61	type A	Agricultural	3	E3/E4	Medium	0.05	0.15	0.026	0.021	0.036	0.043	Medium
SP5	Central	500	Porcelain	na	2284	1000	21.18	na	5	205	160	124	type A	Agricultural	2	E2	Light	0.015	0.03	0.017	0.030	0.023	0.013	Light
SP6	West & Central	500	Glass	0.03	1545	7368	20.10	0.20	5.00	207	158	50	type A	Agricultural	2	E1	Very light	0.005	0.010	0.023	0.023	0.014	0.006	Light
SP7	West & Central	500	Glass	0.00	1628	7380	20.01	0.00	5.00	209	156	52	type A	Agricultural	2	E1	Very light	0.005	0.010	0.015	0.015	0.010	0.005	Light
SP8	Addis Ababa &	400	Glass	0.36	2267	2490	22.83	0.63	1.60	165	200	84	type A	Agricultural	3	E3/E4	Medium	0.045	0.135	0.023	0.020	0.032	0.038	Medium
SP9	South West	400	Porcelain	na	1046	1000	22.94	na	8	213	152	94	type A	Agricultural	2	E1	Very light	0.006	0.012	0.014	0.014	0.010	0.005	Light
SP10	Central	400	Porcelain	na	2092	1000	26.81	na	7	85	280	45	type A	Agricultural	5	E3/E4	Medium	0.045	0.225	0.02	0.014	0.029	0.043	Medium
SP11	Addis Ababa	400	Glass	0.38	2177	438	26.49	0.13	8.00	99	266	18	type A	Agricultural	5	E3/E4	Medium	0.050	0.250	0.024	0.015	0.033	0.051	Medium
SP12	Central	400	Porcelain	na	2141	1000	24.91	na	8	138	227	57	type A	Agricultural	5	E3/E4	Medium	0.045	0.225	0.019	0.013	0.029	0.043	Medium
SP13	Central	400	Porcelain	na	2252	1000	24.97	na	8	154	211	73	type A	Agricultural	4	E2	Light	0.015	0.06	0.017	0.022	0.018	0.014	Light
SP14	Addis Ababa	400	Glass	0.00	2280	504	25.15	0.00	6.00	150	215	69	type A	Agricultural	5	E3/E4	Medium	0.045	0.225	0.019	0.013	0.029	0.043	Medium
SP15	Addis Ababa &	400	Glass	0.26	1984	3600	21.16	0.71	1.40	90	275	9	type A	Agricultural	5	E3/E4	Medium	0.055	0.275	0.044	0.027	0.041	0.067	Medium
SP16	South	400	Porcelain	na	1761	1000	20.42	na	7	173	192	111	type A	Agricultural	3	E2	Light	0.015	0.045	0.018	0.026	0.021	0.014	Light
SP17	Addis Ababa	400	Glass	0.00	2656	876	24.66	0.00	6.00	150	215	69	type A	Agricultural	4	E3/E4	Medium	0.045	0.180	0.017	0.013	0.029	0.038	Medium
SP18	Central	400	Porcelain	na	2702	1000	23.56	na	8	177	188	96	type A	Agricultural	4	E3/E4	Medium	0.045	0.18	0.015	0.011	0.028	0.037	Medium
SP19	Addis Ababa	400	Glass	0.00	2065	1320	26.29	0.00	6.00	123	242	42	type A	Agricultural	6	E3/E4	Medium	0.045	0.270	0.021	0.013	0.029	0.047	Medium
SP20	Central & North	400	Glass	0.75	3138	5568	20.47	3.25	0.31	74	291	74	type A	Agricultural	6	E5/E6	Heavy	0.150	0.900	0.029	0.010	0.080	0.231	Heavy
SP21	Central	400	Porcelain	na	2365	1000	21.97	na	8	92	273	51	type A	Agricultural	5	E3/E4	Medium	0.045	0.225	0.019	0.013	0.029	0.043	Medium
SP22	Central	400	Glass	1.04	2585	96	21.79	0.17	6.00	64	301	23	type A	Agricultural	5	E3/E4	Medium	0.050	0.250	0.025	0.016	0.033	0.051	Medium
SP23	North West	400	Glass	0.56	1807	1740	19.04	0.75	1.33	103	262	23	type A	Agricultural	4	E3/E4	Medium	0.055	0.220	0.037	0.025	0.040	0.059	Medium
SP24	North West	400	Porcelain	na	1804	1000	19.39	na	8	119	246	39	type A	Agricultural	5	E3/E4	Medium	0.045	0.225	0.022	0.015	0.030	0.044	Medium
SP25	North West	400	Glass	2.97	2393	2562	22.51	5.75	0.17	160	205	84	type A	Agricultural	5	E3/E4	Medium	0.040	0.200	0.040	0.029	0.034	0.048	Medium
SP26	North West	400	Porcelain	na	1773	1000	20.94	na	8	147	218	67	type A	Agricultural	4	E2	Light	0.02	0.08	0.02	0.022	0.021	0.019	Light
SP27	North West	400	Glass	0.52	992	3228	20.32	1.25	0.80	149	216	69	type A	Agricultural	4	E5/E6	Heavy	0.150	0.600	0.037	0.016	0.083	0.196	Heavy
SP28	South	400	Porcelain	na	1955	1000	18.45	na	7	146	219	84	type A	Agricultural	3	E3/E4	Medium	0.045	0.135	0.019	0.016	0.031	0.036	Medium
SP29	South	400	Glass	1.14	1198	642	21.92	0.57	1.75	159	206	97	type A	Agricultural	3	E3/E4	Medium	0.050	0.150	0.028	0.023	0.037	0.044	Medium
SP30	South	400	Porcelain	na	1022	1000	22.79	na	7	151	214	89	type A	Agricultural	4	E2	Light	0.02	0.08	0.023	0.026	0.023	0.020	Medium
SP31	South	400	Glass	0.42	1193	1308	21.92	0.43	2.33	159	206	97	type A	Agricultural	3	E3/E4	Medium	0.050	0.150	0.026	0.021	0.036	0.043	Medium
SP32	South	400	Glass	0.06	1432	2640	18.70	0.13	8.00	125	240	63	type A	Agricultural	4	E3/E4	Medium	0.045	0.180	0.021	0.016	0.030	0.040	Medium
SP33	South	400	Porcelain	na	1745	1000	22.32	na	8	168	197	106	type A	Agricultural	3	E2	Light	0.015	0.045	0.018	0.026	0.021	0.014	Light
SP34	South & South	400	Glass	0.60	2399	1650	20.48	0.71	1.40	217	148	98	type A	Agricultural	2	E2	Light	0.010	0.019	0.016	0.016	0.013	0.006	Light
SP35	South West	400	Glass	0.00	2244	390	21.92	0.00	8.00	186	179	67	type A	Agricultural	3	E2	Light	0.010	0.030	0.013	0.023	0.017	0.009	Light
SP36	South	400	Porcelain	na	1603	1000	21.73	na	8	180	185	61	type A	Agricultural	3	E2	Light	0.02	0.06	0.021	0.027	0.023	0.018	Light
SP37	South	400	Glass	0.15	1756	6348	15.98	0.80	1.25	159	206	97	type A	Agricultural	2	E3/E4	Medium	0.050	0.100	0.026	0.026	0.038	0.038	Medium
SP38	South	400	Porcelain	na	918	1000	15.50	na	5	198	167	136	type A	Agricultural	2	E2	Light	0.02	0.04	0.022	0.034	0.027	0.017	Light
SP39	Addis Ababa	230	Glass	0.88	2276	135	26.27	0.13	8.00	110	255	29	type A/B	Industrial/Agricultural	5	E3/E4	Medium	0.060	0.300	0.045	0.027	0.043	0.073	Medium
SP40	Addis Ababa	230	Glass	7.96	2508	93	25.93	0.25	4.00	132	233	51	type A/B	Industrial/Agricultural	5	E3/E4	Medium	0.060	0.300	0.045	0.027	0.043	0.073	Medium
SP41	Addis Ababa	230	Glass	12.50	2514	15	25.93	0.25	4.00	132	233	51	type A/B	Industrial/Agricultural	5	E5/E6	Heavy	0.150	0.750	0.053	0.020	0.085	0.225	Heavy
SP42	Addis Ababa	230	Porcelain	na	2355	1000	26.27	na	8	119	246	38	type A/B	Industrial/Agricultural	5	E3/E4	Medium	0.035	0.175	0.038	0.029	0.032	0.042	Medium
SP43	Addis Ababa	230	Glass	0.07	2221	1053	22.83	0.13	8.00	163	202	82	type A	Agricultural	3	E3/E4	Medium	0.055	0.165	0.033	0.026	0.040	0.052	Medium
SP44	Central	230	Porcelain	na	1779	1000	22.48	na	8	162	203	81	type A	Agricultural	2	E2	Light	0.03	0.06	0.037	0.047	0.039	0.030	Medium
SP45	Addis Ababa	230	Glass	0.78	2414	354	25.67	0.25	4.00	120	245	39	type A	Agricultural	4	E3/E4	Medium	0.060	0.240	0.045	0.030	0.045	0.068	Medium
SP46	Central	230	Porcelain	na	2164	1000	24.91	na	8	138	227	57	type A	Agricultural	4	E3/E4	Medium	0.035	0.14	0.036	0.031	0.033	0.039	Medium
SP47	Addis Ababa	230	Porcelain	na	2437	1000	26.36	na	8	117	248	36	type A/B	Industrial	6	E5/E6	Heavy	0.15	0.9	0.038	0.013	0.082	0.235	Heavy
SP48	Addis Ababa	230	Polymeric composite	0.00	2267	291	27.37	0.00	8.00	99	266	18	type A/B	Industrial	6	E7	Very heavy	0.300	1.800	0.154	0.038	0.169	0.681	Very Heavy
SP49	Addis Ababa	230	Porcelain	na	2105	1000	26.84	na	8	101	264	20	type A/B	Industrial	6	E7	Very heavy	0.4	2.4	0.046	0.010	0.205	0.948	Very Heavy
SP50	Addis Ababa	230	Polymeric composite	0.37	2668	336	23.20	0.13	8.00	161	204	80	type A	Agricultural	3	E5/E6	Heavy	0.055	0.165	0.102	0.080	0.068	0.086	Heavy
SP51	Addis Ababa	230	Polymeric composite	0.30	2938	378	26.17	0.13	8.00	153	212	72	type A/B	Industrial	4	E5/E6	Heavy	0.055	0.220	0.061	0.042	0.048	0.071	Heavy
SP52	Addis Ababa	230	Polymeric composite	0.00	2688	414	22.91	0.00	6.00	181	184	100	type A	Agricultural	4	E3/E4	Medium	0.035	0.140	0.064	0.054	0.045	0.053	Medium
SP53	Central	230	Porcelain	na	2637	1000	23.45	na	6	167	198	86	type A	Agricultural	4	E3/E4	Medium	0.03	0.12	0.032	0.029	0.030	0.032	Medium
SP54	Addis Ababa	230	Polymeric composite	0.00	2608	192	26.36	0.00	8.00	117	248	36	type A/B	Industrial	5	E7	Very heavy	0.300	1.500	0.125	0.034	0.167	0.616	Very Heavy
SP55	Addis Ababa	230	Polymeric composite	0.00	2138	15	25.58	0.00	7.00	127	238	46	type A	Agricultural	4	E7	Very heavy	0.150	0.600	0.128	0.054	0.102	0.242	Heavy

(Continued)

Selected sites for SP5 Estimation	Grid Region	Voltage [kV]	Type of Insulator material	Faults/100 km/year	Altitude [m]	Number of Insulators	Mean PM2.5 [$\mu\text{g}/\text{m}^3$]	Pollution Induced Fault per year	MTBF Actual	Annual rainy days	Annual dry days	Estimated number of pollution critical wetting events per year	Pollution type	General types of environments	NSDD/ESDD ratio	Examples of typical environments	Estimated SPS class	ESDD	NSDD	ESDD from 1st	Corrected ESDD	Final average ESDD	SP5	SP5 Class
SP56	Addis Ababa	230	Polymenic composite	0.89	2099	198	26.84	0.13	8.00	98	267	17	type A	Industrial	6	E7	Very heavy	0.350	2.100	0.169	0.039	0.194	0.843	Very Heavy
SP57	Central	230	Porcelain	na	2089	1000	26.92	na	8	85	280	45	type A	Industrial	6	E7	Very heavy	0.4	2.4	0.039	0.008	0.204	0.944	Very Heavy
SP58	Central	230	Glass	0.65	1897	936	23.22	0.75	1.33	32	333	32	type A	Agricultural	5	E3/E4	Medium	0.035	0.175	0.050	0.038	0.037	0.048	Medium
SP59	Central	230	Porcelain	na	1634	1000	23.45	na	8	34	331	34	type A	Agricultural	5	E3/E4	Medium	0.04	0.2	0.045	0.032	0.036	0.050	Medium
SP60	Central	230	Glass	0.15	2561	2610	22.24	0.50	2.00	116	249	35	type A	Agricultural	4	E3/E4	Medium	0.060	0.240	0.048	0.031	0.046	0.070	Medium
SP61	Central	230	Porcelain	na	908	1000	24.81	na	8	53	312	53	type A	Agricultural/desert	7	E5/E6	Heavy	0.15	1.05	0.048	0.015	0.083	0.257	Heavy
SP62	Central	230	Polymenic composite	2.40	1310	897	22.01	3.00	0.33	25	340	25	type A	Agricultural/desert	4	E7	Very heavy	0.150	0.600	0.376	0.159	0.154	0.366	Very Heavy
SP63	Central	230	Porcelain	na	2630	1000	25.14	na	8	150	215	69	type A	Agricultural	3	E3/E4	Medium	0.055	0.165	0.031	0.024	0.040	0.051	Medium
SP64	Central	230	Glass	0.38	2345	2022	22.83	1.00	1.00	176	189	95	type A	Agricultural	3	E3/E4	Medium	0.060	0.180	0.047	0.035	0.048	0.063	Medium
SP65	Central	230	Porcelain	na	2592	1000	21.18	na	8	198	167	117	type A	Agricultural	2	E2	Light	0.025	0.05	0.03	0.042	0.033	0.024	Medium
SP66	Central & East	230	Polymenic composite	0.22	1325	4284	22.01	1.86	0.54	25	340	25	type A	Agricultural/desert	6	E7	Very heavy	0.350	2.100	0.332	0.077	0.213	0.925	Very Heavy
SP67	East	230	Porcelain	na	1105	1000	22.15	na	7	45	320	30	type A	Agricultural/desert	6	E7	Very heavy	0.4	2.4	0.052	0.011	0.206	0.951	Very Heavy
SP68	South	230	Porcelain	na	2303	1000	20.42	na	8	210	155	148	type A	Agricultural	2	E2	Light	0.03	0.06	0.03	0.038	0.034	0.027	Medium
SP69	Central & South	230	Glass	0.50	2014	669	22.35	0.38	2.67	197	168	116	type A	Agricultural	2	E2	Light	0.015	0.030	0.027	0.048	0.032	0.018	Light
SP70	Central	230	Glass	4.00	1691	153	23.28	0.50	2.00	34	331	34	type A	Agricultural	6	E5/E6	Heavy	0.200	1.200	0.065	0.020	0.110	0.364	Heavy
SP71	Central	230	Glass	0.00	1909	42	25.54	0.00	8.00	61	304	61	type A	Agricultural	6	E5/E6	Heavy	0.150	0.900	0.046	0.016	0.083	0.239	Heavy
SP72	East	230	Glass	0.73	1131	1410	24.66	1.50	0.67	104	261	89	type A	Agricultural	6	E5/E6	Heavy	0.200	1.200	0.070	0.021	0.111	0.366	Heavy
SP73	East	230	Porcelain	na	1201	1000	20.74	na	8	51	314	36	type A	Desert	6	E5/E6	Heavy	0.15	0.9	0.049	0.017	0.083	0.241	Heavy
SP74	East	230	Polymenic composite	1.37	779	867	27.57	1.83	0.55	17	348	17	type A/B	Desert	7	E7	Very heavy	0.400	2.800	0.412	0.083	0.241	1.202	Very Heavy
SP75	East	230	Polymenic composite	0.31	721	1251	29.63	0.63	1.60	31	334	31	type A/B	Desert	7	E7	Very heavy	0.350	2.450	0.284	0.061	0.205	0.959	Very Heavy
SP76	East	230	Porcelain	na	765	1000	28.03	na	6	38	327	23	type A/B	Desert	7	E7	Very heavy	0.4	2.8	0.061	0.012	0.206	1.027	Very Heavy
SP77	East	230	Polymenic composite	0.31	752	702	28.83	0.50	2.00	64	301	49	type A/B	Desert	7	E7	Very heavy	0.350	2.450	0.378	0.081	0.215	1.006	Very Heavy
SP78	East	230	Porcelain	na	802	1000	29.72	na	6	na	na	10	type A/B	Desert	7	E7	Very heavy	0.4	2.8	0.074	0.015	0.207	1.033	Very Heavy
SP79	East	230	Polymenic composite	3.64	1120	312	22.91	1.29	0.78	45	320	30	type A	Desert/Agricultural	6	E7	Very heavy	0.400	2.400	0.335	0.072	0.236	1.092	Very Heavy
SP80	South	230	Porcelain	na	1145	1000	14.32	na	8	85	280	23	type A	Desert	6	E3/E4	Medium	0.05	0.3	0.054	0.032	0.041	0.069	Medium
SP81	South	230	Polymenic composite	0.25	361	1752	16.90	0.75	1.33	57	308	42	type A/B	Desert	6	E7	Very heavy	0.400	2.400	0.301	0.065	0.233	1.075	Very Heavy
SP82	South	230	Porcelain	na	300	1000	16.52	na	8	56	309	25	type A	Desert	6	E7	Very heavy	0.4	2.4	0.062	0.013	0.207	0.956	Very Heavy
SP83	South	230	Porcelain	na	1521	1000	34.61	na	8	88	277	38	type A	Agricultural	7	E5/E6	Heavy	0.15	1.05	0.045	0.014	0.082	0.255	Heavy
SP84	North East	230	Polymenic composite	1.83	1740	1200	32.14	3.13	0.32	57	308	27	type A	Agricultural	7	E7	Very heavy	0.350	2.450	0.359	0.077	0.213	0.997	Very Heavy
SP85	North East	230	Porcelain	na	1820	1000	29.03	na	8	85	280	55	type A	Agricultural	7	E5/E6	Heavy	0.15	1.05	0.04	0.013	0.081	0.253	Heavy
SP86	North East	230	Polymenic composite	5.58	663	1275	39.99	9.75	0.10	62	303	120	type A	Desert	6	E5/E6	Heavy	0.100	0.600	0.431	0.182	0.141	0.334	Very Heavy
SP87	North East & A	230	Polymenic composite	2.40	3178	2106	26.05	6.63	0.15	124	241	57	type A	Agricultural	6	E7	Very heavy	0.300	1.800	0.230	0.057	0.179	0.719	Very Heavy
SP88	North East	230	Porcelain	na	419	1000	38.40	na	8	90	275	60	type A/B	Desert	7	E7	Very heavy	0.4	2.8	0.051	0.010	0.205	1.022	Very Heavy
SP89	North East	230	Polymenic composite	6.83	383	414	39.56	4.50	0.22	67	298	80	type A/B	Desert	7	E7	Very heavy	0.250	1.750	0.438	0.110	0.180	0.715	Very Heavy
SP90	North East	230	Porcelain	na	432	1000	36.54	na	6	49	316	19	type A/B	Desert/Coastal	7	E7	Very heavy	0.4	2.8	0.069	0.014	0.207	1.031	Very Heavy
SP91	West	230	Porcelain	na	1649	1000	18.17	na	8	122	243	44	type A	Agricultural	2	E2	Light	0.03	0.06	0.029	0.037	0.034	0.026	Medium
SP92	North West & W	230	Glass	0.39	2369	762	19.45	0.38	2.67	117	248	37	type A	Agricultural	3	E3/E4	Medium	0.065	0.195	0.048	0.035	0.050	0.069	Medium
SP93	North West	230	Porcelain	na	2481	1000	20.80	na	8	160	205	80	type A	Agricultural	2	E2	Light	0.03	0.06	0.033	0.042	0.036	0.028	Medium
SP94	North West	230	Glass	0.56	2804	810	23.37	0.63	1.60	175	190	95	type A	Agricultural	3	E3/E4	Medium	0.060	0.180	0.040	0.030	0.045	0.060	Medium
SP95	North West	230	Porcelain	na	2418	1000	22.51	na	8	160	205	80	type A	Agricultural	2	E2	Light	0.03	0.06	0.02	0.026	0.028	0.022	Medium
SP96	North West	230	Glass	0.76	2255	588	21.51	0.63	1.60	150	215	70	type A	Agricultural	3	E3/E4	Medium	0.065	0.195	0.048	0.035	0.050	0.069	Medium
SP97	North West	230	Porcelain	na	2814	1000	26.88	na	8	97	268	17	type A	Agricultural	5	E3/E4	Medium	0.035	0.175	0.041	0.031	0.033	0.043	Medium
SP98	North West & N	230	Glass	1.20	2644	2544	23.11	4.13	0.24	129	236	49	type A	Agricultural	5	E5/E6	Heavy	0.200	1.000	0.078	0.026	0.113	0.342	Heavy
SP99	North West	230	Glass	0.00	2970	6	26.23	0.00	8.00	109	256	29	type A	Agricultural	5	E5/E6	Heavy	0.065	0.325	0.052	0.029	0.047	0.083	Medium
SP100	North West	230	Glass	0.00	3104	9	26.02	0.00	8.00	118	247	38	type A	Agricultural	5	E3/E4	Medium	0.060	0.300	0.045	0.027	0.043	0.073	Medium
SP101	North West	230	Glass	1.19	1906	981	25.69	1.63	0.62	131	234	51	type A	Agricultural	5	E3/E4	Medium	0.035	0.175	0.055	0.042	0.039	0.050	Medium
SP102	North West	230	Polymenic composite	0.36	1914	942	25.70	0.50	2.00	129	236	49	type A	Agricultural	4	E3/E4	Medium	0.050	0.200	0.127	0.091	0.070	0.098	Heavy
SP103	North West	230	Porcelain	na	776	1000	24.21	na	8	138	227	58	type A	Desert/Agricultural	5	E5/E6	Heavy	0.15	0.75	0.048	0.018	0.084	0.222	Heavy
SP104	North West	230	Polymenic composite	3.41	750	492	24.83	2.63	0.38	139	226	80	type A	Desert/Agricultural	5	E7	Very heavy	0.150	0.750	0.260	0.098	0.124	0.328	Very Heavy
SP105	North West	230	Porcelain	na	1000	1000	na	na	8	na	na	10	type A	Desert/Agricultural	6	E5/E6	Heavy	0.2	1.2	0.066	0.020	0.110	0.364	Heavy
SP106	North West	230	Porcelain	na	2021	1000	24.65	na	8	160	205	80	type A	Agricultural	3	E3/E4	Medium	0.035	0.105	0.036	0.035	0.035	0.036	Medium
SP107	North West	230	Polymenic composite	0.36	1280	1740	22.73	0.88	1.14	149	216	69	type A	Agricultural	3	E5/E6	Heavy	0.150	0.450	0.157	0.076	0.113	0.233	Heavy
SP108	North	230	Glass	0.69	2147	1005	31.88	0.88	1.14	120	245	70	type A	Desert/Agricultural	6	E5/E6	Heavy	0.150	0.900	0.053	0.018	0.084	0.243	Heavy
SP109	North	230	Porcelain	na	2077	1000	27.42	na	8	94	271	44	type A	Desert/Industrial	7	E5/E6	Heavy	0.15	1.05	0.038	0.012	0.081	0.252	Heavy
SP110	North	230	Porcelain	0.18	1743	1494	24.59	0.38	2.67	55	310	7	type A	Desert/Agricultural	7	E5/E6	Heavy	0.200	1.400	0.082	0.023	0.111	0.398	Heavy

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Selected sites for SPS Estimation	Grid Region	Voltage [kV]	Type of Insulator material	Faults/100 km/year	Altitude [m]	Number of Insulators	Mean PM2.5 [µg/m³]	Pollution Induced Fault per year	MTBF Actual	Annual rainy days	Annual dry days	Estimated number of pollution critical wetting events per year	Pollution type	General types of environments	NSDD/ESDD ratio	Examples of typical environments	Estimated SPS class	ESDD	NSDD	ESDD from 1ST	Corrected ESDD	Final average ESDD	SPS	SPS Class
SP111	North	230	Porcelain	na	2330	1000	27.96	na	8	101	264	51	type A	Agricultural	5	E3/E4	Medium	0.035	0.175	0.024	0.018	0.027	0.035	Medium
SP112	North	230	Glass	2.53	2157	69	27.54	0.38	2.67	99	266	49	type A	Agricultural	6	E5/E6	Heavy	0.150	0.900	0.055	0.019	0.085	0.244	Heavy
SP113	North	230	Porcelain	na	1336	1000	30.85	na	8	58	307	10	type A	Desert/Agricultural	6	E7	Very heavy	0.4	2.4	0.062	0.013	0.207	0.956	Very Heavy
SP114	North	230	Glass	0.86	1851	1137	25.71	1.38	0.73	62	303	12	type A	Agricultural/desert	7	E5/E6	Heavy	0.200	1.400	0.103	0.029	0.114	0.408	Heavy
SP115	North	230	Porcelain	na	1910	1000	25.28	na	8	94	271	44	type A	Agricultural	4	E3/E4	Medium	0.035	0.14	0.041	0.035	0.035	0.041	Medium
SP116	North	230	Glass	0.22	888	1488	26.53	0.50	2.00	92	273	42	type A	Agricultural/desert	6	E5/E6	Heavy	0.200	1.200	0.067	0.020	0.110	0.365	Heavy
SP117	North	230	Porcelain	na	600	1000	30.58	na	8	90	275	40	type A	Agricultural/desert	6	E7	Very heavy	0.4	2.4	0.053	0.011	0.206	0.951	Very Heavy
SP118	North	230	Porcelain	na	1687	1000	33.49	na	7	96	269	46	type A	Agricultural/desert	6	E5/E6	Heavy	0.15	0.9	0.043	0.015	0.082	0.238	Heavy
SP119	North	230	Polymenic composite	0.14	2244	1722	30.19	0.57	1.75	107	258	57	type A	Agricultural	4	E7	Very heavy	0.150	0.600	0.114	0.048	0.099	0.235	Heavy
SP120	North	230	Polymenic composite	0.70	1578	285	34.83	0.29	3.50	86	279	36	type A	Agricultural	5	E7	Very heavy	0.150	0.750	0.140	0.053	0.102	0.268	Heavy
SP121	North	230	Porcelain	na	994	1000	26.36	na	5	94	271	44	type A	Agricultural/desert	6	E5/E6	Heavy	0.15	0.9	0.053	0.018	0.084	0.243	Heavy
SP122	North	230	Polymenic composite	0.00	866	450	26.55	0.00	5.00	83	282	33	type A	Agricultural/desert	5	E7	Very heavy	0.150	0.750	0.151	0.057	0.104	0.274	Heavy
SP123	North	230	Porcelain	na	902	1000	26.81	na	5	87	278	37	type A	Agricultural/desert	6	E5/E6	Heavy	0.15	0.9	0.056	0.019	0.085	0.244	Heavy
SP124	North	230	Polymenic composite	15.69	2103	66	26.50	0.80	1.25	70	295	20	type A	Agricultural	5	E7	Very heavy	0.150	0.750	0.231	0.087	0.119	0.314	Very Heavy
SP125	South	230	Porcelain	na	1765	1000	19.55	na	8	153	212	91	type A	Agricultural	2	E3/E4	Medium	0.035	0.07	0.037	0.044	0.039	0.033	Medium
SP126	South	230	Glass	0.94	1927	312	20.01	0.38	2.67	185	180	123	type A	Agricultural	2	E3/E4	Medium	0.060	0.120	0.042	0.038	0.049	0.054	Medium
SP127	South	230	Porcelain	na	2333	1000	20.34	na	8	168	197	106	type A	Agricultural	3	E3/E4	Medium	0.03	0.09	0.031	0.033	0.031	0.030	Medium
SP128	South	230	Polymenic composite	0.68	2363	1473	20.42	1.50	0.67	61	304	30	type A	Agricultural	3	E5/E6	Heavy	0.150	0.450	0.190	0.092	0.121	0.250	Heavy
SP129	South West	230	Glass	0.00	1845	36	21.73	0.00	8.00	180	185	61	type A	Agricultural	2	E2	Light	0.030	0.060	0.030	0.038	0.034	0.027	Medium
SP130	South West	230	Porcelain	na	1666	1000	21.62	na	8	180	185	61	type A	Agricultural	2	E2	Light	0.03	0.06	0.026	0.033	0.032	0.025	Medium
SP131	South West	230	Glass	0.00	1732	474	22.38	0.00	8.00	148	217	29	type A	Agricultural	3	E3/E4	Medium	0.030	0.090	0.033	0.035	0.032	0.031	Medium
SP132	South West	230	Porcelain	na	1617	1000	21.73	na	8	180	185	61	type A	Agricultural	2	E2	Light	0.03	0.06	0.045	0.058	0.044	0.034	Medium
SP133	South West & W	230	Glass	0.42	2023	1113	21.15	0.63	1.60	154	211	35	type A	Agricultural	2	E3/E4	Medium	0.035	0.070	0.044	0.052	0.044	0.037	Medium
SP134	South West	230	Porcelain	na	1173	1000	22.39	na	8	105	260	45	type A	Agricultural	3	E3/E4	Medium	0.045	0.135	0.046	0.040	0.042	0.049	Medium
SP135	South West	230	Porcelain	na	1967	1000	20.12	na	8	211	154	92	type A	Agricultural	2	E1	Very light	0.007	0.014	0.022	0.022	0.015	0.007	Light
SP136	South West	230	Polymenic composite	0.07	1611	1428	24.58	0.13	8.00	218	147	99	type A	Agricultural	3	E1	Very light	0.005	0.014	0.078	0.078	0.041	0.019	Medium
SP137	South West	230	Porcelain	na	1752	1000	23.31	na	8	205	160	86	type A	Agricultural	2	E1	Very light	0.008	0.016	0.023	0.023	0.016	0.007	Light
SP138	South West	230	Polymenic composite	0.09	1648	2190	22.24	0.25	4.00	170	195	51	type A	Agricultural	2	E3/E4	Medium	0.050	0.100	0.107	0.107	0.079	0.079	Heavy
SP139	South West	230	Porcelain	na	468	1000	26.04	na	8	141	224	22	type A	Agricultural	5	E3/E4	Medium	0.06	0.3	0.062	0.037	0.048	0.082	Medium
SP140	South West	230	Porcelain	na	1676	1000	24.10	na	7	219	146	100	type A	Agricultural	2	E2	Light	0.03	0.06	0.024	0.031	0.030	0.024	Medium
SP141	South West	230	Polymenic composite	0.26	2105	1530	22.90	0.43	2.33	211	154	95	type A	Agricultural	2	E2	Light	0.015	0.030	0.092	0.164	0.090	0.050	Medium
SP142	South West	230	Polymenic composite	0.22	1964	624	23.96	0.17	6.00	228	137	109	type A	Agricultural	2	E2	Light	0.020	0.040	0.077	0.120	0.070	0.045	Medium
SP143	South West	230	Polymenic composite	0.32	1775	1026	20.95	0.43	2.33	213	152	94	type A	Agricultural	2	E2	Light	0.015	0.030	0.104	0.186	0.100	0.056	Medium
SP144	West	230	Glass	0.74	2268	561	18.61	0.50	2.00	185	180	28	type A	Agricultural	2	E2	Light	0.010	0.020	0.043	0.043	0.027	0.012	Light
SP145	West	230	Polymenic composite	0.27	2242	798	18.61	0.38	2.67	185	180	28	type A	Agricultural	2	E2	Light	0.015	0.030	0.127	0.227	0.121	0.068	Heavy
SP146	West	230	Polymenic composite	0.75	2242	120	18.61	0.13	8.00	185	180	28	type A	Agricultural	3	E1	Very light	0.004	0.011	0.104	0.104	0.054	0.025	Medium
SP147	West	230	Porcelain	na	2269	1000	17.80	na	8	122	243	43	type A	Agricultural	3	E1	Very light	0.009	0.027	0.025	0.047	0.028	0.015	Light
SP148	West	230	Polymenic composite	0.00	2272	180	17.72	0.00	8.00	127	238	48	type A	Agricultural	3	E2	Light	0.015	0.045	0.088	0.129	0.072	0.049	Medium
SP149	West	230	Porcelain	na	2262	1000	18.12	na	8	133	232	54	type A	Agricultural	3	E2	Light	0.015	0.045	0.024	0.035	0.025	0.017	Light
SP150	West	230	Polymenic composite	0.88	2429	300	19.03	0.38	2.67	123	242	44	type A	Agricultural	3	E1	Very light	0.005	0.015	0.110	0.110	0.058	0.026	Medium
SP151	West	230	Porcelain	na	1629	1000	19.32	na	8	95	270	16	type A	Agricultural	3	E1	Very light	0.009	0.027	0.038	0.071	0.040	0.021	Medium
SP152	Addis Ababa	132	Polymenic composite	0.00	2616	69	24.92	0.00	7.00	148	217	67	type A	Agricultural	2	E3/E4	Medium	0.055	0.110	0.098	0.094	0.074	0.078	Heavy
SP153	South	230	Glass	14.08	2350	54	20.34	1.00	1.00	168	197	106	type A	Agricultural	3	E3/E4	Medium	0.035	0.105	0.040	0.039	0.037	0.038	Medium
SP154	Addis Ababa	132	Glass	0.00	2514	138	25.93	0.00	8.00	132	233	51	type A/B	Industrial/Agricultural	5	E5/E6	Heavy	0.150	0.750	0.048	0.018	0.084	0.222	Heavy
SP155	North	230	Polymenic composite	0.18	972	225	26.98	0.13	8.00	121	244	71	type A	Agricultural/desert	4	E7	Very heavy	0.150	0.600	0.110	0.046	0.098	0.233	Heavy
SP156	Addis Ababa	230	Polymenic composite	0.00	2198	87	27.44	0.00	3.00	102	263	21	type A/B	Industrial	6	E7	Very heavy	0.350	2.100	0.217	0.050	0.200	0.867	Very Heavy
SP157	Addis Ababa	132	Glass	0.00	2230	198	27.16	0.00	8.00	104	261	23	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.060	0.020	0.110	0.333	Heavy
SP158	Addis Ababa	132	Glass	4.31	2180	87	27.44	0.25	4.00	101	264	20	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.076	0.025	0.113	0.341	Heavy
SP159	Addis Ababa	132	Glass	10.42	2180	9	27.44	0.13	8.00	101	264	20	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.082	0.027	0.114	0.344	Heavy
SP160	Addis Ababa	132	Polymenic composite	2.04	2257	276	27.38	0.14	7.00	103	262	22	type A/B	Industrial	5	E5/E6	Heavy	0.060	0.300	0.131	0.077	0.069	0.116	Heavy
SP161	Addis Ababa	132	Glass	4.41	2267	165	26.36	0.38	2.67	104	261	23	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.077	0.025	0.113	0.342	Heavy
SP162	Addis Ababa	132	Porcelain	12.80	2224	78	27.16	1.00	1.00	104	261	23	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.106	0.035	0.117	0.356	Heavy
SP163	Addis Ababa	132	Polymenic composite	3.13	2099	162	26.84	0.50	2.00	98	267	17	type A/B	Industrial	5	E5/E6	Heavy	0.085	0.425	0.232	0.116	0.100	0.201	Heavy
SP164	Addis Ababa	132	Porcelain	4.17	2234	111	27.44	0.75	1.33	102	263	21	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.097	0.032	0.116	0.352	Heavy
SP165	Addis Ababa	132	Glass	12.50	2159	6	27.44	0.13	8.00	101	264	20	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.086	0.028	0.114	0.346	Heavy

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Selected sites for SPS Estimation	Grid Region	Voltage [kV]	Type of Insulator material	Faults/100 km/year	Altitude [m]	Number of Insulators	Mean PM2.5 [µg/m³]	Pollution Induced Fault per year	MTBF Actual	Annual rainy days	Annual dry days	Estimated number of pollution critical wetting events per year	Pollution type	General types of environments	NSDD/ESDD ratio	Examples of typical environments	Estimated SPS class	ESDD	NSDD	ESDD from IST	Corrected ESDD	Final average ESDD	SPS	SPS Class
SP166	Addis Ababa	132	Porcelain	0.69	2200	111	27.44	0.13	8.00	102	263	21	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.062	0.020	0.110	0.334	Heavy
SP167	Addis Ababa	132	Glass	0.00	2322	63	27.14	0.00	8.00	110	255	29	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.060	0.020	0.110	0.333	Heavy
SP168	Addis Ababa	132	Polymeric composite	0.00	2269	24	27.40	0.00	7.00	107	258	26	type A/B	Industrial	5	E5/E6	Heavy	0.070	0.350	0.161	0.088	0.079	0.145	Heavy
SP169	Addis Ababa	132	Glass	0.00	2200	276	27.44	0.00	8.00	102	263	21	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.060	0.020	0.110	0.333	Heavy
SP170	Addis Ababa	132	Polymeric composite	1.69	2463	84	26.36	0.13	8.00	117	248	36	type A/B	Industrial	5	E5/E6	Heavy	0.095	0.475	0.111	0.052	0.074	0.156	Heavy
SP171	Addis Ababa	132	Polymeric composite	14.29	2404	12	27.14	0.14	7.00	121	244	40	type A/B	Industrial	5	E5/E6	Heavy	0.070	0.350	0.150	0.082	0.076	0.139	Heavy
SP172	Addis Ababa	132	Polymeric composite	0.40	2840	1092	24.06	0.38	2.67	126	239	45	type A	Agricultural	4	E5/E6	Heavy	0.095	0.380	0.110	0.058	0.076	0.145	Heavy
SP173	Addis Ababa	132	Glass	3.00	2270	276	26.27	0.75	1.33	110	255	29	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.082	0.027	0.114	0.344	Heavy
SP174	Addis Ababa	132	Polymeric composite	1.50	2619	126	25.36	0.14	7.00	148	217	67	type A/B	Industrial	5	E5/E6	Heavy	0.090	0.450	0.092	0.045	0.067	0.139	Heavy
SP175	Addis Ababa	132	Polymeric composite	0.00	2598	24	25.77	0.00	7.00	144	221	63	type A/B	Industrial	5	E5/E6	Heavy	0.095	0.475	0.113	0.053	0.074	0.157	Heavy
SP176	Addis Ababa	132	Polymeric composite	6.70	2161	90	27.03	1.13	0.89	93	272	12	type A/B	Industrial	5	E7	Very heavy	0.400	2.000	0.384	0.091	0.245	1.039	Very Heavy
SP177	Addis Ababa	132	Glass	2.78	2075	99	26.84	0.50	2.00	98	267	17	type A/B	Industrial	5	E7	Very heavy	0.400	2.000	0.095	0.022	0.211	0.895	Very Heavy
SP178	Addis Ababa	132	Glass	0.00	2565	69	26.34	0.00	8.00	121	244	40	type A/B	Industrial	5	E5/E6	Heavy	0.150	0.750	0.053	0.020	0.085	0.225	Heavy
SP179	Addis Ababa	132	Glass	0.00	2632	126	25.81	0.00	8.00	142	223	61	type A/B	Industrial	5	E5/E6	Heavy	0.150	0.750	0.046	0.017	0.084	0.221	Heavy
SP180	Addis Ababa	132	Porcelain	1.72	2683	771	22.93	1.38	0.73	176	189	95	type A	Agricultural/Indus	5	E5/E6	Heavy	0.200	1.000	0.063	0.021	0.110	0.335	Heavy
SP181	Central	132	Porcelain	na	2484	1000	22.31	na	8	149	216	68	type A	Agricultural/Indus	5	E7	Very heavy	0.4	2	0.042	0.010	0.205	0.868	Very Heavy
SP182	Central	132	Porcelain	na	2608	1000	22.64	na	8	176	189	95	type A	Agricultural/Indus	5	E3/E4	Medium	0.035	0.175	0.039	0.030	0.032	0.042	Medium
SP183	Addis Ababa	132	Glass	0.00	2782	378	22.14	0.00	8.00	162	203	81	type A	Agricultural/Indus	5	E3/E4	Medium	0.060	0.300	0.040	0.024	0.042	0.071	Medium
SP184	Central	132	Porcelain	na	2367	1000	23.12	na	8	153	212	72	type A	Agricultural/Indus	5	E7	Very heavy	0.4	2	0.043	0.010	0.205	0.869	Very Heavy
SP185	Addis Ababa	132	Glass	9.69	2205	27	27.16	0.13	8.00	104	261	23	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.068	0.022	0.111	0.337	Heavy
SP186	Addis Ababa	132	Glass	3.57	2431	390	25.93	0.50	2.00	119	246	38	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.066	0.022	0.111	0.336	Heavy
SP187	Addis Ababa	132	Polymeric composite	1.10	2676	492	22.18	0.63	1.60	166	199	85	type A	Agricultural	4	E5/E6	Heavy	0.090	0.360	0.116	0.063	0.076	0.141	Heavy
SP188	Central	132	Porcelain	na	2582	1000	22.39	na	8	148	217	67	type A	Agricultural/Indus	5	E7	Very heavy	0.4	2	0.042	0.010	0.205	0.868	Very Heavy
SP189	Addis Ababa	132	Polymeric composite	6.25	2157	270	27.28	1.00	1.00	101	264	20	type A/B	Industrial	5	E5/E6	Heavy	0.085	0.425	0.260	0.129	0.107	0.215	Heavy
SP190	Addis Ababa	132	Polymeric composite	2.08	2574	252	25.81	0.17	6.00	121	244	40	type A/B	Industrial	5	E5/E6	Heavy	0.090	0.450	0.103	0.050	0.070	0.144	Heavy
SP191	Addis Ababa	132	Glass	3.48	2514	138	25.93	0.38	2.67	132	233	51	type A/B	Industrial	5	E5/E6	Heavy	0.200	1.000	0.061	0.020	0.110	0.334	Heavy
SP192	Addis Ababa	132	Polymeric composite	0.00	2138	54	27.44	0.00	7.00	101	264	20	type A/B	Industrial	5	E5/E6	Heavy	0.075	0.375	0.162	0.086	0.080	0.152	Heavy
SP193	Addis Ababa	132	Polymeric composite	3.33	2267	33	26.36	0.20	5.00	104	261	23	type A/B	Industrial	5	E5/E6	Heavy	0.075	0.375	0.177	0.094	0.084	0.159	Heavy
SP194	Central	132	Porcelain	na	1615	1000	23.44	na	8	37	328	37	type A	Agricultural/indus	5	E5/E6	Heavy	0.2	1	0.057	0.019	0.109	0.332	Heavy
SP195	Central	132	Porcelain	2.27	1594	141	23.28	0.75	1.33	42	323	42	type A	Agricultural	5	E5/E6	Heavy	0.200	1.000	0.090	0.030	0.115	0.348	Heavy
SP196	Central	132	Porcelain	1.38	1350	1449	22.67	1.63	0.62	24	341	24	type A	Agricultural/desert	6	E5/E6	Heavy	0.200	1.200	0.122	0.037	0.118	0.392	Heavy
SP197	Central	132	Glass	0.00	970	3	24.62	0.00	8.00	22	343	22	type A	Agricultural/desert	7	E5/E6	Heavy	0.200	1.400	0.122	0.034	0.117	0.418	Heavy
SP198	Central	132	Porcelain	3.42	1542	582	23.70	1.88	0.53	59	306	18	type A	Agricultural	5	E5/E6	Heavy	0.200	1.000	0.140	0.046	0.123	0.373	Heavy
SP199	Central	132	Porcelain	0.00	1483	90	23.24	0.00	8.00	87	278	47	type A	Agricultural	5	E5/E6	Heavy	0.200	1.000	0.063	0.021	0.110	0.335	Heavy
SP200	Central	132	Porcelain	0.00	1562	6	23.45	0.00	8.00	34	331	34	type A	Agricultural	5	E5/E6	Heavy	0.200	1.000	0.088	0.029	0.115	0.347	Heavy
SP201	Central	132	Porcelain	0.98	2099	564	22.10	0.50	2.00	99	266	58	type A	Agricultural	4	E3/E4	Medium	0.040	0.160	0.046	0.037	0.038	0.048	Medium
SP202	Central	132	Glass	0.00	1582	39	23.82	0.00	8.00	100	265	60	type A	Agricultural	5	E3/E4	Medium	0.040	0.200	0.042	0.030	0.035	0.049	Medium
SP203	Central	132	Porcelain	na	2254	1000	22.00	na	8	104	261	64	type A	Agricultural	4	E3/E4	Medium	0.04	0.16	0.045	0.036	0.038	0.048	Medium
SP204	Central	132	Porcelain	0.74	1872	552	21.76	0.38	2.67	92	273	51	type A	Agricultural	5	E3/E4	Medium	0.040	0.200	0.066	0.047	0.044	0.061	Medium
SP205	Central	132	Porcelain	na	2057	1000	21.12	na	8	107	258	67	type A	Agricultural	4	E3/E4	Medium	0.045	0.18	0.046	0.035	0.040	0.053	Medium
SP206	Central	132	Glass	1.07	1845	390	20.78	0.50	2.00	92	273	52	type A	Agricultural	5	E3/E4	Medium	0.040	0.200	0.051	0.037	0.038	0.053	Medium
SP207	Central	132	Glass	0.00	2376	396	21.59	0.00	8.00	194	171	113	type A	Agricultural	2	E2	Light	0.025	0.050	0.026	0.036	0.031	0.022	Medium
SP208	Central	132	Porcelain	na	1835	1000	21.63	na	8	181	184	100	type A	Agricultural	3	E3/E4	Medium	0.04	0.12	0.045	0.041	0.041	0.044	Medium
SP209	Central	132	Glass	0.09	1936	1440	24.16	0.13	8.00	42	323	42	type A	Agricultural	6	E3/E4	Medium	0.035	0.210	0.034	0.024	0.029	0.042	Medium
SP210	Central	132	Glass	0.00	1919	3	25.54	0.00	8.00	61	304	61	type A	Agricultural	6	E3/E4	Medium	0.050	0.300	0.053	0.031	0.041	0.069	Medium
SP211	Central	132	Porcelain	0.19	1905	651	24.12	0.13	8.00	42	323	42	type A	Agricultural	6	E3/E4	Medium	0.035	0.210	0.036	0.025	0.030	0.043	Medium
SP212	Central	132	Glass	0.00	1895	54	23.26	0.00	8.00	15	350	15	type A	Agricultural	6	E3/E4	Medium	0.045	0.270	0.055	0.034	0.040	0.064	Medium
SP213	Central	132	Glass	1.92	1885	150	23.22	0.50	2.00	39	326	39	type A	Agricultural	6	E3/E4	Medium	0.045	0.270	0.058	0.036	0.040	0.065	Medium
SP214	Central	132	Glass	26.04	1707	84	22.69	1.25	0.80	37	328	37	type A	Agricultural	6	E5/E6	Heavy	0.200	1.200	0.108	0.033	0.116	0.385	Heavy
SP215	Central	132	Porcelain	na	1183	1000	22.56	na	6	21	344	21	type A	Agricultural	7	E5/E6	Heavy	0.2	1.4	0.076	0.021	0.111	0.395	Heavy
SP216	Central	132	Polymeric composite	0.00	995	1000	24.73	0.00	6.00	19	346	19	type A	Agricultural/desert	7	E5/E6	Heavy	0.085	0.595	0.195	0.083	0.084	0.198	Heavy
SP217	Central	132	Polymeric composite	0.00	975	9	24.62	0.00	6.00	22	343	22	type A	Agricultural/desert	6	E5/E6	Heavy	0.100	0.600	0.301	0.127	0.113	0.269	Heavy
SP218	Central	132	Polymeric composite	0.00	1048	255	22.50	0.00	6.00	22	343	22	type A	Agricultural/desert	5	E5/E6	Heavy	0.090	0.450	0.193	0.094	0.092	0.189	Heavy
SP219	Central	132	Porcelain	na	915	1000	24.81	na	6	44	321	44	type A	Agricultural/desert	7	E5/E6	Heavy	0.2	1.4	0.068	0.019	0.110	0.391	Heavy
SP220	Central	132	Polymeric composite	8.33	909	24	24.81	0.17	6.00	53	312	53	type A	Agricultural/desert	7	E5/E6	Heavy	0.095	0.665	0.200	0.080	0.088	0.218	Heavy

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Selected sites for SPS Estimation	Grid Region	Voltage [kV]	Type of Insulator material	Faults/100 km/year	Altitude [m]	Number of Insulators	Mean PM2.5 [µg/m ³]	Pollution Induced Fault per year	MTBF Actual	Annual rainy days	Annual dry days	Estimated number of pollution critical wetting events per year	Pollution type	General types of environments	NSDD/ESDD ratio	Examples of typical environments	Estimated SPS class	ESDD	NSDD	ESDD from IST	Corrected ESDD	Final average ESDD	SPS	SPS Class
SP221	Central	132	Polymeric composite	1.11	1667	57	23.44	0.17	6.00	37	328	37	type A	Agricultural	4	E5/E6	Heavy	0.100	0.400	0.161	0.083	0.091	0.178	Heavy
SP222	Central	132	Porcelain	na	1804	1000	22.66	na	6	23	342	23	type A	Agricultural	6	E5/E6	Heavy	0.2	1.2	0.064	0.019	0.110	0.363	Heavy
SP223	Central	132	Polymeric composite	0.00	1643	612	23.44	0.00	6.00	47	318	47	type A	Agricultural	4	E5/E6	Heavy	0.100	0.400	0.125	0.064	0.082	0.160	Heavy
SP224	Central	132	Porcelain	na	1486	1000	21.77	na	6	25	340	25	type A	Agricultural	6	E5/E6	Heavy	0.2	1.2	0.067	0.020	0.110	0.365	Heavy
SP225	Central	132	Polymeric composite	0.30	1491	498	22.42	0.17	6.00	25	340	25	type A	Agricultural	4	E5/E6	Heavy	0.100	0.400	0.157	0.081	0.090	0.176	Heavy
SP226	East	132	Porcelain	na	1177	1000	20.74	na	8	51	314	36	type A	Desert/Agricultural	6	E7	Very heavy	0.4	2.4	0.062	0.013	0.207	0.956	Very Heavy
SP227	East	132	Glass	0.06	1134	2349	24.66	0.13	8.00	104	261	89	type A	Agricultural	5	E3/E4	Medium	0.035	0.175	0.033	0.025	0.030	0.039	Medium
SP228	East	132	Glass	0.00	1195	39	20.74	0.00	8.00	51	314	36	type A	Desert/Industrial	6	E7	Very heavy	0.400	2.400	0.075	0.016	0.208	0.962	Very Heavy
SP229	East	132	Glass	31.25	1195	75	20.74	1.25	0.80	51	314	36	type A	Desert/Industrial	6	E7	Very heavy	0.450	2.700	0.120	0.025	0.237	1.161	Very Heavy
SP230	East	132	Glass	0.00	1266	99	20.92	0.00	8.00	55	310	40	type A	Desert/Industrial	6	E7	Very heavy	0.400	2.400	0.068	0.015	0.207	0.959	Very Heavy
SP231	East	132	Porcelain	na	1323	1000	20.74	na	8	55	310	40	type A	Desert/Industrial	6	E7	Very heavy	0.4	2.4	0.06	0.013	0.206	0.955	Very Heavy
SP232	East	132	Glass	5.99	2081	444	18.01	2.63	0.38	69	296	34	type A	Agricultural	5	E5/E6	Heavy	0.200	1.000	0.101	0.033	0.117	0.354	Heavy
SP233	East	132	Porcelain	na	2033	1000	17.67	na	8	94	271	79	type A	Agricultural	5	E5/E6	Heavy	0.15	0.75	0.045	0.017	0.084	0.221	Heavy
SP234	East	132	Glass	0.79	1583	924	17.81	0.75	1.33	104	261	89	type A	Agricultural	4	E3/E4	Medium	0.045	0.180	0.050	0.038	0.041	0.055	Medium
SP235	East	132	Polymeric composite	0.57	1471	1185	16.65	0.88	1.14	96	269	81	type A	Desert	3	E5/E6	Heavy	0.150	0.450	0.173	0.084	0.117	0.241	Heavy
SP236	East	132	Porcelain	na	1191	1000	15.77	na	8	96	269	81	type A	Desert	6	E5/E6	Heavy	0.2	1.2	0.052	0.016	0.108	0.357	Heavy
SP237	East	132	Porcelain	na	1698	1000	21.90	na	8	158	207	139	type A	Agricultural	4	E3/E4	Medium	0.04	0.16	0.044	0.035	0.038	0.047	Medium
SP238	East	132	Polymeric composite	0.94	1523	222	22.39	0.38	2.67	146	219	127	type A	Agricultural	4	E5/E6	Heavy	0.100	0.400	0.133	0.068	0.084	0.164	Heavy
SP239	East	132	Porcelain	na	1366	1000	22.64	na	8	113	252	94	type A	Agricultural	5	E3/E4	Medium	0.045	0.225	0.032	0.022	0.033	0.049	Medium
SP240	East	132	Polymeric composite	0.00	1117	312	22.91	0.00	4.00	45	320	30	type A	Desert/Agricultural	5	E5/E6	Heavy	0.085	0.425	0.197	0.098	0.092	0.184	Heavy
SP241	East	132	Porcelain	na	1679	1000	18.99	na	8	90	275	75	type A	Agricultural	5	E5/E6	Heavy	0.15	0.75	0.048	0.018	0.084	0.222	Heavy
SP242	East	132	Polymeric composite	0.30	1569	1275	18.51	0.50	2.00	80	285	65	type A/B	Desert/Coastal	3	E5/E6	Heavy	0.100	0.300	0.154	0.091	0.095	0.162	Heavy
SP243	East	132	Porcelain	na	1083	1000	18.43	na	6	79	286	64	type A/B	Desert/Coastal	7	E5/E6	Heavy	0.2	1.4	0.06	0.017	0.108	0.387	Heavy
SP244	North East	132	Porcelain	na	1475	1000	29.14	na	8	69	296	39	type A	Agricultural	6	E5/E6	Heavy	0.2	1.2	0.059	0.018	0.109	0.361	Heavy
SP245	North East	132	Glass	4.41	1723	498	28.59	1.50	0.67	78	287	48	type A	Agricultural	6	E5/E6	Heavy	0.200	1.200	0.095	0.029	0.114	0.379	Heavy
SP246	North East	132	Porcelain	na	1802	1000	29.03	na	8	85	280	55	type A	Agricultural	6	E5/E6	Heavy	0.15	0.9	0.05	0.017	0.084	0.241	Heavy
SP247	North East	132	Glass	1.60	1468	963	28.20	1.38	0.73	57	308	27	type A	Agricultural	6	E5/E6	Heavy	0.200	1.200	0.112	0.034	0.117	0.387	Heavy
SP248	Central	132	Porcelain	na	2758	1000	21.80	na	8	110	255	69	type A	Agricultural	5	E3/E4	Medium	0.035	0.175	0.039	0.030	0.032	0.042	Medium
SP249	North East	132	Glass	5.87	3125	636	26.05	3.38	0.30	121	244	91	type A	Agricultural	6	E5/E6	Heavy	0.200	1.200	0.074	0.022	0.111	0.368	Heavy
SP250	North East	132	Porcelain	na	1286	1000	28.69	na	8	63	302	33	type A	Agricultural/desert	6	E5/E6	Heavy	0.2	1.2	0.063	0.019	0.110	0.363	Heavy
SP251	North East	132	Polymeric composite	46.05	1779	48	29.03	1.75	0.57	85	280	55	type A	Agricultural/desert	5	E5/E6	Heavy	0.100	0.500	0.253	0.117	0.108	0.235	Heavy
SP252	North East	132	Porcelain	na	3235	1000	23.49	na	8	127	238	97	type A	Agricultural	4	E3/E4	Medium	0.055	0.22	0.034	0.023	0.039	0.057	Medium
SP253	North East	132	Polymeric composite	0.08	2596	1218	27.62	0.13	8.00	113	252	83	type A	Agricultural	4	E5/E6	Heavy	0.055	0.220	0.076	0.052	0.053	0.078	Heavy
SP254	North East	132	Porcelain	na	2142	1000	23.99	na	8	39	326	10	type A	Agricultural	5	E5/E6	Heavy	0.065	0.325	0.068	0.039	0.052	0.091	Medium
SP255	North East	132	Glass	4.27	3466	669	23.27	3.50	0.29	137	228	100	type A	Agricultural	3	E5/E6	Heavy	0.200	0.600	0.066	0.028	0.114	0.270	Heavy
SP256	North West	132	Porcelain	na	1607	1000	22.20	na	8	115	250	35	type A	Agricultural	4	E3/E4	Medium	0.055	0.22	0.058	0.040	0.047	0.069	Medium
SP257	North West	132	Glass	0.86	1744	648	21.39	0.50	2.00	114	251	34	type A	Agricultural	4	E3/E4	Medium	0.045	0.180	0.058	0.044	0.044	0.059	Medium
SP258	North	132	Glass	0.00	2364	753	28.08	0.00	8.00	106	259	56	type A	Agricultural	5	E5/E6	Heavy	0.065	0.325	0.046	0.026	0.046	0.080	Medium
SP259	North	132	Porcelain	na	2444	1000	28.30	na	8	107	258	57	type A	Agricultural/desert	5	E3/E4	Medium	0.04	0.2	0.044	0.032	0.036	0.050	Medium
SP260	North	132	Glass	0.00	2016	15	27.65	0.00	8.00	101	264	51	type A	Agricultural/desert	5	E5/E6	Heavy	0.200	1.000	0.065	0.021	0.111	0.336	Heavy
SP261	North	132	Glass	0.21	1447	981	25.94	0.25	4.00	69	296	19	type A	Agricultural/desert	5	E5/E6	Heavy	0.200	1.000	0.078	0.026	0.113	0.342	Heavy
SP262	North	132	Porcelain	na	1875	1000	26.17	na	8	72	293	22	type A	Agricultural/desert	5	E5/E6	Heavy	0.2	1	0.06	0.020	0.110	0.333	Heavy
SP263	North	132	Glass	0.00	2395	51	27.42	0.00	8.00	94	271	44	type A	Desert/Industrial	6	E5/E6	Heavy	0.200	1.200	0.055	0.017	0.108	0.359	Heavy
SP264	North	132	Polymeric composite	0.00	2133	300	26.15	0.00	5.00	69	296	19	type A	Agricultural	5	E5/E6	Heavy	0.070	0.350	0.157	0.086	0.078	0.143	Heavy
SP265	North	132	Porcelain	na	2091	1000	26.50	na	5	70	295	20	type A	Agricultural	5	E5/E6	Heavy	0.2	1	0.065	0.021	0.111	0.336	Heavy
SP266	Central	132	Porcelain	na	1653	1000	20.50	na	8	61	304	61	type A	Agricultural	5	E3/E4	Medium	0.045	0.225	0.051	0.035	0.040	0.059	Medium
SP267	South	132	Glass	0.65	1649	831	22.51	0.50	2.00	80	285	18	type A	Agricultural	5	E3/E4	Medium	0.050	0.250	0.073	0.047	0.048	0.075	Medium
SP268	South	132	Porcelain	na	1973	1000	21.20	na	8	113	252	51	type A	Agricultural	5	E3/E4	Medium	0.045	0.225	0.049	0.033	0.039	0.058	Medium
SP269	South	132	Glass	3.36	1901	720	18.82	2.13	0.47	96	269	34	type A	Agricultural	4	E5/E6	Heavy	0.200	0.800	0.110	0.040	0.120	0.327	Heavy
SP270	South	132	Glass	1.01	1877	726	19.14	0.63	1.60	150	215	88	type A	Agricultural	3	E3/E4	Medium	0.040	0.120	0.044	0.040	0.040	0.044	Medium
SP271	South	132	Porcelain	na	1981	1000	18.31	na	8	132	233	70	type A	Agricultural	4	E3/E4	Medium	0.045	0.18	0.047	0.035	0.040	0.053	Medium
SP272	South	132	Glass	0.92	1189	1158	19.85	1.00	1.00	101	264	39	type A	Agricultural	5	E5/E6	Heavy	0.200	1.000	0.098	0.032	0.116	0.352	Heavy
SP273	South	132	Porcelain	na	1216	1000	21.85	na	8	134	231	72	type A	Agricultural	5	E5/E6	Heavy	0.2	1	0.054	0.018	0.109	0.330	Heavy
SP274	South	132	Porcelain	1.58	1927	312	20.01	0.63	1.60	185	180	123	type A	Agricultural	3	E3/E4	Medium	0.040	0.120	0.061	0.056	0.048	0.052	Medium
SP275	South & South	132	Glass	2.56	1784	732	22.08	1.88	0.53	222	143	103	type A	Agricultural	2	E5/E6	Heavy	0.200	0.400	0.081	0.042	0.121	0.236	Heavy

(Continued)

Selected sites for SPS Estimation	Grid Region	Voltage [kV]	Type of Insulator material	Faults/100 km/year	Altitude [m]	Number of Insulators	Mean PM2.5 [µg/m³]	Pollution Induced Fault per year	MTBF Actual	Annual rainy days	Annual dry days	Estimated number of pollution critical wetting events per year	Pollution type	General types of environments	NSDD/ESDD ratio	Examples of typical environments	Estimated SPS class	ESDD	NSDD	ESDD from 1st	Corrected ESDD	Final average ESDD	SPS	SPS Class
SP276	South West	132	Porcelain	na	1698	1000	21.39	na	8	213	152	94	type A	Agricultural	2	E1	Very light	0.009	0.018	0.03	0.030	0.020	0.009	Light
SP277	South	132	Glass	0.91	1212	1025	21.82	1.13	0.89	178	187	116	type A	Agricultural	3	E3/E4	Medium	0.045	0.135	0.056	0.048	0.047	0.054	Medium
SP278	South	132	Porcelain	na	1281	1000	21.82	na	8	214	151	152	type A	Agricultural	2	E3/E4	Medium	0.045	0.09	0.047	0.049	0.047	0.045	Medium
SP279	South	132	Porcelain	0.00	1979	234	20.96	0.00	8.00	115	250	53	type A	Agricultural	4	E3/E4	Medium	0.035	0.140	0.053	0.045	0.040	0.047	Medium
SP280	South	132	Glass	0.82	1930	387	22.28	0.29	3.50	133	232	71	type A	Agricultural	3	E3/E4	Medium	0.035	0.105	0.039	0.038	0.037	0.037	Medium
SP281	South	132	Porcelain	na	1736	1000	22.24	na	7	163	202	101	type A	Agricultural	3	E3/E4	Medium	0.045	0.135	0.048	0.042	0.043	0.050	Medium
SP282	South	132	Porcelain	na	1732	1000	16.34	na	8	161	204	99	type A/B	Industrial/Agricultural	5	E3/E4	Medium	0.04	0.2	0.046	0.033	0.036	0.051	Medium
SP283	South	132	Glass	0.28	2607	1404	18.20	0.38	2.67	215	150	153	type A	Agricultural	2	E2	Light	0.010	0.020	0.029	0.029	0.020	0.009	Light
SP284	South	132	Glass	1.15	2509	1320	20.72	1.38	0.73	205	160	143	type A	Agricultural	3	E3/E4	Medium	0.035	0.105	0.042	0.041	0.038	0.039	Medium
SP285	South	132	Glass	0.63	1871	342	22.02	0.25	4.00	168	197	106	type A	Agricultural	3	E3/E4	Medium	0.035	0.105	0.035	0.034	0.035	0.035	Medium
SP286	South	132	Porcelain	na	1496	1000	21.45	na	8	182	183	120	type A	Agricultural	2	E2	Light	0.03	0.06	0.047	0.060	0.045	0.035	Medium
SP287	South	132	Glass	0.13	2477	849	19.43	0.13	8.00	191	174	129	type A	Agricultural	2	E1	Very light	0.005	0.010	0.038	0.038	0.022	0.010	Light
SP288	South	132	Porcelain	na	1901	1000	16.28	na	8	159	206	97	type A	Agricultural	2	E3/E4	Medium	0.04	0.08	0.045	0.050	0.045	0.040	Medium
SP289	South	132	Glass	0.22	1452	1722	15.14	0.50	2.00	97	268	35	type A	Desert	5	E5/E6	Heavy	0.200	1.000	0.080	0.026	0.113	0.343	Heavy
SP290	South	132	Porcelain	na	1267	1000	14.71	na	8	113	252	51	type A	Desert	5	E5/E6	Heavy	0.2	1	0.057	0.019	0.109	0.332	Heavy
SP291	South	132	Polymers composite	0.15	3247	1221	18.39	0.25	4.00	162	203	100	type A	Agricultural	2	E3/E4	Medium	0.050	0.100	0.069	0.069	0.060	0.060	Medium
SP292	South	132	Porcelain	na	1210	1000	17.31	na	8	94	271	32	type A	Agricultural	4	E3/E4	Medium	0.06	0.24	0.064	0.042	0.051	0.078	Medium
SP293	South	132	Polymers composite	0.00	1067	843	20.58	0.00	8.00	198	167	136	type A	Agricultural	3	E5/E6	Heavy	0.100	0.300	0.104	0.061	0.081	0.137	Heavy
SP294	South	132	Porcelain	na	1568	1000	16.58	na	8	99	266	37	type A	Agricultural/desert	3	E3/E4	Medium	0.05	0.15	0.058	0.048	0.049	0.059	Medium
SP295	South West	132	Glass	0.00	1909	285	21.15	0.00	8.00	198	167	79	type A	Agricultural	3	E1	Very light	0.007	0.021	0.031	0.066	0.036	0.017	Light
SP296	South West	132	Glass	0.18	1718	690	21.05	0.13	8.00	221	144	102	type A	Agricultural	2	E1	Very light	0.007	0.013	0.047	0.047	0.027	0.012	Light
SP297	South West	132	Porcelain	na	1719	1000	23.10	na	8	240	125	121	type A	Agricultural	2	E1	Very light	0.008	0.016	0.028	0.028	0.018	0.008	Light
SP298	South West	132	Glass	0.00	1838	156	23.10	0.00	8.00	236	129	117	type A	Agricultural	2	E1	Very light	0.008	0.015	0.030	0.030	0.019	0.009	Light
SP299	South West	132	Porcelain	na	1728	1000	25.43	na	8	241	124	122	type A	Agricultural	2	E1	Very light	0.008	0.016	0.028	0.028	0.018	0.008	Light
SP300	South West	132	Glass	0.19	2278	516	25.15	0.13	8.00	246	119	127	type A	Agricultural	2	E1	Very light	0.007	0.014	0.040	0.040	0.024	0.011	Light
SP301	South West	132	Porcelain	na	1549	1000	24.58	na	8	206	159	87	type A	Agricultural	2	E2	Light	0.01	0.02	0.032	0.032	0.021	0.010	Light
SP302	South West	132	Glass	0.12	1917	897	25.67	0.13	8.00	244	121	125	type A	Agricultural	2	E1	Very light	0.008	0.015	0.027	0.027	0.017	0.008	Light
SP303	South West	132	Porcelain	na	1615	1000	26.88	na	8	255	110	136	type A	Agricultural	3	E1	Very light	0.005	0.015	0.027	0.027	0.016	0.007	Light
SP304	South West	132	Glass	0.28	1874	795	24.96	0.25	4.00	248	117	129	type A	Agricultural	2	E1	Very light	0.008	0.016	0.049	0.049	0.029	0.013	Light
SP305	South West	132	Porcelain	na	1377	1000	25.73	na	8	232	133	113	type A	Agricultural	2	E1	Very light	0.0085	0.017	0.032	0.032	0.020	0.009	Light
SP306	South West	132	Glass	0.00	1718	60	21.73	0.00	8.00	180	185	61	type A	Agricultural	2	E2	Light	0.030	0.060	0.039	0.050	0.040	0.031	Medium
SP307	West	132	Glass	0.65	1822	1098	19.65	0.75	1.33	214	151	57	type A	Agricultural	3	E1	Very light	0.009	0.027	0.054	0.101	0.055	0.029	Medium
SP308	West	132	Glass	0.44	1278	834	20.22	0.38	2.67	194	171	37	type A	Agricultural	3	E1	Very light	0.009	0.027	0.055	0.103	0.056	0.030	Medium
SP309	West	132	Glass	1.33	1576	729	22.07	1.13	0.89	202	163	45	type A	Agricultural	3	E2	Light	0.010	0.030	0.071	0.127	0.068	0.038	Medium
SP310	West	132	Porcelain	na	1952	1000	19.47	na	8	184	181	27	type A	Agricultural	2	E1	Very light	0.0065	0.013	0.038	0.038	0.022	0.010	Light
SP311	West	132	Glass	0.11	1842	1128	17.44	0.13	8.00	164	201	9	type A	Agricultural	3	E3/E4	Medium	0.045	0.135	0.055	0.048	0.046	0.054	Medium
SP312	West	132	Glass	0.15	1498	777	19.23	0.13	8.00	171	194	14	type A	Agricultural	3	E3/E4	Medium	0.045	0.135	0.051	0.044	0.045	0.052	Medium
SP313	West	132	Porcelain	na	1573	1000	19.51	na	8	163	202	10	type A	Agricultural	3	E3/E4	Medium	0.06	0.18	0.076	0.057	0.059	0.078	Medium
SP314	West	132	Porcelain	na	2083	1000	19.71	na	8	195	170	38	type A	Agricultural	2	E1	Very light	0.0065	0.013	0.035	0.035	0.021	0.010	Light
SP315	West	132	Polymers composite	0.13	1332	777	19.02	0.13	8.00	201	164	44	type A	Agricultural	3	E1	Very light	0.005	0.015	0.129	0.129	0.067	0.031	Medium
SP316	West	132	Porcelain	na	2097	1000	18.47	na	8	192	173	35	type A	Agricultural	2	E1	Very light	0.0065	0.013	0.035	0.035	0.021	0.010	Light
SP317	West	132	Porcelain	na	1717	1000	17.27	na	5	162	203	10	type A	Agricultural	2	E2	Light	0.03	0.06	0.063	0.081	0.055	0.043	Medium
SP318	West	132	Polymers composite	0.00	1384	1170	19.11	0.00	5.00	186	179	29	type A	Agricultural	3	E1	Very light	0.004	0.011	0.156	0.156	0.080	0.037	Medium
SP319	West	132	Porcelain	na	1791	1000	25.67	na	5	202	163	45	type A	Agricultural	2	E1	Very light	0.005	0.01	0.04	0.040	0.023	0.010	Light
SP320	Addis Ababa	132	Porcelain	4.17	2514	33	25.93	0.13	8.00	132	233	51	type A/B	Industrial	4	E3/E4	Medium	0.035	0.140	0.037	0.031	0.033	0.039	Medium
SP321	South	132	Glass	3.90	2081	72	18.32	0.43	2.33	146	219	84	type A	Agricultural	3	E3/E4	Medium	0.040	0.120	0.044	0.040	0.040	0.044	Medium
SP322	East	132	Polymers composite	3.76	1223	774	24.05	3.50	0.29	94	271	79	type A	Agricultural	4	E5/E6	Heavy	0.100	0.400	0.279	0.143	0.122	0.237	Heavy
SP323	East	132	Porcelain	na	507	1000	16.83	na	6	62	303	47	type A/B	Desert	6	E7	Very heavy	0.4	2.4	0.071	0.015	0.208	0.960	Very Heavy
SP324	East	132	Polymers composite	0.38	517	1290	16.31	0.67	1.50	69	296	54	type A/B	Desert	3	E5/E6	Heavy	0.150	0.450	0.235	0.114	0.132	0.272	Heavy
SP325	Addis Ababa	132	Polymers composite	40.00	2224	27	27.16	1.20	0.83	104	261	23	type A/B	Industrial	4	E5/E6	Heavy	0.100	0.400	0.335	0.172	0.136	0.265	Heavy
SP326	Addis Ababa	132	Polymers composite	0.00	2598	57	25.77	0.00	6.00	144	221	63	type A/B	Industrial	5	E5/E6	Heavy	0.090	0.450	0.107	0.052	0.071	0.146	Heavy
SP327	East	132	Porcelain	na	1032	1000	25.18	na	6	79	286	64	type A	Agricultural/desert	6	E5/E6	Heavy	0.2	1.2	0.061	0.018	0.109	0.362	Heavy
SP328	East	132	Polymers composite	0.57	1224	168	23.94	0.33	3.00	115	250	96	type A	Agricultural/desert	4	E5/E6	Heavy	0.100	0.400	0.150	0.077	0.088	0.173	Heavy
SP329	East	132	Polymers composite	0.81	1136	117	25.95	0.33	3.00	45	320	30	type A	Agricultural/desert	6	E5/E6	Heavy	0.100	0.600	0.230	0.097	0.099	0.234	Heavy
SP330	East	132	Porcelain	na	1185	1000	23.47	na	6	59	306	44	type A	Agricultural/desert	7	E5/E6	Heavy	0.2	1.4	0.063	0.018	0.109	0.388	Heavy

(Continued)

Selected sites for SPS Estimation	Grid Region	Voltage [kV]	Type of Insulator material	Faults/100 km/year	Altitude [m]	Number of Insulators	Mean PM25 [ug/m ³]	Pollution Induced Fault per year	MTBF Actual	Annual rainy days	Annual dry days	Estimated number of pollution critical wetting events per year	Pollution type	General types of environments	NSDD/ESDD ratio	Examples of typical environments	Estimated SPS class	ESDD	NSDD	ESDD from IST	Corrected ESDD	Final average ESDD	SPS	SPS Class
SP331	North West	132	Polymeric composite	0.00	1352	537	21.64	0.00	3.00	154	211	74	type A	Agricultural/desert	4	E5/E6	Heavy	0.055	0.220	0.147	0.101	0.078	0.114	Heavy
SP332	North West	132	Porcelain	na	1152	1000	21.87	na	3	154	211	74	type A	Agricultural/desert	5	E3/E4	Medium	0.05	0.25	0.045	0.029	0.039	0.061	Medium
SP333	South West	132	Glass	0.00	1964	312	23.96	0.00	8.00	228	137	109	type A	Agricultural	2	E1	Very light	0.008	0.015	0.029	0.029	0.018	0.008	Light
SP334	South	132	Polymeric composite	0.00	1834	531	18.87	0.00	6.00	142	223	80	type A	Agricultural	4	E5/E6	Heavy	0.095	0.380	0.104	0.055	0.075	0.142	Heavy
SP335	South	132	Porcelain	na	1707	1000	21.42	na	6	113	252	51	type A	Agricultural	4	E5/E6	Heavy	0.2	0.8	0.055	0.020	0.110	0.300	Heavy
SP336	South West	na	na	na	412	na	25.80	na	na	164	201	na	type A	Desert	5	E7	Very heavy	0.3	1.5	na	na	0.300	1.106	Very Heavy
SP337	South West	na	na	na	856	na	19.89	na	na	93	272	na	type A	Agricultural	5	E7	Very heavy	0.3	1.5	na	na	0.300	1.106	Very Heavy
SP338	South West	na	na	na	498	na	24.84	na	na	41	324	na	type A	Desert	6	E7	Very heavy	0.3	1.8	na	na	0.300	1.208	Very Heavy
SP339	South	na	na	na	845	na	15.16	na	na	111	254	na	type A	Desert	5	E7	Very heavy	0.3	1.5	na	na	0.300	1.106	Very Heavy
SP340	East	na	na	na	229	na	15.87	na	na	74	291	na	type A/B	Desert/Coastal	6	E7	Very heavy	0.3	1.8	na	na	0.300	1.208	Very Heavy
SP341	East	na	na	na	224	na	15.96	na	na	42	323	na	type A/B	Desert/Coastal	6	E7	Very heavy	0.3	1.8	na	na	0.300	1.208	Very Heavy
SP342	East	na	na	na	588	na	23.85	na	na	57	308	na	type A/B	Desert/Coastal	7	E7	Very heavy	0.3	2.1	na	na	0.300	1.301	Very Heavy
SP343	East	na	na	na	1098	na	19.04	na	na	59	306	na	type A/B	Desert/Coastal	7	E7	Very heavy	0.3	2.1	na	na	0.300	1.301	Very Heavy
SP344	East	na	na	na	1424	na	21.57	na	na	74	291	na	type A/B	Desert/Coastal	7	E7	Very heavy	0.3	2.1	na	na	0.300	1.301	Very Heavy
SP345	North East	na	na	na	830	na	34.27	na	na	32	333	na	type A/B	Desert/Coastal	7	E7	Very heavy	0.35	2.45	na	na	0.350	1.635	Very Heavy
SP346	North East	na	na	na	525	na	37.77	na	na	46	319	na	type A/B	Desert/Coastal	7	E7	Very heavy	0.4	2.8	na	na	0.400	1.992	Very Heavy
SP347	North East	na	na	na	258	na	40.24	na	na	66	299	na	type A/B	Desert/Coastal	7	E7	Very heavy	0.4	2.8	na	na	0.400	1.992	Very Heavy
SP348	North	na	na	na	-121	na	54.39	na	na	16	349	na	type A/B	Desert/Coastal	5	E7	Very heavy	0.45	2.25	na	na	0.450	2.017	Very Heavy
SP349	North West	na	na	na	639	na	29.32	na	na	115	250	na	type A	Agricultural	5	E5/E6	Heavy	0.075	0.375	na	na	0.075	0.142	Heavy
SP350	North West	na	na	na	621	na	22.46	na	na	150	215	na	type A	Agricultural	5	E5/E6	Heavy	0.075	0.375	na	na	0.075	0.142	Heavy
SP351	North West	na	na	na	1725	na	18.24	na	na	185	180	na	type A	Agricultural	4	E1	Very light	0.0035	0.014	na	na	0.004	0.002	Very Light
SP352	West	na	na	na	621	na	22.63	na	na	163	202	na	type A	Agricultural	4	E3/E4	Medium	0.05	0.2	na	na	0.050	0.070	Medium
SP353	North West	na	na	na	1179	na	23.67	na	na	127	238	na	type A	Agricultural/desert	5	E5/E6	Heavy	0.075	0.375	na	na	0.075	0.142	Heavy
SP354	North East	na	na	na	98	na	42.68	na	na	66	299	na	type A/B	Desert/Coastal	7	E7	Very heavy	0.4	2.8	na	na	0.400	1.992	Very Heavy
SP355	North East	na	na	na	574	na	36.73	na	na	58	307	na	type A/B	Desert/Agricultural	7	E7	Very heavy	0.35	2.45	na	na	0.350	1.635	Very Heavy
SP356	East	na	na	na	1337	na	17.35	na	na	121	244	na	type A	Desert	5	E2	Light	0.02	0.1	na	na	0.020	0.020	Light
SP357	East	na	na	na	812	na	16.61	na	na	84	281	na	type A/B	Desert	5	E7	Very heavy	0.3	1.5	na	na	0.300	1.106	Very Heavy
SP358	East	na	na	na	1024	na	16.56	na	na	79	286	na	type A/B	Desert	5	E7	Very heavy	0.3	1.5	na	na	0.300	1.106	Very Heavy
SP359	South	na	na	na	944	na	13.96	na	na	86	279	na	type A	Desert/Agricultural	6	E7	Very heavy	0.25	1.5	na	na	0.250	0.922	Very Heavy
SP360	South West	na	na	na	2067	na	27.41	na	na	285	80	na	type A	Agricultural	2	E1	Very light	0.005	0.01	na	na	0.005	0.002	Very Light
SP361	North East	na	na	na	789	na	42.56	na	na	35	330	na	type A/B	Desert	7	E7	Very heavy	0.4	2.8	na	na	0.400	1.992	Very Heavy
SP362	East	na	na	na	608	na	17.74	na	na	56	309	na	type A/B	Desert/Coastal	7	E7	Very heavy	0.3	2.1	na	na	0.300	1.301	Very Heavy
SP363	North West	na	na	na	1645	na	26.70	na	na	39	326	na	type A	Agricultural	5	E5/E6	Heavy	0.075	0.375	na	na	0.075	0.142	Heavy
SP364	North West	na	na	na	2360	na	19.86	na	na	173	192	na	type A	Agricultural	2	E1	Very light	0.005	0.01	na	na	0.005	0.002	Very Light