Electricity Infrastructure Climate Change Impact Resilience Techniques – A Case Study of the South African Metropolitan Municipalities

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ABSTRACT

The South African electricity sector faces several challenges which compromise the reliability and stability of municipal electricity service delivery. Factors such as theft, vandalism, lack of investment, load shedding and extreme weather events emanating from climate change impacts, threaten the resilience of electricity infrastructure. The study undertook an investigation to understand the impact of climate change on electricity infrastructure throughout metropolitan municipalities in South Africa. This is imperative to progress the efforts to develop electricity infrastructure resilience techniques.

The South African electricity infrastructure is vulnerable to damage and failure due to climate change impacts and human factors such as lack of appropriate maintenance practices, inadequate asset planning, and poor management. These factors threaten the longevity and reliability of electricity service delivery across metropolitan municipalities.

A qualitative approach was employed to collect data concerning the current state of electricity infrastructure, and the impact of climate change events and human factors thereupon. The data sample was selected from the metropolitan municipalities in South Africa. Semi-structured, virtually recorded interviews were carried out, with the support of an interview guide which was prepared prior to the interviews.

The study findings present the most common challenges faced by metropolitan municipalities as far as the operation and maintenance of electricity distribution infrastructure is concerned. The recurrence of several climate-related incidents and manmade challenges are outlined, and possible solutions to build resilience are proposed.

This study found that metropolitan municipalities are aware of the compounding effect of climate change and anthropogenic issues such as infrastructure sabotage and neglect. The key finding showed that the endeavour to enhance the electricity transmission and distribution infrastructure must follow a holistic approach that considers interlinkages between technical performance, financial constraints, human behaviour, and the unpredictability of climate change events.

As such, holistic suitable electricity infrastructure resilience techniques are proposed as they are fundamental to managing and improving electricity infrastructure resilience. The proposed suitable electricity infrastructure climate change resilience techniques include: improving the management of existing electricity infrastructure, the prioritisation and allocation of dedicated electricity infrastructure maintenance budgets, accelerated implementation of metropolitan municipalities’ existing climate change response strategies, investment into climate impact early warning systems at the municipal level, and an innovative and proactive approach to the development of new electricity transmission and distribution infrastructure. Furthermore, the report concludes with recommendations and suggestions for further research that would enhance metropolitan municipalities' electricity infrastructure resilience against climate change impact.

KEYWORDS: Challenges, Climate Change, Electricity, Infrastructure, Maintenance, Metropolitan Municipality, Resilience.

DECLARATION

I, Busisiwe Charlotte Matshonyonge (née Manabe), declare that this research report is my own original work except as indicated in the references and acknowledgements. It is submitted in partial fulfilment of the requirements for the degree of Master of Management in Energy Leadership at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other university.

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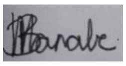
Signature: 

Signed at Paulshof, Sandton, 2191, South Africa, on the 23rd day of February 2025.

DECLARATION OF PUBLICATION

Declaration of a research paper that will be submitted to a suitable peer-reviewed journal for publication, after examination by the University of Witwatersrand.

DEDICATION

This body of work is dedicated to my parents, Mr. Thulani and Mrs. Monica Manabe, who raised me to believe that all things are possible, and who encouraged me to read and develop my full potential, to “stand on my own two feet,” in the words of my dad, and as my mom taught, to finish what I start. It is also dedicated to myself, as a confirmation that I can do remarkable things, and that the best days of my career are still ahead of me.

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I wish to express my gratitude to all the individuals who generously agreed to take part in my study. Both my mind and my professional network have been enriched through the crossing of our paths. This report could not have been compiled without your invaluable contribution. I am equally grateful to the University's Postgraduate Research and Innovation Office for providing me with academic resources and support along the way, particularly for data analysis. I humbly acknowledge my research supervisor, Dr Stanley Semelane, for giving his time, knowledge, and guidance to help see this work to completion. I also acknowledge my husband, Mukovhe Matshonyonge, for his consistent love and support, and his belief in the goals which this work set out to accomplish.

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LIST OF ACRONYMS and ABBREVIATIONS

AMEU	Association of Municipal Electricity Utilities
BRT	Bus Rapid Transit
CIDB	Construction Industry Development Board
COP	Conference of the Parties
COVID-19	Corona Virus Disease of 2019
CSIR	Council for Scientific and Industrial Research
DC	Direct Current
DEA	Department of Environmental Affairs
ESI	Electricity Supply Infrastructure
GW	Gigawatt
ICT	Information and Communications Technology
IEA	International Energy Association
IFRS	International Financial Reporting Standards
IPCC	Intergovernmental Panel on Climate Change
NDCs	Nationally Determined Contributions
OEM	Original Equipment Manufacturers
P	Participant
PV	Photovoltaic
SA	South Africa
SAWS	South African Weather Service
SCADA	Supervisory Control and Data Acquisition

SCI	Save the Children International
UNDP	United Nations Development Programme
UNDRR	United Nations Office for Disaster Risk Reduction
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	UN International Strategy for Disaster Reduction
WCED	World Commission on Environment and Development

CHAPTER 1. INTRODUCTION

1.1 Introduction

This chapter will outline the research problem and purpose, as well as describe the context and significance of the study. Additionally, the limitations and assumptions adopted for this research will be detailed.

1.2 Purpose of the study

The purpose of this study is to evaluate the factors which contribute to the failure of electricity infrastructure in South Africa, through a case study of South African metropolitan municipalities. The aim is to develop a solution towards the greater resilience of electricity infrastructure to maintain optimal performance of energy infrastructure and critical service delivery.

1.3 Context of the study

The South African government declared an electricity crisis in January 2008 (Dilika, 2023), when extended periods of power outages known as loadshedding, became a regular occurrence. In the years that followed, power outages became commonplace, as a growing population's electricity demands rapidly outpaced the state's supply capability. During 2019 South Africans experienced more than 530 hours of consistent blackouts (Trace, 2020), largely caused by the shortage of electricity generation capacity. The total duration of annual loadshedding hours had increased by more than 200% in the year 2021, as South Africans were subjected to 1 169 hours without electricity (Pierce et al., 2022). The first nine months of the year 2022 demonstrated a further weakening of the country's electricity generation capacity, with 1 949 hours of loadshedding recorded, translating to more than 4 000 gigawatt-hours' worth of productivity lost (Pierce et al., 2022). Frequent breakdowns of generation units throughout various Eskom power stations resulted in 74 days of Stage 6 loadshedding in the year 2023, placing strain on the sensitive operations of schools and hospitals, and demonstrating the urgency of the need for enduring solutions and improved crisis management efforts from the government (Rondganger, 2023). Moreover, the electricity infrastructure in rural and urban areas has continued to show signs of vulnerability – to theft and vandalism, harsh environmental conditions, and technical failures (Chabalala, 2024). This points to energy service delivery challenges at both the national and municipal levels.

This study focuses on the metropolitan municipalities in South Africa, to determine the extent to which climate change-related events have impacted electricity infrastructure and service delivery, and to explore methods in which electricity infrastructure may be made more resilient.

According to Deetman et al. (2021), electricity distribution infrastructure is designed with population and load growth in mind, however, the impact of climate change events, which are now more evident and frequent (Save the Children International, [SCI], 2023), even in countries which are not deemed to be disaster-prone, is not taken into cognizance during the design, installation, and maintenance processes of electricity distribution infrastructure.

Both the capital and operational expenditure associated with energy and electricity infrastructure are significant (Khonjelwayo and Nthakheni, 2020). This warrants a long-term outlook when developing such infrastructure for various applications. Components such as power transformers, miniature substations, power distribution kiosks and their protective structures, overhead lines, and underground cables, are universally designed with an average expected useful life of 20 to 30 years (Fitzemeyer & Tocci, 2019), with periodic maintenance being carried out throughout the useful lifetime of the asset. The impact of unpredictable environmental events is not often considered, leaving end users stranded or poorly serviced when these conditions arise.

Understanding the far-reaching impacts of flash floods and heavy rainfall directly linked to climate change will allow equipment manufacturers, electricity industry insurers, policymakers, and electricity infrastructure operators, to plan and invest for resilience, in addition to technical efficiency and economic feasibility. (Fang & Sansavini, 2017). Heavy rainfall and flooding have a negative impact on civil and transportation infrastructure, both of which rely on the equally vulnerable energy and electricity infrastructure to operate optimally, (Kershaw, 2017).

Electricity infrastructure vulnerabilities not linked to climate change must also be understood and addressed, to enhance the efficacy of any resilience techniques which emerge, (Farrell et al., 2004).

Chen et al. (2022), show that comprehending the impacts of climate change on electricity supply infrastructure (ESI) is crucial to ensuring the reliability of power supply. However, most current studies focus only on the physical effects without considering the economic impacts of climate change. Moreover, they fail to provide a cost-benefit analysis for various mitigation projects. To address this gap, the study by (Chen et al., 2022) utilises a moderate climate system model to project future temperature trends which quantifies both the physical and economic impacts of long-term temperature increases on existing ESI components. Furthermore, the study examines the maximum climate-related impacts in a large, energy-intensive economy like China from 2018 to 2099, which are estimated to result in approximately US$258 billion worth of damage on existing ESI assets. These challenges are attributed to future global temperature rise. Similarly, Ngepah et al. (2022) indicates that the impact of climate change in South Africa is projected to increase in the coming years and climate related hazards are likewise expected to increase in frequency and intensity between the years 2030 and 2050. Therefore, the development of robust and resilient electricity infrastructure is critical to maintaining energy security, especially in metropolitan municipalities that are responsible for driving economic development in South Africa. As a result, this study aims to enhance efforts against the climate change related impacts on the South African electricity infrastructure through a case study of South African metropolitan municipalities.

1.4 Research Problem

Electricity infrastructure across South Africa is collapsing (Mirzania et al., 2023; Erasmus, 2024). As a result, there is a need to increase the resilience of infrastructure as part of the government's electricity access and energy security mandates (Dube et al., 2022).

Extreme weather conditions have become more prevalent in South Africa, with record high temperatures being recorded in the years 2010, 2016, and 2019, while 2015 and 2017 were recorded as the driest years since 1981 (Miller et al., 2020). Climate change events such as flooding due to prolonged periods of heavy rainfall were correctly projected to increase in the eastern regions of the country from the year 2019 forward (Miller et al., 2020). Consequently, vulnerability has been observed in the built environment as well as electricity infrastructure. While this has led to prolonged disturbances in the delivery of essential services such as electricity and water in both urban and rural human settlements, it is not the sole cause of infrastructure collapse. Poor maintenance practices and inadequate asset management are also contributing factors.

Design and maintenance models for infrastructure which is used to deliver basic services to the public need to become more robust, to ensure that the infrastructure is less vulnerable to collapse or failure over time. In the absence of electricity infrastructure resilience interventions, power outages and technical failures are likely to persist and exacerbate high levels of poor service delivery and stagnant economic growth. As such, it is imperative to understand the major causes of electricity infrastructure failures, to allow South Africa to design electricity infrastructure resilience mechanisms that are practical and future-proof.

1.5 Research Objectives

The objectives of this study are to:

i. Evaluate electricity infrastructure development and best practice maintenance techniques in developing countries.

ii. Identify the common causes of electricity infrastructure failure both locally and globally.

iii. Propose a development and maintenance solution to enhance the resilience of electricity infrastructure in the South African context.

Throughout this study, existing energy infrastructure maintenance methods will be evaluated, with the view of identifying those methods and techniques which protect the longevity and efficiency of electricity infrastructure. Additionally, the impact of both manmade and climate change related electricity infrastructure failures will be evaluated to assist in developing suitable electricity infrastructure resilience techniques. Lastly, electricity infrastructure resilience techniques relevant to the study area will be proposed, to enhance the climate change adaptation and mitigation measures required to preserve equipment and support continuous electricity service delivery.

1.6 Significance of the study

This research aims to propose suitable electricity infrastructure maintenance and resilience techniques that can assist in mitigating the impact of climate change disasters.

Ayres et al. (2013) assert that energy is an irreplaceable driver of economic growth and national development. A reliable electricity supply is required for continued socioeconomic development in Africa (Wolde-Rufael, 2006). There is a correlation between the availability of electricity and the quality of life enjoyed by residents of developing countries. While South Africa boasts an electrification rate above 85%, (Lemanski et al., 2025), the performance of the related infrastructure declines where there is a lack of maintenance, or where restoration of services is delayed after a fault or failure related to extreme weather conditions. The lack of infrastructure resilience mechanisms undermines the efforts to increase access to electricity (Jasiūnas et al., 2021). Robust maintenance practices are required to ensure the continuous, affordable, and safe operation of critical infrastructure which is used to deliver public services such as electricity, water and sanitation, and transportation (UNDRR, 2022).

To guarantee the optimal performance and reliability of electricity infrastructure, strategic planning and significant investments must be made towards the maintenance thereof. The Construction Industry Development Board (CIDB) shows that the cost of maintaining energy and built environment infrastructure assets often comprises greater than 80% of the lifetime cost (CIDB, 2007). The planning, design, and building stages of infrastructure are often found to constitute 20% or less of the lifetime cost, however, it is at the planning stage that decisions are made in favour of saving costs throughout the useful life of the asset. These types of decisions bring about the opposite of the desired result, as compromises at the inception stage compromise the longevity of an asset and result in premature ageing, emergency refurbishment, and costly replacement of infrastructure (CIDB, 2007). By developing electricity infrastructure resilience techniques which span the entire useful life of an asset, service delivery will be improved, and in turn, economic activity will be encouraged.

In addition to the long-term financial investment in maintenance as a climate change mitigation measure, to enhance the resilience of electricity infrastructure, it is necessary to assess the potential factors which contribute to the failure of electricity infrastructure. In this way, the operators of critical electricity infrastructure may be better prepared to protect infrastructure from permanent damage and frequent disturbances in service delivery. Electricity infrastructure resilience techniques should be proactive and preventative, rather than merely reactive (van Harte et al., 2017).

This research seeks to contribute positively to the ongoing pursuit of rigorous infrastructure development planning and service delivery strategies which affect leaders from national to regional levels, and more importantly the end-users whose right it is to receive reliable services.

The study utilises a qualitative research methodology to comprehend the susceptibility of electricity infrastructure to climate change and identify necessary maintenance measures to bolster infrastructure resilience.

1.7 Delimitations of the study

According to Coker (2022), all research is confined and strictly defined. Delimitations are the boundaries defined by a researcher to set limits on what is included and excluded, thereby keeping a project manageable and centred on the research questions or objectives (Coker, 2022). For this specific study, the researcher has chosen the South African metropolitan municipalities where climate change related electricity infrastructure disasters are likely to have a significant impact due to the number of customers serviced by metropolitan municipalities in South Africa. This is a major delimitation for this study as other South African energy municipalities are excluded. Further delimitations of the study are listed below:

i. This study will explore the factors which determine or predict the success or failure of electricity infrastructure in the South African metropolitan municipalities.

ii. The research will evaluate the increasing frequency and consequences of extreme weather events but will not venture into meteorology.

iii. Best practices in physical asset management and maintenance methods will be explored, however the technical detail of electricity infrastructure manufacturing is excluded.

iv. While recent and factual data from the case study municipalities will be analysed, no physical site visits or environmental investigations will take place.

v. The study will investigate electricity infrastructure design, operation, and maintenance, without analysing the end-user experience; and

vi. The study would not conduct the cost-benefit analysis of resilient electricity infrastructure against those vulnerable to climate change disasters.

vii. This research exclusively focuses on the electricity sector, through a case study of the South African metropolitan municipalities. Eskom as well as the oil and gas sectors are not considered.

viii. The study focus is limited to climate related electricity infrastructure failures.

1.8 Definition of terms

Asset – in this study an asset is a resource that is owned and / or used by a specific entity to operate a business or render a service and to yield financial benefit. Assets may be tangible, immovable, measurable, or intangible and movable (Investopedia, 2024).

Asset Management – the process of continuously monitoring and improving the availability, reliability, safety, and durability of plant, equipment, and service assets (Davis, 2007).

Climate Change – the present patterns of change in the general global weather conditions caused by the increasing temperature of the earth's surface. This temperature increase is caused by both natural and human activity and is referred to as global warming (Salonen & Reiser, 2023).

Climate Change Impact – a distinct effect or influence of an event attributable to climate change (Tabari, 2020)

Infrastructure Development – the process through which physical structures that support socio-economic activities are planned, built, financed, and maintained. These include facilities and systems such as electricity, water, and transportation (Srinivasu et al., 2013).

Infrastructure Resilience – resilience in terms of energy and electricity infrastructure is the ability of a system or structure to anticipate, tolerate and swiftly recover from an external, high-impact and often infrequent disturbance (Panteli & Mancarella, 2015).

Maintenance – the acts of planning, budgeting, and implementing the repair, refurbishment and renewal, and provision for replacement of infrastructure throughout its lifetime to maximise its usefulness (CIDB, 2007).

Metropolitan Municipality – a form of local government, established in densely populated areas characterised by large-scale development, several established industrial and commercial districts and the responsibility to deliver all key municipal services, including water, waste management, and electricity throughout the metropolitan region, which includes a central city surrounded by smaller urban areas. A metropolitan municipality in South Africa also possesses exclusive legislative and executive authority in its region (President of the Republic of South Africa, 1998).

N-1 – the basic level of redundancy in electrical power transmission and distribution networks, where "N" indicates the number of components in the network, and "minus 1" refers to the loss of any single component (Mahan, 2023). N-1 redundancy refers to the power system's ability to withstand a disruption in a single transmission line, cable, transformer, or circuit breaker without resulting in a total loss of power to end-users (Gjerde, 2024).

Reliability – "the probability that a system will perform its intended functions without failure, within design parameters, under specific operating conditions, and for a specified period of time" (Breitfelder et al., 2000).

Sustainable Development – defined by the World Commission on Environment and Development (WCED) as, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987).

1.9 Assumptions

Research assumptions are elements which reveal the perspective of the researcher and yet are out of the researcher's control. These are presuppositions which may have an influence on the outcome of the study (Leedy & Ormrod, 2015).

The assumptions guiding this study are the following:

i. Municipalities across South Africa utilise similar and comparable electricity infrastructure, meaning that electricity infrastructure resilience techniques which emerge from this study will be replicable to other electricity service providers. This means that through this case study, the proposed maintenance techniques would be replicable to other electricity and electricity service providers.

ii. Electricity infrastructure performance reports and asset registers exist and are accessible in larger local municipalities.

iii. The impact of natural disasters on infrastructure resilience is measurable.

1.10 Structure of the Report

This research comprises six chapters, the first three of which form the proposal, while the final three provide evidence of the study which was carried out.

This introductory chapter frames the problem to be researched and the context in which it exists and holds significance, while also providing the boundaries and key concepts of the research.

The study context, the research problem, and its significance as well as the research objectives and the study delimitations are outline in **Chapter 1**. Current and relevant literature pertaining to the research problem and proposed solution is surveyed in **Chapter 2**. The chosen method and instruments of research to investigate the problem and its possible solution are detailed in **Chapter 3**, including all ethical considerations. The findings of the study are presented in **Chapter 4**, referring to the research objectives stated in Chapter 1. In **Chapter 5** the findings of the study are further discussed with specific references being made to each research objective and proposition. Conclusions regarding the research objectives and recommendations for future research characterise the final **Chapter 6**.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

This purpose of this Chapter is to briefly survey the existing modern literature relevant to the research. This section will provide an overview of climate change and its widespread impact on infrastructure. The common infrastructure maintenance and resilience techniques which exist will be discussed, followed by a collation of the existing arguments and theories pertaining to the factors which contribute to the failure or longevity of electricity infrastructure. This section will conclude with a summary of the themes and arguments which are relevant to the development of electricity infrastructure resilience techniques in South Africa.

2.2 Conceptual or theoretical framework

The existing climate change and infrastructure resilience theories are given below:

i. Urban resilience theory: Resilience has emerged as an important theory in the fields of urban planning and public security (Kong et al., (2022). Urban planning requires security risks related to population growth, urbanisation, and human behaviour to be taken into cognisance, to allow for the development of resilient socio-economic systems (Kong et al., 2022).

ii. Climate resilience theory: To accurately measure and the impacts of climate change and prepare for future scenarios, the vulnerability of human beings and the built environment must be measured using a climate resilience index. This index considers the magnitude of the impact, and the adaptability or potential mitigation of a system to climate change (Subiyanto et al., 2020).

The proposition of this study is that electricity infrastructure is more vulnerable to climate change than it is to any other potential risk, and resilience techniques must be developed, to protect electricity infrastructure and maximise its output. Moreover, the theory of smart cities and eco-city theory shows that sustainable cities can develop strategies and concepts that can prevent climatic damages (Blagojević et al., 2020). Furthermore, the climate change disasters experienced in the eThekwini Metropolitan Municipality demonstrate that electricity infrastructure is vulnerable to climate change disasters (Majodina et al., 2018). This means that there is a need to develop suitable electricity infrastructure maintenance solutions that will enhance the resilience of electricity infrastructure against climate change risk.

2.3 A brief background on South African metropolitan municipalities

As this research endeavours to propose electricity infrastructure climate change resilience techniques for metropolitan municipalities, it necessitates a brief background of the latter.

i. Formation and responsibility of South African metropolitan municipalities

South Africa is currently divided into nine provinces, and further into district, local, and metropolitan municipal regions (Jeeva, 2019). This spatial arrangement was made concrete as late as 1996, when the Constitution of the Republic of South Africa, (Republic of South Africa, 1996), was finalised (Jeeva, 2019). The demarcation and further categorisation of these administrative entities was cemented in 1998, through the passing of new legislature such as the Municipal Structures Act 117 of 1998, the Municipal Demarcation Act 27 of 1998, and the Municipal Act 32 of 2000. By the year 2011, eight metropolitan municipalities had been recognised, as they are today (Jeeva, 2019). These include Mangaung in the Free State Province, eThekwini in KwaZulu-Natal, Nelson Mandela Bay and Buffalo City in the Eastern Cape, the Western Cape's City of Cape Town, and the Cities of Tshwane, Ekurhuleni, and Johannesburg, in Gauteng province respectively (Municipalities South Africa, 2025).

The eight metropolitan municipalities were given the charge of delivering public services such as water, sanitation, housing, and electricity to citizens living within their demarcated areas (Republic of South Africa, 2000). The procurement of all necessary elements to successfully deliver these services became the core business of the municipalities. The sale and distribution of electricity to domestic, commercial, and industrial users has become the greatest source of income for metropolitan municipalities, however, recent history has revealed the deterioration of both public service delivery and the financial wellness of the municipalities

(Fourie and Van der Waldt, 2021). As the nation's main producer of electricity, Eskom sells electricity to municipalities, who then sell it to customers, with the transmission and distribution network infrastructure being divided between the utility and various municipalities. Mazele and Amoah, (2022), Khonjelwayo et al. (2020), as well as Ateba and Prinsloo, (2019) lament the poor management of this infrastructure and its far-reaching consequences on service delivery and the socio-economic health of the cities. The scope of this research does not venture into the deeper analysis of metropolitan municipality operations or politics however, it is noteworthy that the financial, political, and technical woes of the municipality are seen in the poor quality of service delivery, especially as far as water, electricity, and public transportation are concerned.

ii. South African metropolitan municipality electricity business outlook.

The Department of National Treasury's Cities Support Program reported that the electricity distribution model used by metropolitan municipalities has ceased to be sustainable, as a result of inadequate maintenance, poor regulation, non-cost reflective tariffs, and general underinvestment (Department of National Treasury, 2017). The 2021 State of Local Government Report published by the Department of Cooperative Governance identified the areas of improvement for metropolitan municipalities, including greater diligence in the management of finances, the employment of competent officials throughout the municipal structure, and an emphasis on strengthening electricity service delivery, among others. The financial stability of metropolitan municipalities in South Africa has attracted much scrutiny by academics and the business community, however Meyer and Neethling, (2021) maintain that no universal financial health index has yet been developed. Fourie et al. (2021) further indicate that the financial ill-health of municipalities across the country is demonstrated by the low hiring rate of skilled human resources such as chief financial officers, technical directors, and general departmental managers to oversee excellent essential service delivery. In the populous Gauteng Province, which hosts three of the eight metropolitan municipalities in the country, the Department of Statistics found that there was an increase in vacant posts, from 24 in the year 2021, to 43 in the year 2022 (Department of Statistics, 2024a). In the Eastern Cape, where two metropolitan municipalities are found, unoccupied vacancies in managerial roles remained the same between 2021 and 2022. This indicates a trend of inadequate skilled capacity within the critical leadership and management roles in many metropolitan municipalities. Low revenue collection in metropolitan municipalities not only hampers electricity infrastructure maintenance efforts, but it also hinders the municipality from being able to hire, train, and retain employees with the necessary skills to properly manage the municipality's electricity infrastructure and other assets, and contribute to the expected quality of service delivery.

Literature reveals that to combat matters of electricity infrastructure performance, network maintenance, and climate change risk mitigation, the causes and consequences of financial instability within metropolitan municipalities must first be dealt with (Mokwebo et al., 2025).

2.4 A brief background of climate change

The phenomenon of climate change is a matter of great concern for the socio-economic wellbeing of the global population. It has been defined by the United Nations Framework Convention on Climate Change (UNFCCC) as the changes in the prevailing weather trends in a region over time, attributable both directly and indirectly to human activity, and leading to the altered composition of the earth's atmosphere (UNFCCC, 2011). The Intergovernmental Panel on Climate Change (IPCC) offers a seemingly opposing definition, which states that climate change is any variation in climate which could be attributed either to the natural patterns of the earth or to human activity, observed with the passing of time (Pielke, 2004). Ahmed (2023) supports the view that climate change refers to significant variations in weather conditions observed over longer periods, brought about by natural and anthropogenic factors. Pielke (2004) remarked that having incompatible or varied definitions of climate change brings about a lack of direction and urgency in the policy decisions which should align to mitigate or adapt to the reality and threat of climate change for the global community.

The scientific explanation of climate change summarised by Garnaut, (2008) agrees with the IPCC's view that the changes in the weather patterns and atmospheric composition of the earth are largely natural occurrences.

The sun drives the climate of the planet, providing solar energy which regulates the terrestrial, aquatic, and atmospheric conditions. Solar irradiance is the rate at which solar energy reaches the earth’s surface, and is the major natural driver of climate change (Ahmed, 2023). Among the five layers which compose the gaseous protective barrier between the earth and the sun, it is the two innermost heat-absorbing layers, namely the troposphere and the stratosphere, which have the greatest influence on the earth’s temperature and weather patterns, (Garnaut, 2008). Approximately one-third of the solar energy which the surface of the earth receives is reflected into space, while the remaining two-thirds is absorbed by the surface, oceans, and atmosphere surrounding the earth. The thermal radiation which the land and oceans emit is absorbed by the various layers of natural gases which compose the atmosphere and is then radiated back to earth in a cycle known as the Greenhouse Effect (Garnaut, 2008). This phenomenon heats the surface of the earth, creating atmospheric and environmental conditions which are suitable to sustain plant, animal, and human life (UNISDR, 2008).

The natural greenhouse effect, driven by solar irradiance, is perpetual and brings about necessary fluctuations in global air and land temperatures, ocean currents and ice concentration, sea levels, precipitation, and seasonal patterns throughout the earth, (Ahmed, 2023; Bhargawa & Singh, 2019). According to Wang et al. (2021), the timing of the four seasons which govern the ecosystems of the earth and socio-economic behaviour of human beings, had already shown signs of change from 1952, and was projected to continue in a warming trend until the worst-case scenario year of 2100. Climate change is unequivocally altering the length of warmer seasons, thereby causing plants and animals that thrive in winter and autumn to become more vulnerable to extinction, (Wang et al., 2021; Bhargawa et al., 2019). Figure 1 demonstrates the shrinkage of the cooler seasons and the extension of summer or hot weather, exacerbated by climate change and persistent global warming.

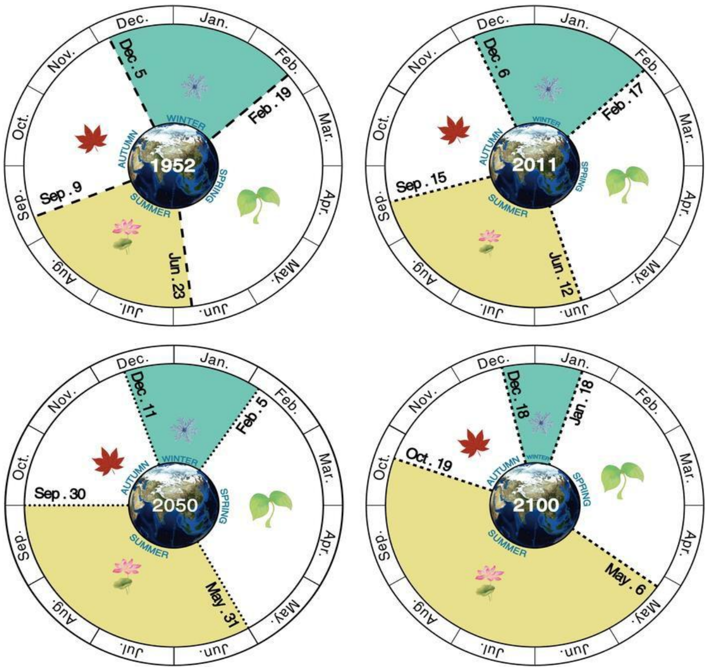

Figure 1: The start and length of seasons in the Northern Hemisphere from 1952 to 2100 (Wang et al., 2021).

The United Nations noted in 2007 that global temperatures were increasing more rapidly in the previous decades, resulting in warmer air and ocean temperatures, as well as rising sea levels throughout the planet (United Nations International Strategy for Disaster Reduction, [UNISDR], 2008). According to Ahmed, (2023) this temperature increase has been attributed to a greater presence of the greenhouse gases carbon dioxide, methane, nitrous oxide, nitrogen oxides, ozone, water vapour, and halogenated gases in the atmosphere.

The rapid temperature increase linked to the concentration of greenhouse gases is the main anthropogenic cause of climate change. Any human activity which results in significant carbon emissions directly contributes to global warming and climate change (Mikhaylov et al., 2020). The combustion of fossil fuels such as crude oil, natural gas, and coal has been beneficial for the industrialisation of many countries, and yet detrimental to the state of the earth's atmosphere. Agriculture, urban expansion, and even the development of solar and wind energy plants are further examples of activities which are beneficial to human social and economic development, yet harmful to the earth, as the increased carbon dioxide emissions associated with these activities deplete the natural and necessary carbon sink of the earth (Ahmed, 2023; Yoro & Daramola, 2020). According to Ahmed, (2023) and Mikhaylov et al. (2020), carbon-intensive industries such as aviation and maritime transportation also play a role in the changing climate. Aircraft engine exhaust fumes are emitted in the troposphere, with the exhaust fumes creating an imbalance in the atmospheric temperature by absorbing solar radiation that should be reflected into space (Ahmed, 2023; Mikhaylov et al., 2020).

While it is accepted that natural processes contribute to global temperature increases, the role of human activities related to industrialisation and population growth cannot be neglected (UNISDR, 2008; Kershaw, 2017). The recognition that the socioeconomic activities of different countries pose a threat to the wellbeing of the ecosystems of the earth gave rise to the Paris Agreement on Climate Change, an international treaty which came into effect after the 21st United Nations Climate Change Conference (Conference of the Parties or COP21), held in Paris, France, in December 2015. Under this agreement, 196 countries became signatories to a legally binding commitment to modify the behaviour of their communities and economies, to reduce carbon emissions to levels which will restrain the global temperature increase to 1.5°C higher than they were in the historical period preceding industrialisation (UNFCCC, 2015). Following the inception of the Paris Agreement, governments have embarked on country-specific strategies and efforts to reduce carbon emissions and implement climate change adaptation and mitigation measures towards the achievement of the Paris Agreement's goal, by the year 2030 (Pan et al., 2017). These Nationally Determined Contributions (NDC's) embody the long-term, actionable plans undertaken to curb global warming and to monitor the world's collective progress in limiting the warming of the earth and to prevent the myriads of dangers associated with a global temperature increase of 2°C, (Pan et al., 2017). During the subsequent COP gatherings, it was reiterated that developed and developing countries are not equally responsible for human-induced global warming and thus cannot be held to the same level of accountability to curb its impact (Pan et al., 2017). The ongoing debates and the mechanisms which exist to monitor the efficiency of climate action efforts by different countries, testify to the reality of climate change and the threat which it presents to the international community (Cappelli et al., 2021).

2.5 A review of climate change disasters worldwide

Rising global temperatures are not the only sign of climate change. Climate-related disasters are varied, widespread and increasingly unpredictable, having an impact on all spheres of society. This section provides an overview of the shock environmental events exacerbated by climate change. Climate change events are discussed in two broad categories, namely, extreme heat, and extreme wet conditions.

2.6 Extreme heat

As the understanding of climate change is centred around increasing temperatures, it follows that one of the consequences of climate change is extreme heat. A heat wave is a prolonged occurrence of hot weather accompanied by high levels of humidity (Marx, 2021; Kershaw, 2017). Heat waves vary according to region and are always relative to the normal daily minimum and maximum temperature experienced by a geographic location in any given season, (Marx, 2021; Meehl & Tebaldi, 2004). Extreme heat impacts human health, by increasing the presence of insects and pests which favour humid conditions and carry disease (Department of Environmental Affairs [DEA], 2011), and by increasing human susceptibility to heat stroke and dehydration.

Heat waves have a negative bearing on crop productivity, food security, the health of livestock and marine life and the likelihood of wildfires (Kershaw, 2017; Raymond et al., 2020). During times of excessive heat and humidity, the agricultural sector suffers losses in the yield of temperature-sensitive crops ranging from rice, maize, and wheat to legumes, which form the basis of many countries' staple diets and agricultural import and export trade (Raymond et al., 2020). Unexpectedly low crop yields result in lower income for both subsistence and commercial farmers. Abbass et al. (2022) found that longer periods of heat can sometimes help agriculture by increasing the yield of crops which typically take longer to mature. Changing heat patterns clearly influence the agricultural sector. The need to protect crops from extended periods of unfavourable environmental conditions and to preserve the livelihood of those who take part in the sector has given rise to innovative farming technologies and water conservation methods (Abbass et al., 2022).

Extreme heat may lead to drought, when prolonged periods of hot weather begin to deplete clean water sources such as rivers, lakes, and dams, as the heat also delays expected seasons of rainfall (Abbass et al., 2022). Oceans suffer from the change and loss in biodiversity when excessive heat alters the temperature of the marine ecosystem (Sala et al., 2021). The loss of essential water reservoirs to drought, and the diminished availability of ground water for use by plants, animals, and people alike, is another danger associated with climate change. Human health is endangered by these circumstances, as it takes longer and longer to recover from illnesses caused by heat (Raymond et al., 2020).

Excessive bouts of heat in areas which are already dry brings about dust storms and hazardous wildfires, which are not easy to predict nor to control (Marx et al., 2021). Although there are manmade wildfires caused largely by negligence or malicious intent, natural causes for wildfires, such as lightning strikes, volcanic activity, and spontaneous combustion of dry vegetation and organic material, (Di Virgilio et al., 2019), are more common and are directly linked to climate change. The ignition of a wildfire displaces people and animals, as hectares of habitats and human settlements are burnt beyond repair (Bandh et al., 2021). Extreme wildfire events have historically been followed by long periods of drought, such as the California wildfire season of 2017 (Bandh et al., 2021). Wildfires can be ignited in especially woody regions, characterised by vast hectares of undisturbed forestry, or dry vegetation growing in mountainous areas. Figure 2 depicts a wildfire raging in a coastal town of South Africa, Western Cape, in 2017. The fires were attributed to climate change, as an otherwise moist region experience a natural onset of wildfire during a heat wave.

Figure 2: Aftermath of wildfire naturally ignited in a forest (Hatchuel, 2022).

Figure 2 demonstrates that the aftereffects of a wildfire naturally ignited in a forest due to unusually dry conditions (Hatchuel, 2022).

Meehl et al. (2004) observed that the frequency and duration of periods of extreme heat affect various human systems, and that a collaboration across different sectors of science, business, education, and government is required to better plan and prepare for the consequences thereof.

2.7 Extreme wet conditions

Climate change disturbs the natural cycles of the earth, resulting in heavy rainfall, floods, tsunamis, and storms (Kershaw, 2017). According to Abbass et al. (2022), the drastic increases in global temperatures observed over the last decade have been modifying evaporation and precipitation trends across the globe. Kershaw (2017) noted that the impact of high-speed winds, high levels of rainfall and hazardous storms was becoming more severe by the decade, since the 1950's. The consequences of extreme wet conditions always include the displacement of people as human settlements are left emersed in water, badly flooded, or completely disintegrated by harsh wind and rain. It is worth noting that other forms of civil infrastructure, power systems, food cultivation, and the daily activities of society such as commuting, are severely disturbed during times of extreme wet conditions (Abbass et al., 2022). Weather extremes brought about by climate change have proven to be responsible for the emergence of communicable diseases, as air and water quality are altered along with weather patterns. This has caused the health systems of the world to become more vulnerable to overwhelm, as seasonal illnesses become more prevalent (DEA, 2011).

Figure 3: Coastal urban area flooded after heavy rains (Daily Maverick, 2024)

Figure 3 illustrates a recent example of flooding caused by heavy rainfall in the Western Cape province of South Africa. Although the rain fell within the expected May to August period, it was reported after six consecutive days of rain that it was above normal for the region at the time of year (van Diemen, 2024). Drainage systems become overwhelmed in the event of heavy rainfall and floods, leaving communities compromised as a result (Kourtis & Tsihrintzis, 2021). demonstrates the reality and impact of heavy rainfall attributed to climate change.

Storm surges are directly linked to climate change as the atmospheric conditions which align to create a storm are occurring more sporadically, due to increasing air, water, and terrestrial temperatures (Kershaw, 2017; Abbass et al., 2022). In a study of weather extremes based in the United Kingdom, Kershaw,(2017) noted the widespread devastation caused by the “Great Storm of 1987,” to demonstrate the danger of storms as a natural disaster. When unprecedented wind speeds progress into heavy rainfall, structures which are designed to withstand tonnes worth of pressure, collapse. Power lines delivering electricity for hundreds of kilometres weaken under the power of a torrential downpour, sparking failures which result in prolonged service downtime. Railways connecting various economic hubs are either flooded or experience structural damages which similarly require large sums of money to repair (Kershaw, 2017).

Commercial farmers are equally affected by dry and wet conditions, as the quality of soil and the saturation of ground water are drastically impacted when a region experiences extremely wet weather (Kershaw, 2017).

Coastal regions take severe strain in the event of an extreme storm, as large waves moving at high speeds can soak kilometres worth of civil infrastructure along the shoreline (Kershaw, 2017). The convergence of warming oceans, rising sea levels and climate-induced chemical reactions in the earth's core results in dangerous events such as earthquakes and tsunamis (Kershaw, 2017). Both types of events occur at varying scales of severity, and both result in damage to infrastructure along with loss of life when they strike. Cappelli et al. (2021) observed earthquakes and tsunamis occurrence more frequently, with incrementally severe impacts in the previous two decades. The extent of damage left by a storm or tsunami event requires time and significant financing to repair. The increasing frequency of these events means that restoration efforts must outpace the occurrence of extreme weather events (Raymond et al., 2020).

In a study of climate change disasters and their impact on countries with varied economic profiles and levels of development, Cappelli et al. (2021) demonstrated that natural disasters were occurring more frequently between 1992 and 2018, as shown in Figure 4.

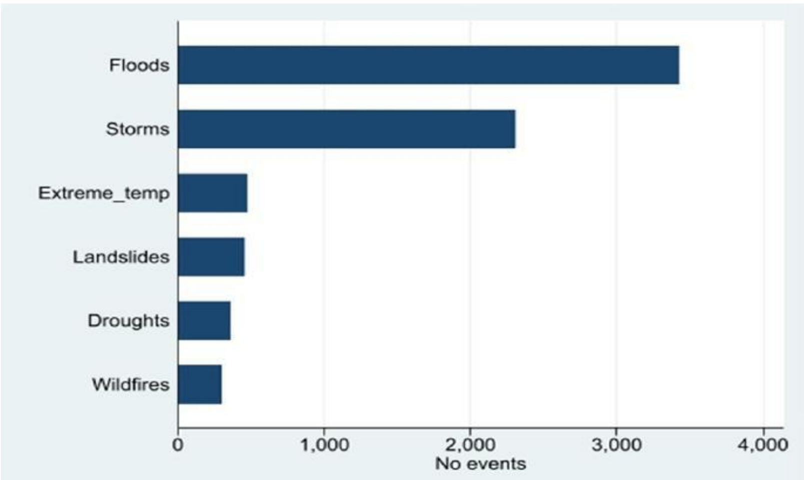

Figure 4: Number of climate-related disasters in 1992 – 2018 (Cappelli et al., 2021)

Figure 4 demonstrates that extreme wet weather conditions or hydrological disasters were happening more often from 1992 to 2018, in a survey of 149 countries, while environmental conditions exacerbated by extreme heat were also on the rise.

Although climate modelling has advanced significantly, the occurrence of hazardous climate events remains largely unpredictable. In view of this dilemma, countries have recognised that their climate risk response should be twofold, considering both adaptation and mitigation strategies (UNFCCC, 2015). The United Nations classifies adaptation strategies as those interventions that help to protect people, and the natural and built environments against current and projected impacts of climate change (DEA, 2011; United Nations Development Program [UNDP], 2024). Climate change adaptation measures are necessarily subjective or contextual and are tailored to the specific needs and vulnerabilities of regions and communities. The cultivation of more resilient crops, creative water storage and conservation methods, and the construction of flood defence mechanisms, are examples of adaptation measures. The goal is to become better prepared for the somewhat inevitable occurrence of a climate disaster, based on historical learnings and forward-looking projections (UNDP, 2024). Mitigation strategies on the other hand are concerned with reducing or preventing anthropogenic greenhouse gas emissions. Transitioning from fossil fuels to less-pollutive energy sources, afforestation, and reforestation, employing technologies and practices to promote energy efficiency and the policies and regulations which accompany these efforts are examples of the climate change mitigation response (UNDP, 2024). Every country needs to respond in both ways, as is demonstrated by the previously mentioned NDC's.

The reality of climate change caused by rapidly rising global temperatures, is a matter of concern for the entire global community, as the impact of weather extremes stretches across sectors, industries, and demographics.

2.8 Electricity infrastructure failure and consequences

This section of the literature review will survey the common factors which cause energy infrastructure to fail and will briefly describe the level of their impact on infrastructure performance, durability, and critical service delivery.

In the field of maintenance and asset management, physical and intangible assets and systems which are vital to the continued social and economic wellbeing of people, and which support vital societal functions, are classified as critical infrastructure (Rehak & Hromada, 2018). While infrastructure can be further defined according to its various components and their function in different sectors of society, Rehak et al. (2018) assert that the complexity and vulnerability of the infrastructure to various types of disturbances is attributed to its interlinked or interdependent nature. In an assessment of the aftermath of the Hurricane Katrina on civil and electrical infrastructure in New Orleans, United States in 2005, Little, (2012) concurred with the notion that service delivery is indeed severely impacted by the occurrence of a natural disaster but found that the negative impact is exacerbated by the interdependent nature of the various infrastructure systems that serve society.

The common disturbances or threats faced by critical infrastructures and their associated sub-systems and components have been broadly categorised as follows (Rehak et al., 2018):

i. Biological, for example a pandemic such as COVID-19,
ii. Geological, such as landslides and earthquakes,
iii. Criminal, referring to intentional vandalism or theft against a system,
iv. Technological, where emergencies or crises arise in the functioning of water, transport, or other engineering systems, and
v. Climatological, where natural disasters cause a prolonged disruption in infrastructure performance and service delivery, as has been noted by Kwasinski et al. (2019), Little, (2012) and Panzieri and Setola (2008).

Rinaldi et al. (2001) and Rehak et al. (2018) argue that the decreased performance of any critical infrastructure system is directly linked to the intensity and frequency of any type of disturbance, which also points to the quality of the various components that are manufactured. The severity and duration of any electricity infrastructure system fault is also determined by the operational state in which the system is found when a fault occurs. An example relevant to the South African context is that of a power outage, where its impact is more widespread and disturbing to human activities during times of peak demand and usage than during off-peak times (Strbac et al., 2016).

Rehak et al. (2018) and Panzieri et al. (2008) further elaborate on the types of failures which may be imposed on a critical infrastructure network such as an electricity system. These include successive or cascading faults, where a disturbance in one portion of the system triggers a fault in another connected system, thereby causing infrastructure performance failure with a longer estimated restoration time (Rehak et al., 2018). Escalating failure results when a disruption in one infrastructure causes a disruption in an independent system, for example where a power failure in one region of a large city disturbs a bus rapid transit (BRT) system for several hours at a time, more so if the power failure occurs during times of peak traffic, as noted by Strbac et al. (2016). Another category of infrastructure failure is a 'common cause,' where two or more components or systems within a certain type of infrastructure are interrupted at the same time, due to a natural disaster or an upstream electrical fault (Rehak et al., 2018).

Little (2012) further argues that infrastructure failures are caused by the presence of unpredictable risks which may not be easily mitigated before they arise, and by the lack of proper asset management techniques such as record keeping and performance monitoring.

Panzieri et al. (2008) stress that although the elements which compose electricity production and distribution infrastructure, transportation and telecommunications networks are designed as independent systems to deliver varying services, they have become increasingly dependent and interdependent on one another. Design and operational evolutions have been implemented in the quest to increase efficiency, reduce costs, and promote innovation, largely supported by Information and Communication Technologies (ICT) (Panzieri et al., 2008; Strbac et al., 2016).

A brief survey of the common factors which contribute to failures in electricity infrastructure and other critical infrastructure systems reveals that interdependence is one of the main factors which increase the vulnerability of infrastructure to faults and failures. If the potential impact of a failure is not assessed with economic, technological, and social factors all taken into cognizance, electricity infrastructure resilience will continue to be compromised.

2.9 Impact of climate change on electricity infrastructure

This research is concerned with the proven impact that climate change is having on critical infrastructure, which includes any system or asset which plays a major role in maintaining the health, safety, security and social or economic wellbeing of people (Karagiannis et al., 2017). Infrastructure related to energy and electricity, such as overhead transmission lines, telecommunication signal towers, power distribution equipment, and various types of power generation technology, is vulnerable to extreme weather as it is often installed outdoors and is expected to operate efficiently for 20 to 45 years before replacement. Karagiannis et al. (2017) further elaborate that such critical infrastructure must be protected for the sake of community resilience.

The literature indicates that common causes of power system failure include equipment faults, electricity supply shortage, operational error, and fire (Hines et al., 2009), and that system operators are usually prepared to quickly combat these through fault-finding and preventative maintenance techniques. However, extreme weather events such as intense lightning strikes, heavy rainfall leading to flooding, harsh windstorms, frost, and drought are more detrimental to system operation and reliability as they cause disturbances with a wider geographical reach (Hines et al., 2009; Fu et al., 2018).

Fu et al. (2018) found that electrical system resilience has previously been measured using current climate conditions and limited supply and demand forecasts, while the impact of future climate-related hazards, energy policy evolution, and power demand and supply projections have not been widely considered. The impact of climate change hazards on electricity infrastructure is expanded on in the following subsections of the literature review.

2.10 Electrical transmission infrastructure

The vulnerability of electricity transmission infrastructure to climate-induced damage and eventual collapse was demonstrated by Fu et al. (2018). In their study of power system vulnerability to severe weather, Fu et al. (2018) forecast that loss of load occurrences, (power demand exceeding available generation capacity) would become more prevalent, in response to increased intensity and frequency of windstorms over time. In a worst-case scenario of a 50% increase in windstorm intensity and frequency, a probable loss of up to 45 GW of electricity during the peak winter demand period was demonstrated. Overhead transmission lines impacted by storms or fires linked to climate change can cause cities and surrounding areas to go without electricity and network connectivity for extended periods (Fu et al., 2018). In a case study of extreme weather patterns in Great Britain, Kershaw, (2017) exposed the far-reaching impact of the unprecedented "Great Storm of 1987," on electrical infrastructure in Great Britain. Although wet weather conditions were a norm for the region, this storm marked the beginning of an increasing frequency and intensity of windstorms accompanied by heavy rain and flooding (Kershaw, 2017). In addition to the damages suffered by human settlements and railway networks, electricity transmission lines were destroyed, worsening the impact of the storm (Kershaw, 2017).

The current-carrying capacity and efficiency of overhead conductors are compromised during snowstorms (Küfeoğlu et al., 2014) and heat waves, as conductivity is optimal within specific parameters such as temperature and distance. Temperature extremes bear long-term consequences which minimise the effectiveness of electricity transmission infrastructure (Burillo et al., 2018; Cronin et al., 2018).

i. Lightning strikes

Lightning strikes are projected to become more prevalent in tropical regions where an upward trend in seasonal temperature increases has been observed (Price, 2009). With land surface temperatures rising in response to a warming climate, droughts inevitably ensue as a result of excessive evaporation. There is a direct correlation between greater concentrations of water vapour in the troposphere and the frequency of lightning strikes (Price, 2009). According to Zalhaf et al. (2022), intense lightning strikes give rise to several fault conditions in high voltage DC transmission lines, such as over-voltages which result in insulation flashover and the failure of shielding wires designed to protect the transmission network from lightning strikes (Zalhaf et al., 2022). In a separate study, Dowdy, (2020) agreed that although lightning is a common feature of a rainstorm; more intense lightning strikes are occurring across all continents, owing to global warming, and this is endangering kilometres worth of electricity supply infrastructure as a result. High voltage towers and overhead conductors are often installed in dry, open areas, where a wildfire is easily ignited when temperatures rise rapidly (Dowdy, 2020). Figure 5 demonstrates the perilous outcome of an extreme lightning strike on electricity transmission infrastructure. Regional temperature increases caused by climate change can produce a continuous chain of disasters (Pielke, 2004).

Figure 5: Intense lightning impact on electricity infrastructure (Insulator News and Market Report, 2021).

As illustrated in Figure 5, intense lightning strikes have been known to spark wildfires, leading to the devastation of any surrounding vegetation and air pollution due to heavy smog reaching the regions located in close proximity to the centre of the disaster.

ii. Thermal power plants

Thermal power stations are vulnerable to climate change as rising global temperature contribute to lower thermal efficiencies during the process of fossil fuel feedstock combustion, leading to lower power outputs (Cronin et al., 2018). According to study by Zhang et al. (2021), increasing temperatures during the 2012 – 2014 period resulted in reduced thermal efficiencies at numerous coal-fired power plants in northern China. It was further noted that the decommissioning of old generation units could not sufficiently curb the inefficiencies, as they were caused largely by the warmer ambient temperatures in the region (Zhang et al., 2021). The efficiency of combined-cycle gas turbines and coal-to-gas conversion technology have been proven to decrease significantly, with an increase in air temperatures (Burillo et al., 2018).

A warming climate gives rise to water scarcity, as a consequence of decreased precipitation (Burillo et al., 2019). This compromises the water-intensive cooling processes in thermal power plants leading to load reductions or unplanned periods of total shutdown (Cronin et al., 2018).

iii. Solar PV plants and wind farms

The increased adoption of renewable energy technologies such as solar PV plants, onshore and offshore wind turbines and hydroelectrical plants, has slowly reduced the share of carbon emissions caused by fossil fuel combustion. These systems which are designed to take advantage of the freely available natural resources such as the sun and wind, alongside rivers and dams adapted for hydroelectric power generation, are vulnerable to failure and damage caused by climate change. By way of illustration, the occurrence of a typhoon can result in expensive damages to solar panels installed in tropical regions. Solar plants primarily exist to supplement electricity generation capacity without increasing carbon emissions. The technology that was created to alleviate climate change finds itself vulnerable to the same. Figure 6 illustrates a solar plant damaged by such a typhoon in Japan, in 2016.

Typhoons, along with cyclones, hurricanes, and other forms of strong winds and heavy rainfall, have been noted in sections 2.4 and 2.7 as extreme weather events attributable to climate change. Their impact reaches to the destroying of renewable energy technologies designed to improve one aspect of global warming, namely carbon emissions (Hsu et al., 2018).

Figure 6: Climate change impact on solar panels in Japan (Hsu et al., 2018)

Cronin et al. (2018) further notes that excessive heat compromises the efficiency of solar panels, resulting in the continued reliance on fossil fuels for stable electricity generation.

The severity of the long-term negative impact of climate hazards such as hurricanes and floods were further demonstrated by Kwasinski et al. (2019), in a case study of Puerto Rico. The small island nation relies on a power generation mix of fossil fuels and renewable energy technologies. The existing transmission and distribution networks linked to the conventional steam, diesel and combined cycle coal combustion generation technology were already aging, with some transmission lines strung on poles placed in mountainous regions (Kwasinski et al., 2019). The infrastructure experienced extensive damage, leading to prolonged disturbances in electricity distribution for citizens in rural and central Puerto Rico, when Hurricane Maria struck in September 2017 (Kwasinski et al., 2019). Many power plants and substations were flooded, while numerous utility-scale PV plants were damaged due to the severe wind speeds. Wind turbine performance is compromised when wind speeds are well below the desirable levels for optimal energy output, or when wind speeds are stronger than the rated optimal wind speed, leading to damages such as those shown in Figure 7.

Figure 7: Climate change impact on Wind turbines (Kwasinski et. al., 2019)

The Punta Lima Wind Farm located in eastern Puerto Rico lost all thirteen of its wind turbines to the hurricane, resulting in a loss of 25MW of power to the country (Kwasinski et al., 2019). Outside of the absolute curtailment of wind energy output caused by extreme weather events, Cronin et al. (2018) reiterate that non-ideal climate conditions compromise the efficiency of renewable energy systems such as wind farms.

iv. Hydropower plants

Hydropower plants exploit the natural potential and kinetic energy of water as it flows from a higher altitude to a lower altitude, providing the force required to operate turbines and generate clean electricity (Auestad et al., 2018). While hydropower is considered a mature renewable energy technology, having emerged in the nineteenth century, its dependence on the mass availability of water makes it susceptible to the negative impact of rising global temperatures (Auestad et al., 2018). The two major threats facing hydropower generation are drought, leading to water scarcity and impeded levels of electricity production, and floods, which cause water reservoir spillage, resulting in water wastage and less efficient electricity output (Predin et al., 2021).

Modern studies, (Bonaldo et al., 2023; Shu et al., 2022; Chernet et al., 2013), have revealed that the negative impacts of climate change on hydropower plants are common to various geographic locations. In the African nation of Zambia, the drought seasons of 2015, 2016, 2019, and 2022 severely threatened the availability of water and electricity, as the nation's power grid is dominated by hydropower (Ahmed, 2021). Figure 8 depicts the impact of the severe 2022 drought season on the Zambian Kariba Dam, exposing a lack of drought-resilience mechanisms and climate-focused energy planning. Hydropower systems hold the potential to enhance water availability and provide a relatively clean source of electricity. These benefits are rendered null in the face of droughts and floods induced by global warming and climate change.

Figure 8: Drought-stricken Kariba Dam, Zambia (Ahmed & Ahmed, 2021)

According to Majodina et al. (2018), the knowledge and understanding of electricity infrastructure planning and development that is future-focused and climate-aware is rather low in developing countries. Government acknowledges the need to create and implement climate change adaptation and mitigation measures to build and sustain the resilience of electricity infrastructure and all associated social, environmental and economic systems, (DEA, 2011), yet there remains a strong case for the development of resilience techniques to ensure energy security and good service delivery in the future.

v. Geothermal technologies

Geothermal technology harnesses the natural heat of the earth's core to produce energy for electricity generation and other heating applications. According to Ciapała et al. (2021), high temperatures reduce the effectiveness of shallow geothermal systems through increased heat losses. The exploitation of geothermal resources becomes less efficient and less profitable where the earth's ground and core temperatures are significantly increased due to a changing climate (Ciapała et al., 2021). Dao et al. (2024) and Archer, (2019) provide further evidence that the advantages of the geothermal energy technology are jeopardised through global warming, as increased ground temperature may trigger earthquakes in regions which would otherwise benefit from the clean and affordable use of geothermal energy.

vi. Bioenergy feedstock

Plant material has been utilised as an alternative fuel and heating source by agricultural communities for many generations, and in recent times bioenergy has become a scalable alternative to fossil fuel and petrochemicals (Freitas et al., 2021). Bioenergy feedstock such as organic waste, woody plants, crops including sugar cane, sorghum, soybean, and corn rely on specific levels of solar radiation, air conditions, and water availability to thrive (Freitas et al., 2021).

Figure 9: Bioenergy feedstock destroyed by drought (Williams, 2024).

Figure 9 demonstrates the effects of climate change induced drought on corn crops which are essential to the successful exploitation of biomass for energy production.

In their analysis of the efficiency of bioenergy technologies, Emery et al. (2020) further emphasised the negative impact of climate change on various feedstocks, noting that prolonged droughts compromise the process of fertilisation, resulting in diminished crop quality for bioenergy applications. This reiterates the observation that renewable and alternative energy technologies which aim to combat climate change, find themselves vulnerable to the negative impacts of the same, thereby stressing the need for the development of resilience techniques.

2.11 South African metropolitan municipality climate change response strategies

As one of the most authoritative strategic planning documents for the improvement of electricity access for all in South Africa, the National Development Plan 2030, (National Planning Commission, 2012), indicated that it is not a lack of climate response policies which hinders the nation's climate change adaptation progress, instead it is poor developmental planning and the vulnerability of the societal majority. Consequently, provincial, and local government have the responsibility to tighten the strategic planning, which is specific to their respective metropolitan municipalities, in an effort to be prepared when climate change incidents occur. The Municipal Act indeed mandates all municipalities to compile integrated development plans and disaster response plans, however, this is a broad instruction, which does not pay greater attention to electricity transmission and distribution infrastructure. To demonstrate that local government development plans do exist, the climate change response strategies of metropolitan municipalities in South Africa, are listed in Table 1 below:

Table 1: South African metropolitan municipality climate change response strategies

Metropolitan municipality	Principal climate change response strategy	Publication year	Focus on electricity infrastructure	Source
City of Johannesburg	Climate Action Plan	2021	The plan highlights actions to maintain the effectiveness of City Power, the municipality's electricity transmission and distribution arm.	City of Johannesburg, (2021)
City of Ekurhuleni	Ekurhuleni Energy and Climate Change Strategy	2007	The strategy highlights the need for sufficient funding to be allocated towards electricity distribution system repair and maintenance.	Sustainable Energy Africa, (2007)
City of Tshwane	Climate Action Plan	2021	The plan highlights the City's plans to incorporate greater levels of clean and renewable energy to its energy mix, as a climate resilience technique, and to encourage the sustainability of the electricity distribution business.	City of Tshwane, (2021)
eThekwini	Durban Climate Action Plan	2019	Electricity transmission and distribution infrastructure is mentioned under the climate change mitigation section.	eThekwini Municipality, (2019)
City of Cape Town	Climate Change Action Plan	Published as a policy in 2017, reviewed and became a strategy in 2019, revised in 2021	The plan highlights substations, underground cables, and overhead conductors among the "at-risk public infrastructure". The plan emphasises communication methods used by the metropolitan municipality to keep citizens and infrastructure safe.	City of Cape Town, (2021)

Metropolitan municipality	Principal climate change response strategy	Publication year	Focus on electricity infrastructure	Source
Nelson Mandela Bay	Climate Change and Green Economy Action Plan	2015	The plan emphasises the adoption of energy efficiency measures and the addition of renewable electricity to its energy mix.	Nelson Mandela Bay Municipality, (2015)
Buffalo City	Climate Change Strategy	2015	The plan indicates that electricity infrastructure must be made more resilient against extreme wind, storms, and excessively high temperatures.	Buffalo City Metropolitan Municipality, (2015)
Mangaung	Climate Change Adaptation and Mitigation Strategy	Drafted in 2015, accepted in 2017	The strategy outlines the municipality's goal to decrease reliance on carbon-intensive electricity supply and harness its natural solar resources to promote clean energy.	NM Envirotech Solutions, (2017)

Source: Author’s adaptation, (2025).

Table 1 provides an overview of the existing climate change response strategies of metropolitan municipalities, which are available in the public domain. Although further investigation into the present implementation progress and the effectiveness of the plans, policies, and strategies listed in Table 1 would provide greater insight into the current condition of electricity infrastructure and climate change resilience progress in each of the metropolitan municipalities, it is beyond the scope of this research, and may be considered in a separate study.

What the listed publications prove is that there is progress towards meeting the social, economic, and environmental development goals laid out in the National Development Plan 2030,(National Planning Commission, 2012). As observed by Ali (2021), excellent public service delivery requires resolve from policymakers, government, and communities alike. The South African government provides for the support of metropolitan municipalities to implement their strategies through sub-departments such as the National Treasury's Cities Support Program, and the Department of Cooperative Governance's Municipal Infrastructure Support Agency. The effectiveness of the existing plans to assist citizens, the natural environment, and the electricity infrastructure of metropolitan municipalities to withstand climate change shocks, is yet to be observed and properly documented.

2.12 Electricity infrastructure resilience techniques

The productivity and continuous growth of an economy is reliant upon the availability of modern, functional public infrastructure in the form of water, transport, and energy systems, which are growing increasingly interdependent (Rioja, 2013; Mazele et al., 2022). The overview of climate change and its impact on infrastructure revealed that electricity or power delivery systems must be particularly stable, reliable, and resilient to fluctuating environmental conditions. Electricity infrastructure practitioners are presented with the challenge of implementing sound climate change adaptation and mitigation strategies to enhance the resilience of electricity infrastructure.

To curb the negative impact of warmer air temperatures on power generation, Burillo et al. (2018) suggests the construction of power generation plants in cooler locations, to prevent the decline of thermal efficiency. The challenge of rising ambient temperature calls for the development of more effective power transformer cooling technologies (Burillo et al., 2018). Thermal power plants may also be made more resilient by implementing flood protection and using moisture resistant feedstocks, such as natural gas, to combat the negative effects of weather extremes (Burillo et al., 2018; Abbass et al., 2022).

In an evaluation of various techniques to improve electricity infrastructure resilience, Rioja, (2013) noted the critical role of implementing robust maintenance methods to ensure that operators and end users harness the maximum useful life of the various components and equipment involved in the delivery of essential services supported by electricity infrastructure.

In their exploration of the origins and evolution of power system maintenance, Alvarez-Alvarado et al. (2022) agreed that power system maintenance best practices must be identified, to prevent the failure of power grid operation, and to ensure that the system remains secure, adequate, efficient, and reliable.

Various types of maintenance exist, depending on the need that needs to be addressed. The First Industrial Revolution, which occurred in England between 1760 and 1870, gave birth to the idea of maintenance, which was largely corrective in nature (Alvarez-Alvarado et al., 2022). Today, one of the most widely understood types of infrastructure maintenance techniques is corrective maintenance. It is synonymous with fault-finding, as it is concerned with identifying, isolating, and rectifying a fault, so that the operational condition of a component may be restored within a predetermined time limit and before it suffers complete damage. The decision to either disrupt a service or a system temporarily to carry out corrective maintenance or to refurbish or replace a component is determined by the associated cost and long-term benefit of either action (Alvarez-Alvarado et al., 2022). Corrective maintenance evolved and gave rise to preventive maintenance, whose objective is to reduce the risk and rate of equipment failure, by carrying out periodic maintenance, rather than waiting for failure or damage to occur. As industry continued to evolve and the need for more efficient technologies arose, the branch of predictive maintenance was introduced. Alvarez-Alvardo et al. (2022) further elaborate that predictive maintenance aims to maximise the profitability of system components while decreasing the likelihood of failure. Not unlike preventive maintenance, predictive maintenance is carried out according to component-specific schedules, depending on the function of a component and the wear and tear associated with it. Maintenance strategies which exist within the predictive maintenance strategy help electricity infrastructure planners and operators to monitor the age and health of power system components and to make decisions based on the associated risk and cost of maintenance work. The language of maintenance has further evolved with the entrance of the Fourth Industrial Revolution in 2011, where a more holistic approach to infrastructure maintenance emerged, termed 'asset management' (Alvarez-Alvarado et al., 2022). Asset management in the sphere of energy and electricity involves a combination of maintenance strategies which are tailored to specific systems and applications. Asset management must be cost-effective and result in the improved quality and reliability of the services associated with the assets (Davis, 2007; Gitelman et al., 2020; Alvarez-Alvardo et al., 2022).

Alongside adequate and proactive infrastructure maintenance techniques, there is a need for evolution and innovation in the manufacturing and construction standards which govern the electricity sector. Power supply authorities tend to be the custodians of network design and construction standards, and rightly so, as it is theirs to operate. The materials used to produce coastal and inland infrastructure vary according to the expected environmental conditions in industrial, commercial, and domestic applications. The recent increase in unpredictable weather conditions calls for the design and manufacturing standards to be strengthened and adapted to the projected and not only the historical environmental conditions. As an example, in remote areas which tend to be serviced by overhead conductors strung upon wooden poles, measures should be taken to reduce the vulnerability of conductors to excessive heat.

Just as disaster-prone regions utilise early warning systems to protect people from floods, earthquakes, hurricanes, hailstorms, and other disruptive, climate-related weather events, electricity infrastructure operators could benefit from employing technologies which can foresee events which threaten the health and functionality of electricity infrastructure. Such warning systems should then be further developed to be able to remotely deploy protective measures, to reduce the service downtime associated with any event which endangers the infrastructure.

Decentralisation of energy production and distribution systems presents an opportunity to increase the resilience of electricity infrastructure. As noted by

Rinaldi et al. (2001), interdependency increases the risk of infrastructure failure. Creating smaller, less dependent systems may aid in building the resilience of electricity infrastructure. As the world employs more and more smart systems to integrate services across sectors, it is imperative that decentralisation does not reduce the efficiency, convenience, and reliability that characterise a strong electricity system.

Little has been published to enhance the knowledge of electricity infrastructure resilience techniques. Should electricity infrastructure development not increase the level of proactiveness to maintain optimal operation, electricity infrastructure resilience to natural and manmade hazards will remain low.

2.13 Conclusion

It is essential for electricity infrastructure to not only be sufficient to meet the needs of a growing economy, but also resilient to present dangers such as climate change impact and inherently technical vulnerabilities throughout the useful life cycle. The literature suggests that electricity infrastructure will remain vulnerable to climate hazards unless robust asset management strategies are implemented.

Climate change has been revealed to be an imminent danger towards human beings and the systems and structures which create a functioning society. Weather extremes attributable to global warming and climate change continue to displace populations and to compromise food security, energy security, and human health. Extreme weather events also have a bearing on electricity infrastructure, calling for urgent action to be taken towards the development of sound techniques to build resilience, and yield the greatest outputs from electricity infrastructures and the essential services they deliver.

CHAPTER 2. LITERATURE REVIEW explored the research objectives through an overview of climate change, its impact, and the concept of electricity infrastructure resilience. The propositions garnered from the literature review are summarised in the consistency matrix presented in Table 2.

Table 2: Research objectives and propositions

RO #	Research Objective	Proposition #	Proposition Statement
1	Evaluate electricity infrastructure development and best practice maintenance techniques	1	Electricity infrastructure resilience techniques and policies must be developed to improve maintenance efforts and prevent climate-related vulnerabilities.
2	Identify electricity infrastructure failure and consequences	2	The interdependent nature of electricity infrastructure is a major cause of failure, underpinned by extreme weather events caused by climate change, vandalism, and neglect by human beings.
3	Propose a development and maintenance solution to enhance the resilience of electricity infrastructure.	3	Proactive and future-focused design, manufacturing, and maintenance techniques should be deployed, alongside early fault or disaster detection and decentralisation of electricity service delivery infrastructure.

Source: Author’s adaptation (2025).

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Introduction

Having assessed the existing literature pertinent to electricity infrastructure resilience, the current chapter will describe the chosen research approach, research design, and data collection methods employed by this study, to explore the propositions outlined in the previous chapter. The research instrument will be described, followed by the limitations of the study and the factors which will prove the credibility of the chosen research method. The chapter will conclude with the applicable ethical considerations and consistency Table 5.

3.2 Research Approach

According to Jackson et al. (2007) and Fossey et al. (2002), qualitative research methodologies are those which are concerned with comprehending the dimensions of circumstances and events and their influence on the human experience. The research approach is guided by the assumptions and delimitations stated in the first chapter. This study is focused on the resilience of electricity infrastructure.

A qualitative research method shall be utilised to examine the current state of electricity infrastructure in various metropolitan municipalities of South Africa, to gain insights on the impact of climate change disasters on the reliability and functionality of the infrastructure. The aim is to collect factual and current data which shall be utilised to formulate scalable, practical actions which can be taken towards the development of electricity infrastructure resilience techniques.

3.3 Research Design

The research design outlines the manner in which a researcher aims to collect and analyse data using an appropriate population and sample which will yield trustworthy and transferrable results (Klopper, 2008).

The research problem and context, as well as the type of data required to carry out the study all determine the research design (Kothari, 2004). According to Klopper, (2008), the strategy commonly employed in qualitative research is either universal or specific, general or contextual, where the goal of the research may be explanatory, exploratory, or descriptive.

The characteristics of this research design will be contextual and explanatory, as data will be collected from a sample that is assumed to have similar knowledge and experiences that will be used in the research.

3.4 Data Collection Methods

The data collection process is intended to achieve the research objectives (Kothari, 2004). Data collection methods are the actions and decisions which the researcher will take towards the gathering, analysis, and interpretation of data, (Klopper, 2008). The data collection tools available to the qualitative researcher include surveys, questionnaires, focus groups, the conduction of interviews, and the analysis of documents relevant to the study area and research objectives (Klopper, 2008; Kothari, 2004; Bowen, 2009).

After identifying the type of electricity infrastructure used in South African metropolitan municipalities, a questionnaire will be designed to gain insight from research participants with similar experiences and areas of expertise.

Literature (Phellas et al., 2011), differentiates between self-completed questionnaires and interviews, citing the advantages and disadvantage of the former in Table 3 below.

Table 3: Advantages and disadvantages of the questionnaire as a qualitative research tool

Data collection through self-completed questionnaires	
Advantage	**Disadvantage**
Allows participants to respond at their own pace, at the time and place of their choosing.	No opportunity to elaborate further or to explain the nuances in their responses.
Identical questions asked to all participants will allow for collation and comparison of the data gathered.	Likely to exclude participants with a lower level of literacy, where questionnaires are administered either physically or electronically.

Data collection through self-completed questionnaires	
Advantage	**Disadvantage**
Cost-effective administration.	May result in low response rate when the participant has no personal interest in the research topic, or when there is no direct interaction between the researcher and the respondent.

Source: Phellas et al. (2011)

To avoid the pitfalls of self-completed questionnaires described in Table 3, the questionnaires in this research will be administered verbally by way of scheduled, semi-structured interviews. There will be a combination of closed and open-ended questions, to allow for deeper and more diverse insights to be gleaned from the responses of the research participants, and to draw sound conclusions regarding electricity infrastructure resilience in South African metropolitan municipalities.

3.5 Population and sample

Sampling and population selection in research places much focus on the principles of suitability and sufficiency (Fossey et al., 2002). This means that the success of a qualitative study requires the most suitable choice and quantity of individuals, events, places, and types of data to allow for a complete comprehension of the research subject (Fossey et al., 2002). The nature of qualitative sampling can either be purposive or theoretical. The purposive or purposeful sampling gravitates towards appropriate sources of information, while theoretical sampling aims to build a theory through the analysis of data extracted from persons, processes, or circumstances (Fossey et al., 2002).

The population and sample selection for this study will adhere strictly to the research context and delimitations stipulated in CHAPTER 1. INTRODUCTION.

3.6 Population

The context of this research is metropolitan municipalities in South Africa. Therefore, the chosen population will include electricity and electricity infrastructure professionals working within the eight metropolitan municipalities throughout five South African provinces, namely Eastern Cape, Western Cape, KwaZulu-Natal, Free State, and Gauteng. Individuals who are members of the Association of Municipal Electricity Utilities, (AMEU), and have appropriate knowledge and experience of electricity infrastructure will also be engaged to take part in the study. District municipalities and local municipalities are excluded from the study.

The population is limited to metropolitan municipalities as they constitute a population of 1 000 to 2 000 permanent residents per square kilometre, and are the hubs of economic activity (Jeeva, 2019). Furthermore, this research assumes that a comprehension of climate change impacts on electricity infrastructure within the chosen study population will yield results which are representative of and applicable to the excluded population. This research aims to gather data which will be develop into actionable and scalable electricity infrastructure resilience techniques.

3.7 Sample and sampling method.

The qualitative study can often collect large amounts of data from a relatively small-sized sample (Fossey et al., 2002). While there is no agreed minimum number of participants required for the qualitative research to be sound, Teherani et al. (2015) and Fossey et al., (2002) remark that the data collected from participants must exhibit sufficient depth of knowledge and experience with the subject of research. A purposive sample of between six and ten respondents is considered adequate, provided that the respondents will have diverse yet comparable experiences pertaining to the research topic (Malterud et al., 2016). Nevertheless, an average sample size of fifteen to fifty respondents is often recommended for a qualitative study (Marshall et al., 2013).

The sample which will be taken for the current study is described in Table 4.

Table 4: Profile of research respondents (by position or context and not name)

Description of respondent type	Number to be sampled
i. Senior professionals in the electricity planning department of South African metropolitan municipalities, electricity depot managers, and electricity infrastructure employees	10
ii. Members of the AMEU	2
TOTAL number of respondents	12

Source: Author's adaptation, (2024)

This study anticipates engaging a sample size ranging between nine and twelve participants, as literature indicates that ten is an acceptable minimum standard sample size for sound qualitative research, stating that data saturation or redundancy is more likely to occur as qualitative sample sizes begin to exceed fifty participants (Mason, 2010; Guest et al., 2006). Cresswell (2013) found that sample sizes for qualitative studies ranging from two to more than 300 produce credible research conclusions. Additionally, Ayre, (2022) states that qualitative study samples smaller than fifteen are found to produce sufficient data for analysis when the research instrument facilitates the extraction of specific and meaningful topical insights. The study aims to engage between one and two employees within each of the eight metropolitan municipalities, and a minimum of one active member of the AMEU, using an interview guide prepared prior to the interviews.

3.8 Research instrument

A research instrument is the tool which the researcher will use to conduct their research and collect data for their study (Phellas et al., 2011). The chosen research instrument will be a semi-structured interview, conducted using a combination of closed and open-ended questions prepared beforehand, yet not shared with the respondents until the time of the interview.

A semi-structured interview is characterised by interpersonal communication between a researcher or interviewer and an individual or collective of respondents and carries the advantage of fostering reciprocity between the interviewer and interviewee (Kallio et al., 2016). An interview guide will be compiled, consisting of questions which cover the theme and topics relevant to the study (Kallio et al., 2016). Each respondent will answer the same set of questionnaires, to allow the researcher to obtain information that is reliable and comparable (Kallio et al., 2016).

To encourage the highest quality of responses from the chosen participants, the research instrument will be kept concise, and include an introductory note from the researcher (Phellas et al., 2011). Moreover, a clear interview protocol framework will be followed, which includes the following:

i. Aligning interview questions with research objectives.
ii. Devising a conversation that is investigative.
iii. Obtaining feedback on the questionnaire or interview to ascertain that respondents have responded with understanding; and
iv. Practising the interview or testing the questionnaire (Castillo-Montoya, 2016).

The four steps above will be followed to create an interview guide, accompanied by a concise and professional cover letter, which will inform the invited respondents of the research, its objectives, the manner in which collected data will be stored and used, and of their rights as research participants (Castillo-Montoya, 2016; Kallio et al., 2016).

Additionally, the interviews will be conducted online or in person and all interviews held will be recorded.

3.9 Procedure for data collection

Having identified the population and sample suitable to this research, a list of respondents will be created, which will include the details of the individuals described in Table 4.

The energy and electricity departments of the metropolitan municipalities will be directly communicated with, using telephonic conversation and electronic mail, to introduce the researcher and the current study, and to request the participation of the respondents. Virtual semi-structured interviews will be scheduled, using the virtual meeting platform Microsoft Teams, Zoom Meeting Platform or similar, according to the availability of the respondents. Respondents will be asked to provide their research participation consent in writing, using a standard document to be shared with all respondents. During the interview, respondents will be informed that the conversation will be recorded for research purposes only, and that the audio-visual recording will remain in the possession of the researcher for a period of up to three years. As part of the consent, respondents will be asked to complete the full interview and answer all questions.

The method of communication with respondents will be mainly electronic, as the population and sample are spread throughout numerous geographic locations.

3.10 Data analysis and interpretation

After securing the participation of interview participants and conducting the semi-structured interviews, in-depth analysis and interpretation of the data collected will follow, guided by common principles including transcription of the interviews; thorough evaluation of the data to gain insights; data coding system development; and drawing links between the data collected to formulate prevalent themes or theories to address the research problem (Smith et al., 2011). Data will be analysed using an interpretation of the following five steps, recommended by LeCompte (2000):

i. Arranging the collected data in order – for this study, this step will entail sorting and saving all the recorded interviews in secure computer folders (LeCompte, 2000).

ii. Coding of the data set – this will entail the revisiting of each interview recording, observing, and listening for specific themes, insights, and even emotions which are common to all respondents, and categorising or coding these observations. The coding process will intentionally search for frequency, omission, and declaration. Frequency refers to how often the respondents provide identical answers to a specific question or how often similar challenges are alluded to be respondents (LeCompte, 2000). Omission will be the noting of information which is expected to emerge through the interviews but does not. This property is also called exclusion and may prompt the researcher towards recommendations for future studies (LeCompte, 2000). Declaration will be an important code which emerges as respondents are expected to reveal information specific to their context (LeCompte, 2000) and regarding electricity infrastructure resilience.

iii. Creating sets or taxonomies – the third step is similar to the second, as it is concerned with identifying patterns and links among all the collected data (LeCompte, 2000). For this study, a Microsoft Excel spreadsheet will be used to group the all the responses to a question together.

iv. Creating patterns – the fourth step to be followed in the analysis of the qualitative data will be to draw patterns and relationships between the questions, the responses, and the context of the respondents (LeCompte, 2000).

v. Propose a solution to the research problem – once all the data has been collected, organised, and evaluated for patterns, a solution to the research problem will be proposed (LeCompte, 2000).

Using the above as a guide to understanding and organising the data, information collected through semi-structured interviews with electricity professionals in South African metropolitan municipalities will be analysed and interpreted or explained to formulate a solution towards electricity infrastructure resilience.

3.11 Limitations of the study

Study limitations are practical considerations, constraints or drawbacks of the research, which may affect its validity (Taherdoost, 2016).

The current study of electricity infrastructure resilience is subject to the following limitations:

i. Only eight municipalities will be engaged, and furthermore, only two respondents from each of the metropolitan municipalities will be interviewed. Although the population and sample size are appropriate for the context of the qualitative study, the defined number of participants is relatively small. This calls for the interview guide to be robust and to encourage the sharing of detailed information.

ii. The interviewer will have limited time to engage with the research participants, as interviews will be conducted during a one-time, predetermined appointment. Additional information will be drawn from literature and subsequent engagements with the participants, with their understanding that the research is ongoing.

iii. The study will utilise recent yet historical information to build an understanding of the research objects, namely the current condition or health of electricity infrastructure components. Physical site visits to verify or support the information shared by the participants will not take place.

3.12 Trustworthiness

The trustworthiness of a qualitative study is concerned with its ability to be expanded and applied to a different population in similar contexts (Lincoln et al., 1986). The rigour or soundness of the research must be ensured by conducting the research in such a way that it will be conclusively transferable, credible, dependable, and confirmable. These characteristics are briefly described in the following sub-sections.

i. Transferability

Qualitative data must collect, analyse, and interpret data which can find relevance to different contexts and populations (Klopper, 2008). Meeting these criteria will render the research as transferable.

To ensure the transferability of the study, an identical questionnaire will be administered to the research respondents, and the research context and assumptions will be strictly adhered to. In this manner, findings will be accurately comparable and allow for sound recommendations to be made towards the resilience of electricity infrastructure.

ii. Credibility

It is the responsibility of the researcher to establish confidence in the truth, credibility, or integrity of the findings (Klopper, 2008). Methods of guaranteeing reasonable credibility include data triangulation, which is the use of diverse sources of data, practising peer evaluation or group discussion to cross-check the data (Lincoln et al., 1986), and in cases of the immersive research method, prolonged engagement, which refers to spending sufficient or extended time observing the research subjects (Klopper, 2008). The researcher's selectivity in population, sample, and the questions compiled for the interview guide should intentionally create credibility, rather than subjectivity (Klopper, 2008; LeCompte, 2000).

To ensure credibility, this study will engage individuals who work in a variety of cities and professional roles, and who have an array of different qualifications and experiences within the arena of electricity infrastructure. No participants will be coerced into providing a specific response.

iii. Dependability

To achieve dependability, Lincoln et al. (1986), and Shenton, (2004) advise that the processes followed as the research is conducted should be described in detail, including the methods of data sampling, collection, analysis, and interpretation.

Descriptions of the research context and findings should be thorough to prove the dependability of the study (Shenton, 2004).

To ensure that the research is dependable, consistency will be a core value during the administration of interviews. Information shared by the respondents will be verified against other factual, public, sources of information, with the consent of the research respondents.

iv. Confirmability

Confirmability in qualitative research is the counterpart of the quantitative criterion of objectivity and requires a researcher to be aware of their own biases as they approach the data (Shenton, 2004).

To ensure confirmability, the transcription function the virtual platforms will be utilised, to supplement the audio-visual recording, and notes will be taken by the interviewer throughout the process. The interviews will be formally scheduled through electronic, traceable calendar invitations, and participants will be asked to confirm their availability and participation consent, in electronic, written format. Record-keeping will be the main method of ensuring confirmability.

v. Ethical considerations

Research ethics refers to moral behaviour in the context of research (Wiles, 2012, p. 4). The Singapore Statement on Research Integrity highlights four guiding principles for the conduction of research which involves human involvement, namely honesty, good stewardship, accountability, and fairness or professionalism (Resnik, 2011). Furthermore, the universal principles of ethical research which were embodied in the Belmont Report, include the following:

i. Beneficence and non-maleficence, which refers to the moral obligation to do good to a fellow human being and to avoid doing harm.

ii. Autonomy and respect for individuals.

iii. Justice and non-discrimination; and

iv. Prudence and transparency, on the part of the researcher (National Commission for the Protection of Human Subjects of Biomedical and Behavioural Research, 1979).

The ethical considerations factored into this research will follow the guidelines provided by the Belmont Report and the Singapore Statement. Research respondents will not be made to take part in the study without their free, informed, and written consent.

The identity of the participants will be kept confidential. Their anonymity will be guaranteed due to the interviews not being conducted in group settings, and the identities of the respondents will not be divulged in the presentation and discussion of the findings. The research instrument will be designed in a manner which accommodates a diversity of demographics and backgrounds.

The research will be conducted primarily in South African English, however the interviewees will be allowed to provide responses in their chosen language, provided that the content of the interview guide remains consistent among all the respondents.

Justice will be upheld by selecting research respondents solely based on the research objectives and context.

Formal ethical clearance for the study will be obtained from the ethics committee within the Wits Business School prior to the commencement of data collection.

3.13 Consistency table

To conclude this section, the consistency matrix provided in the previous chapter, (Table 2), is extended in Table 5.

Table 5: Consistency table - research objectives, propositions, data collection and analysis

RO #	Research Objective	Proposition #	Proposition Statement	Data Collection Detail	Data Analysis Method
1	Evaluate electricity infrastructure development and best practice maintenance techniques	1	Electricity infrastructure resilience techniques and policies must be developed to improve maintenance efforts and prevent climate-related vulnerabilities.	Interview questions one through five	Interview and thematic analysis
2	Identify electricity infrastructure failure and consequences	2	The interdependent nature of electricity infrastructure is a major cause of failure, underpinned by extreme weather events caused by climate change, vandalism, and neglect by human beings.	Interview questions six through ten	Interview and thematic analysis
3	Propose a development and maintenance solution to enhance the resilience of electricity infrastructure.	3	Proactive and future-focused design, manufacturing, and maintenance techniques should be deployed, alongside early fault or disaster detection and decentralisation of electricity service delivery infrastructure.	Identify patterns and develop a replicable theory and suggested actions to solve the research problem.	Thematic analysis

Source: Author's adaptation (2025).

CHAPTER 4: FINDINGS AND DISCUSSION

4.1 Introduction

This chapter provides the reflections of the research respondents on the challenges common to electricity infrastructure in metropolitan municipalities across South Africa, and the emerging opportunities to build resilience throughout the municipal electricity service supply chain. The responses from 12 participants with varied experiences within the municipal electricity sector formed the basis of the outcomes described throughout this chapter. The chapter begins with a brief description of the demographic of the research respondents, followed by a discussion of the codes and subsequent themes obtained from the data collected. This section concludes with a summary of the research findings, in view of the reviewed literature and the research objectives outlined in Chapters 1 and 2 of this report.

4.2 Demographic of research respondents

A total of twelve respondents were interviewed, with an equal number of male (M) and female (F) professionals represented. The respondents' roles within the municipal electricity sector ranged between junior field technicians to chief engineers and seasoned departmental heads, with an average 18 years of work experience among them. The Participant (P) representing the AMEU was the most senior respondent in terms of electricity industry experience, while P10 had the least work experience within the focus population of metropolitan municipalities. Virtual interviews with an average duration of thirty-two minutes to one hour were conducted using the Microsoft Teams platform. The demographic profile of the research respondents is summarised in Table 6.

Table 6: Research Respondents' Demographic Summary

Participant ID	Organisation or Municipality Represented	Gender	Role	Years of Experience
P1	City of Ekurhuleni	F	Senior Engineering Technician	18
P2	City of Ekurhuleni	F	Senior Engineering Technician	17
P3	City of Tshwane	M	Functional Head: Electricity Tariffs & Revenue Protection	16
P4	City of Tshwane	F	Director: Energy and Electricity Technical Services	20
P5	City of Tshwane	F	Engineering Technologist: Protection & Test High Voltage	7
P6	City of Johannesburg	M	Project Manager: Metering	20
P7	City of Johannesburg	F	Head of Department	22
P8	eThekwini Metropolitan	M	Chief Engineer	18
P9	eThekwini Metropolitan	F	Chief Engineering Technician - Diagnostics & Maintenance	24
P10	City of Cape Town	M	Engineering Support / Field Technologist	1
P11	Nelson Mandela Bay Metropolitan	M	Deputy Director	20
P12	Association of Municipal Electricity Utilities	M	Strategic Advisory	40

Source: Author’s adaptation (2025)

i. Sample Size Justification.

CHAPTER 3. RESEARCH METHODOLOGY outlined the importance of obtaining sufficient data which yields valuable and trustworthy information during the qualitative research process. While Braun and Clarke (2020) as well as Fossey et al. (2002) argue that no definitive minimum sample size exists consistently in literature, the qualitative data collected must exhibit depth of knowledge, (Malterud et al., 2016) and allow clear themes relevant to the research objectives and propositions to be drawn out during both collection and analysis. Throughout this research, the final purposive sample described in Table 6 had similar experiences within the transmission and distribution levels of municipal electricity supply and were found to produce comprehensive data, relevant to the research objectives of this report. The quality of the data obtained from a relatively small sample was aligned to the qualitative data analysis concept of "information power," which is characterised by strong dialogue quality, narrow study aim and the specificity of the chosen sample (Malterud et al., 2016). This is complementary to the concept of data saturation, which refers to the observed replication of earlier information through the addition of data sources, thus allowing the researcher to end sampling for the study (Morse, 1995).

4.3 Data coding and theme generation

Thematic analysis was utilised to evaluate and sort the research responses into codes and later into recurring code groups, which became the themes extracted from the data. The method of analysis was inductive, (Williams & Moser, 2019), as no themes or categories were created prior to data collection and analysis.

The data recorded in the interview transcripts yielded ten recurring ideas or themes, (Riger & Sigurvinsdottir, 2016), out of 13 categories (codes) which were created by statements or ideas which were prevalent throughout the interview process. Data coding and theme generation was carried out in cognizance of the research objectives stated in Section 1.5 and the research propositions indicated in Table 5.

The codes which occurred most frequently throughout the interview transcripts were the following: vulnerable infrastructure types, common infrastructure challenges, futureproofing, and the awareness of climate change. The codes which occurred least frequently include external risks as well as standards and specifications. All codes are within the context of electricity infrastructure within a metropolitan municipality, and themes are based on the interview guide, which was designed to address the research objectives and propositions.

Table 7: Data themes and associated codes

Research Objective (RO)	Code Group (Theme)	Associated Code/Category	Frequency
1	1. Dedicated Climate Response Funding	1. Budget Allocation	20
		2. Awareness of Climate Change	26
	2. Electricity Industry Service Delivery Guidelines	3. Standards & Specifications	6
	3. Implementation of Maintenance Philosophies	4. Infrastructure Asset Care	13
2	4. Electricity Infrastructure Failures Attributable to Climate	5. Climate-Related Challenges	20
	5. Electricity Infrastructure More Prone to Damage and Failure	**6. Vulnerable Infrastructure Types**	35
	6. Human Behaviour-Linked Electricity Infrastructure Failures	**7. Common infrastructure challenges**	51

Research Objective (RO)	Code Group (Theme)	Associated Code/Category	Frequency
	7. Non-technical Electricity Infrastructure Challenges	8. Administrative Challenges	18
		9. External Risks	2
3	8. Climate Change Adaptation & Mitigation	**10. Future proof**	30
	9. Equip Internal Staff to Use Resilience-Building Technologies	11. Awareness of Climate Change	26
		12. Skills Development	12
	10. Transmission & Distribution Network Design	13. Network configuration	16

Source: Author's adaptation (2025)

4.4 Findings pertaining to proposition 1.

The first research objective was to evaluate electricity infrastructure development and best practice maintenance techniques. The reviewed literature broadly highlighted the importance of implementing various maintenance techniques, to increase electricity network efficiency and to achieve the maximum value of an electrical power system throughout the useful lifecycle of its collective parts (Alvarez-Alvarado et al., 2022). Richard et al. (2000) indicate that power system reliability can be greatly improved through concerted maintenance management efforts, helping utilities such as municipalities to remain competitive in the electricity market. Rioja (2013) further elaborates that the neglect of necessary maintenance to electricity infrastructure and other critical service amenities weakens both the condition of infrastructure and the confidence of customers. Where there is a lack of maintenance philosophy for various elements of the electricity transmission and distribution system, ad-hoc costs to attend to faults and breakdowns are incurred by the municipality, and subsequently passed on to the consumers (Rioja, 2013). This research found that there is a disparity between the theoretical awareness of the former observation, and the current practices of certain metropolitan municipalities' electricity departments, as demonstrated by the sentiments of Participant P11:

"Lack of maintenance is also a huge challenge," Participant 11.

Similarly, P9 made the following remark,

"...there's no maintenance plan," Participant 9.

The data revealed that electricity infrastructure maintenance plans within some metropolitan municipalities in South Africa are either outdated or not yet in existence. It was further observed that where there are challenges which threaten the revenue or financial health of the municipality as a business entity, processes which naturally support infrastructure maintenance practices are undermined, creating a maintenance backlog. These challenges are discussed further in Section 4.5

All municipalities in South Africa form part of the Local Government and are governed by several pieces of legislation. Those most relevant to this study include the Municipal Systems Act 32 of 2000, and the recently amended Electricity Regulation Act 4 of 2006. Research participants revealed that municipalities as electricity service providers are also guided by industry standards such as the National Rationalised Specifications (NRS) 047 and 048, which are compiled in harmony with the overarching electricity and energy industry regulatory body NERSA – the National Energy Regulator of South Africa. These specifications exist to create a sense of uniformity in the manner in which electricity industry role players conduct themselves, in the quest to maintain good quality of electricity supply. Speaking about the need to create and periodically review infrastructure maintenance plans in keeping with the electricity supply industry specifications, P3 stated the following:

"All the departments are required to submit their standard procedures in terms of dealing with each and every eventuality," Participant 3.

A response given by P11 uncovered what may be a shortcoming of the widely accepted specifications:

“NRS 048 and NRS 047 is based on an urban area,” Participant 11

The participants’ remarks above confirm that the South African metropolitan municipalities have guidelines and specifications which support their efforts to deliver reliable electricity supply of superior quality to the customers in their jurisdiction. The comment by P11 however suggests that not all supply areas or customers are identical, and that the existing quality of supply specification may not be adequately considering infrastructure performance challenges of varied geographical locations and even socio-economic situations.

When interview questions linked the matter of infrastructure maintenance back to the core of climate change resilience, participants were found to be well aware of climate change as a major risk to the operation and maintenance of electricity network infrastructure. Seven of the twelve participants responded that electricity transmission and distribution infrastructure are at greater risk of failure and damage due to the present unpredictable element of extreme or abnormal weather patterns attributed to climate change in their region. A visual representation of the terms used by interviewees in this regard is given in Figure 10.

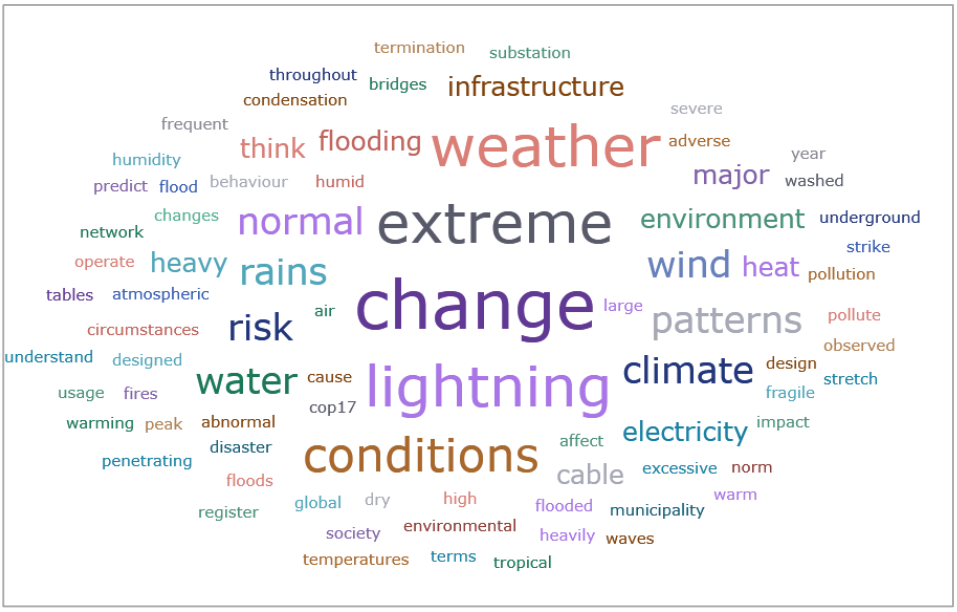

Figure 10: Recorded phrases demonstrating climate change awareness (Author’s adaptation, generated by Atlas.ti, 2025)

Challenges threatening electricity service delivery in South Africa are varied and are not merely technical or environmental (Kanyane, 2014). This is recognised by P3 who made the following remark:

"Under normal circumstances, without climate change, electricity infrastructure is very fragile," Participant 3.

Baker and Phillips (2019) agree that economic and regulatory challenges exist, calling for a holistic approach to building the resilience of the municipal electricity service delivery system. Upon analysis of the data collected throughout this study, climate change was perceived to be a prominent challenge, with the following thoughts from P4 and P9:

"…major risk for the society at large," Participant 4,

"I have observed quite a few changes in terms of our weather patterns," Participant 9.

Electricity infrastructure maintenance, the implementation of industry specifications, and the increased awareness of and indeed preparation for the reality of climate change cannot be discussed at length without addressing the undeniable factor of the financial stability of the municipality and its various departments. It was found that well-meaning electricity departments within metropolitan municipalities are often hamstrung in their efforts to maintain good service delivery and to perform routine maintenance, due to the apparent lack or mismanagement of funds. It was noted by P11 that metropolitan municipalities do have a budget allocated to electricity infrastructure development and maintenance:

"There is a regular maintenance budget," Participant 11.

Simultaneously, P7 elaborated that the trend among South African metropolitan municipalities is the existence of a general disaster fund, in which no specific portion is dedicated to addressing electricity infrastructure failures attributable to climate change or extreme weather conditions:

"There is a disaster funding but not necessarily dedicated to climate change and electricity infrastructure," Participant 7.

The impact of other electricity infrastructure challenges on municipal budgeting or revenue is explored in Section 4.5.

The first proposition statement made in Table 5 was that electricity infrastructure resilience techniques and policies must be developed to improve maintenance efforts and prevent climate-related vulnerabilities. The data collected throughout this study highlighted the importance of moving from awareness of electricity infrastructure maintenance shortcomings, towards planning for enhanced service delivery and infrastructure performance, and finally to the implementation of electricity infrastructure maintenance techniques to build resilience and to curb the prevailing trends which undermine service delivery.

4.5 Findings pertaining to proposition 2.

Four of the ten themes generated from this study were related to the second research objective, which was to identify the causes and consequences of electricity infrastructure failures. Research participants revealed that network sabotage in the form of deliberate infrastructure damage, equipment theft, and illegal electrical connections at the domestic supply level is commonplace throughout the country. The most frequently cited challenges faced by metropolitan municipalities were vandalism, theft, illegal connections, and ageing infrastructure, as seen in Figure 11.

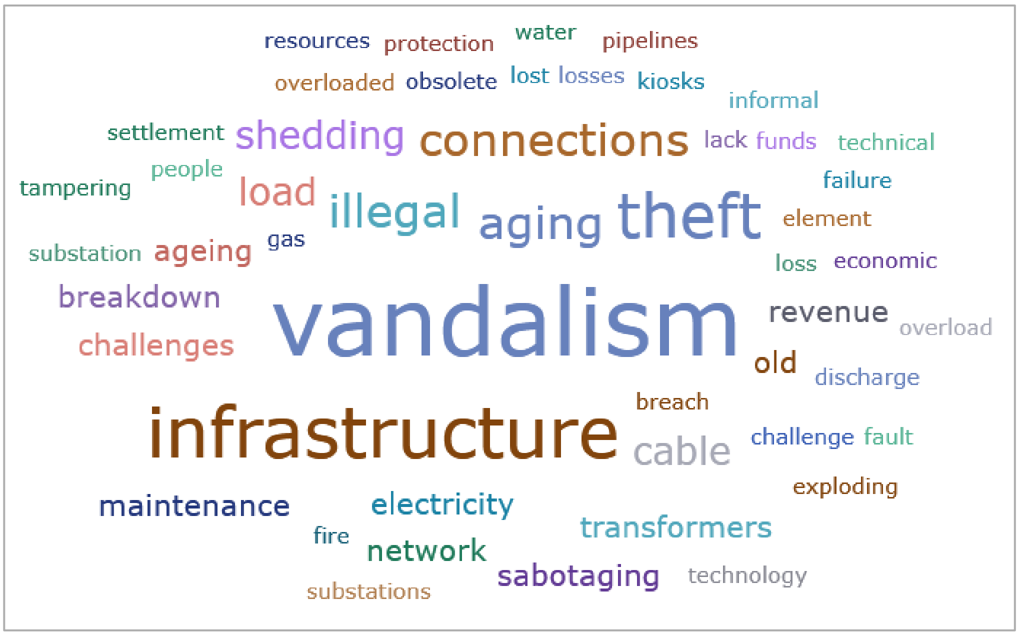

Figure 11: Recorded phrases demonstrating common infrastructure challenges (Author's adaptation, generated by Atlas.ti, 2025)

The South African population increased by 1.33% between July 2023 and July 2024 (Department of Statistics, 2024b). This correlated with increased urbanisation and consequently, an increased demand for electricity supply in urban and peri-urban areas alike (Nguyen, 2023). It is well-known that the country's social and economic development goals call for the maintenance and expansion of critical public services infrastructure such as water, transport, and electricity, (National Planning Commission, 2012), however, the National Treasury's Cities Support Program reported an ongoing trend of underinvestment and inadequate maintenance of these assets across metropolitan municipalities (Department of National Treasury, 2017). The extent of the challenges which stem from this situation is expressed by P4:

"We have challenges of maintenance of infrastructure," and "theft and vandalism," Participant 4.

The prevalence of vandalism and network sabotage within metropolitan municipalities was further revealed through the repeated use of the word "vandalism" throughout the interview transcripts, such as with P1:

"vandalism," Participant 1,

P11:

"element of vandalism," Participant 11,

and P7:

"high level of vandalism," Participant 7.

One of the challenges which were repeatedly cited by the respondents of this study was that of aging or obsolete electricity infrastructure. The International Trade Administration, (2024) noted that an ageing distribution network restricts the country's ability to improve access to electricity. The factor of aged infrastructure contributes to the technical losses recorded on electricity transmission and distribution networks, according to Ali, (2021), and Eberhard et al. (2014) argued that technical and non-technical losses linked to inefficiencies caused by ageing infrastructure and an unbalanced network have been fluctuating adversely since 2012. These realities were corroborated by P3 and P4, who respectively stated:

"…infrastructure is aging," Participant 3, and,

"Our infrastructure is also old and outdated," Participant 4.

P7 further expressed the impact which aging infrastructure has on a populous metropolitan municipality, stating:

"…our losses are very high," Participant 7.

This research went on to find that while electricity distribution networks are highly interdependent in nature, (Liu et al., 2020), there are elements which are more vulnerable to failure, damage, and the compounded impact of both climate-related incidents and human neglect. These elements include underground medium voltage cables of various insulation types, substation buildings and associated components, both gas-insulated and air-insulated switchgear and steel poles used to support both street lighting luminaires and overhead conductors. The following responses to a question regarding vulnerable components of electricity infrastructure networks within the metropolitan municipalities provide evidence:

"…protection parts in the substation," Participant 5,

"…distribution Substations," Participant 9,

"…mostly our overhead lines," Participant 10, and even

"…our batteries in the substation are always being stolen," Participant 4.

It is evident that the poor performance of electricity distribution systems in many of the metropolitan municipalities begins at the upstream level of distribution substations, which are often situated in urban areas, as shown in Figure 12.

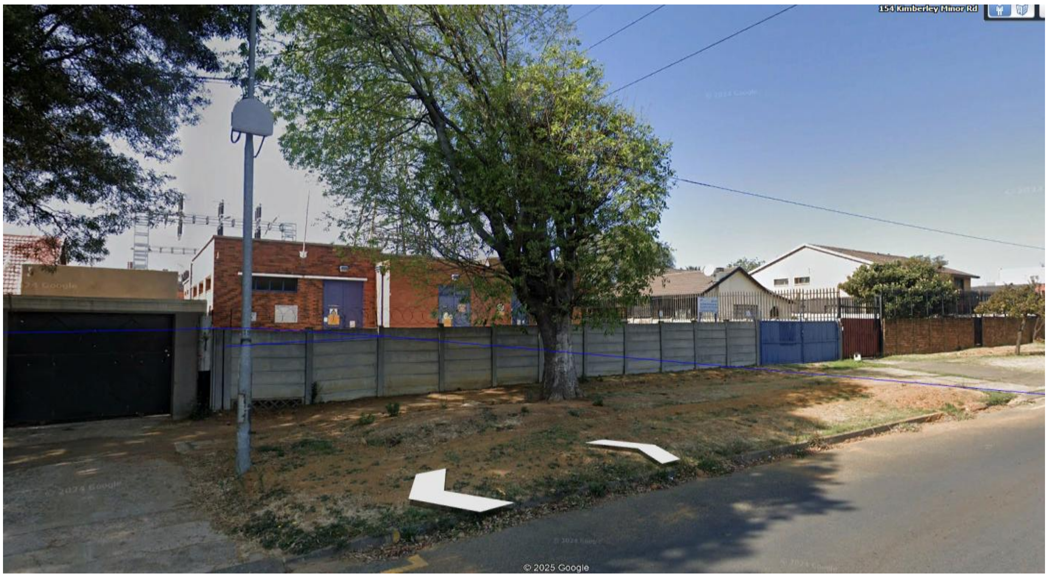

Figure 12: Robertsham Substation in the City of Johannesburg (Google Earth Pro, 2025).

Figure 12 demonstrates how the geographic location of various elements of the distribution network may contribute to their vulnerability to theft, vandalism, or other types of damages and failures. In a study which assessed 132kV electricity distribution substations in South Africa, Rathebe and Mbazima, (2023) made similar findings, indicating that the increased visibility of high-voltage and medium-voltage equipment in some urban centres contributes to greater levels of cable theft and vandalism.

Building on the research participants' demonstrated awareness of climate change as a major risk to the reliable operation and maintenance of electricity infrastructure, the following response was garnered when climate-related impacts on the latter were investigated:

"We had two floods last year," Participant 11.

Furthermore, P8 stated:

"I have seen the impact of heavy rains and flooding, where even substations are left flooded and that leads to prolonged, unplanned power outages," Participant 8.

This study found that many metropolitan municipalities in South Africa have experienced repeated episodes of disruptive, unexpected weather events, which interrupt electricity service delivery, in recent times. One such example is that of the proliferating wildfires in the Western Cape (Imray, 2023). Corresponding with this, P10 commented on their experience with harsh climate conditions as follows:

"We do get our distribution infrastructure burned by wildfires, I must say, because of extreme heat," Participant 10.

Unusually high atmospheric temperatures do not immediately compromise electricity infrastructure, as high voltage to low voltage underground cables and overhead conductors are almost universally manufactured to operate optimally at temperatures reaching between 50°C and 70°C, (Eland Cables, 2025), with an allowance of up to 90°C for certain types of cable insulation and temporary overload conditions. Rather, it is the accelerated deterioration of insulating materials, which positions extreme heat due to climate change as a threat to electricity infrastructure performance (Kim et al., 2025). The proven risk of substation damage and consequent power supply disruptions caused by extreme heat in a metropolitan municipality is illustrated by Figure 13 below:

Figure 13: An example of electricity distribution infrastructure combusting due to extreme temperatures in the North of Durban, KwaZulu Natal (Habbib, 2025).

Figure 13 demonstrates the impact of a recent heat wave on electricity distribution infrastructure within a metropolitan municipality in South Africa.

This study also found that the impact of unprecedented lightning strikes coupled with the continuous theft of lightning protection equipment and batteries which power communication equipment places substations in metropolitan municipalities at even greater risk of poor performance, and costly damage. This is illustrated in Figure 14.

Figure 14: Substation switchgear after an explosion in the City of Johannesburg (Luvhengo, 2023).

Remarks from P2 elaborated on the reality of the above illustrations:

"Nowadays when heat is too extreme…it's even difficult for our own electricians to go on site if it's too hot," Participant 2.

Additionally, P6 shared a similar experience:

"Sometimes you just have lightning that actually hits the transformer," Participant 6.

The findings which resulted in the four themes, labelled number 4 to number 7 in Table 7 supported the second proposition of this study, which was that electricity distribution networks consist of many components which are linked and dependent upon one another, and as such, climate change-related weather events, network vandalism, sabotage and neglect create a combined negative impact on electricity service delivery in metropolitan municipalities. These findings emphasise the need for immediate action from electricity industry and national leadership to achieve the goals determined in the National Development Plan 2030.

4.6 Findings pertaining to proposition 3.

Having reviewed the literature to obtain a background of the electricity distribution industry in South Africa and a broad overview of climate change and its impact on electricity service infrastructure and delivery, this section will present the findings in line with the third objective of this research: to propose a development and maintenance solution to enhance the resilience of electricity transmission and distribution infrastructure.

Infrastructure resilience is characterised by the design, construction, and management of various systems and structures in such a way that they exhibit longevity – efficiency and reliability – under both normal and adverse circumstances, with the ability to absorb and rapidly recover from system shocks (Janta et al., 2024). Embedded in this definition are the infrastructure's shock-absorption capabilities and swift recovery time. Throughout this study the term infrastructure has been used to refer to the various components and equipment associated with the transmission and distribution of electricity by metropolitan municipalities, although literature, (Rehak et al., 2018, and Wall, 2021) explains that water, transport, telecommunications, and other types of energy networks form part of the infrastructure that builds a thriving economy and society. Fu et al. (2018) indicate that electricity utilities in developed and developing nations are under pressure to meet growing energy and electricity demands to support economic growth while striving to reduce the carbon footprint of the same. This study found that electricity infrastructure professionals are aware of the need to build the resilience of the networks by adopting a long-term approach to planning, operations, and maintenance. Respondents stressed the importance of having concrete and well-managed finances available to implement solutions, with P4 saying:

"…measures that they need to put in place is the budget," Participant 4.

Respondents gave suggestions to curb both technical and non-technical losses, with P3 stating:

"The municipality can improve in terms of the quality or the robustness of the infrastructure that the municipalities develop;
ensuring that everything is developed
according to high standards," Participant 3.

The suggestion given by P3 supports the observation made by Gallegos et al. (2024), that electricity service quality and the management and operation of existing electricity infrastructure networks are greatly enhanced when modern technologies such as advanced distribution management systems are embraced and leveraged. While modernisation of the electricity distribution network would move the country towards better infrastructure performance and management, the associated financial investment may lead to much higher electricity tariffs for customers, especially at the domestic level (National Planning Commission, 2012). With the goal of resilience and sustainability of the electricity distribution industry in view, the National Development Plan 2030 goes on to state that tariff increases can be offset by the development and implementation of industry policies which foster a more competitive electricity distribution market and promote investment in new infrastructure altogether (National Planning Commission, 2012).

Alongside the modernisation of the electricity distribution infrastructure to build network resilience is the need for skilled and knowledgeable staff to operate and maintain it. P8 remarked that metropolitan municipalities should:

"…invest in the skills required to run with software that can identify the health status of an asset and what type of maintenance or attention it requires before it fails," Participant 8.

This sentiment further supports the observation made by P6, when answering a question regarding resilience techniques and solutions which metropolitan municipalities could consider in the immediate future:

"…because you are having new equipment that is outsourced…then you depend on the external sources," Participant 6.

This study found that electricity infrastructure climate change resilience cannot be achieved solely through technological advancement, but capacity building initiatives should be incorporated to allow for professionals across the municipal electricity value chain to remain effective in their work. P2 added that metropolitan municipalities should:

"…motivate people to learn more," Participant 2.

While this report does not aim to investigate the root cause of the apparent skills deficits in some metropolitan municipalities, the study has found that electricity infrastructure resilience requires an investment in both network modernisation and resource capacity building.

In addition, this study found that innovative and proactive changes in electricity network configuration would greatly contribute to infrastructure resilience. Panteli et al. (2015) argue that while the term resilience has various definitions for different industries, in electricity, it encompasses an element of network redundancy. Various electricity distribution network typologies exist however, the ring feed or ring main distribution system is favoured because it allows for redundancy and power supply continuity in the event that a distribution feeder should fail for any reason (Bhusal et al., 2020). Notably, the characteristic of redundancy, which refers to the distribution system's ability to maintain power supply to a large group of consumers while recovering from a fault in the supply network, is also named a measure of system resilience by Bie et al. (2017). P11 responded in support of this concept, saying that metropolitan municipalities can build resilience by:

"…design[-ing] a network that is firm," Participant 11.

In this context, the word "firm" speaks of the electrical distribution's ability to continue supplying all its customers even when one transformer or branch of a distribution circuit in a ring feed system is temporarily compromised. This research found that one way to enhance electricity infrastructure resilience is to ensure a reasonable level of redundancy in the distribution network. Thus, even unexpected system faults and failures caused by climate-related events can be more easily remedied.

The final three themes extracted from the data were associated with the final proposition made in Table 5 – that proactive, future-focused design, manufacturing and maintenance techniques should be deployed, alongside early fault or disaster detection, as well as the decentralisation of electricity service delivery infrastructure. This research did not delve into the latter discussion of infrastructure decentralisation however, it is notable that the geographical arrangement of electricity networks has an impact on the resilience thereof (Fu et al., 2018).

4.7 Summary of the findings

This research study had three objectives, and the interview guide used as the data collection tool was designed to investigate how electricity infrastructure in metropolitan municipalities may be made more resilient, particularly against climate change. It was found that electricity infrastructure at the metropolitan municipality level faces several challenges – some anthropogenic, some natural – and that the compound effect of both calls for immediate action to be taken, to maintain the reliability and sustainability of the electricity distribution industry. The research participants revealed that vandalism, illegal connections or electricity theft, network tampering, and sabotage are among the persistent challenges faced by the metropolitan municipality electricity distribution industry throughout the country. Furthermore, the impact of the aforementioned issues was found to extend into administrative challenges in the form of compromised revenue collection, constrained maintenance budgets, and sparsely allocated disaster response funding. Additionally, this research revealed that the impact of extreme or harsh weather conditions ascribed to climate change is a felt reality within the electricity distribution industry, as respondents cited their experiences mainly with flooding, spontaneous fires, and lightning strikes causing significant damage to electricity distribution infrastructure, and subsequently prolonged power supply interruptions in their region. Towards resilience building, this study found that there is a need to modernise electricity infrastructure and upskill operators and maintenance teams to harness its full value. The need for climate change action to progress from planning to implementation was also reflected in the findings of this study.

4.8 Comparison of literature review and own findings

This section provides a comparison of the propositions following the literature review and the outcomes of the study in Table 8. The literature review provided theoretical responses to the research objective, while the study provided more practical responses to the subject of electricity infrastructure climate change resilience, in the context of the metropolitan municipalities in South Africa.

Table 8: Comparison of literature review with current study findings

RO #	**Research objective**	**Prop#**	**Proposition –** (Literature review response to RO)	**Findings from current study**
1	Evaluate electricity infrastructure development and best practice maintenance techniques in developing countries.	1	Electricity infrastructure resilience techniques and policies must be developed to improve maintenance efforts and prevent climate-related vulnerabilities.	Electricity distribution infrastructure maintenance efforts need to be strengthened to facilitate enhanced electricity service delivery. This requires significant financial investment as metropolitan municipalities face maintenance backlogs exacerbated by insufficient maintenance planning, and a lack of dedicated climate disaster response funding.
2	Identify the common causes of electricity infrastructure failure both locally and globally.	2	The interdependent nature of electricity infrastructure is a major cause of failure, underpinned by extreme weather events caused	Ageing electricity infrastructure, vandalism, illegal connections, and theft are the largest causes of infrastructure failure across

RO #	Research objective	Prop#	Proposition – (Literature review response to RO)	Findings from current study
			by climate change, vandalism, and neglect by human beings	metropolitan municipalities. The impact of extreme weather conditions such as heat waves, floods, and lightning strikes compound the issue, resulting in a greater need for financial investment to resolve the challenges and maintain electricity access for customers.
3	Propose a development and maintenance solution to enhance the resilience of electricity infrastructure in the South African context	3	Proactive and future-focused design, manufacturing, and maintenance techniques should be deployed, alongside early fault or disaster detection and decentralisation of electricity service delivery infrastructure	Modern technology coupled with capacity-building efforts are required, as well as network strengthening techniques such as redundancy and undergrounding of existing infrastructure, to build resilience. Robust plans and budgets should be put into place to allow for proactive response to climate change-related electricity infrastructure failures.

Source: Author's adaptation (2025).

4.9 Conclusion

Throughout this chapter, an inductive thematic analysis was followed, to present the findings of the qualitative study undertaken to investigate electricity infrastructure climate change resilience techniques in the metropolitan municipalities of South Africa. The practical insights gained from research participants were outlined given the research objectives and propositions and have contributed to existing knowledge and discourse on the electricity distribution industry and climate change risk in the country.

CHAPTER 5: CONCLUSIONS

5.1 Introduction

Conclusions regarding the current study and its findings in light of **the reviewed literature** are provided in this chapter, including a final comparison between the literature-based research propositions and the conclusions drawn from the current study, in Table 9. The researcher's recommendations and suggestions for further research are narrated in **Chapter 6**.

5.2 Conclusions regarding research objective 1

The first objective of this research placed an emphasis on electricity infrastructure development and maintenance. Throughout the study it was discovered that there are various factors which affect the type, frequency, and effectiveness of electricity distribution infrastructure maintenance in the metropolitan municipality setting. Such factors include the major role which insufficient income or loss of revenue due to unmetered electricity connections and how this affects the basic level of resources which should be channelled towards routine and preventative maintenance of infrastructure. Most metropolitan municipalities were formed 80 to 100 years ago, which should make the maintenance or replacement of ageing and even obsolete distribution infrastructure a priority. The study also revealed that the growing intensity of unusual environmental conditions ascribed to climate change further compromises the existing electricity infrastructure as maintenance and refurbishment intervals are becoming smaller. Important components such as underground cables, overhead conductors, and lightning protection devices face greater exposure to natural elements and are thus the more vulnerable parts of the electricity distribution network. The spatial configuration of distribution networks and the decentralisation of supply networks are challenges worth investigating, although the primary challenges are those which have been mentioned.

5.3 Conclusions regarding research objective 2

The second objective of this research was to identify the causes and consequences of electricity infrastructure failures. Factors of human neglect or infrastructure mismanagement were highlighted throughout the data collection and analysis process, which brought the understanding that electricity infrastructure challenges are varied in nature, and the experience of customers is usually a result of compounding challenges. The literature reviewed in this study stressed the negative impact which extreme weather conditions have on electricity distribution infrastructure, and the data which was collected confirmed the reality thereof. A major finding of the study was that electricity infrastructure fails at a planning or management level before it fails technically. Similar to what emerged upon exploring the first objective of this research, it was found that equipment theft and failure which lead to weaker service delivery, are worsened by the insufficiency of funds which should support infrastructure maintenance and even infrastructure security. Additionally, where metropolitan municipalities are unable to charge cost-reflective electricity tariffs to their customers or to collect sufficient revenue to sustain them, it results in a shortage of capable operations and maintenance resources.

5.4 Conclusions regarding research objective 3

The third research objective sharpened the focus of the research on to electricity infrastructure climate change resilience. Having established the reality of climate change in South Africa and the research participants' awareness thereof, the study aimed to generate resilience techniques to contribute to ongoing research. Through the findings of the current study, possible solutions to the challenges narrated by the second research objective and proposition, were produced. Before the adoption of modern technologies or the implementation of climate response plans can proceed effectively, metropolitan municipalities require accurate inventories or asset registers, to ascertain the true condition of the electricity distribution infrastructure in their ambit. Thereafter, the capital investment required to strengthen the network should be determined. Importantly, this research concluded that electricity infrastructure in the metropolitan municipalities needs to become smarter, to detect technical and climate-related faults sooner, and to execute maintenance routines which are unique to each element of the distribution network.

This research concludes that the existing integrated development plans, energy reports, and electricity transmission and distribution master plans of various metropolitan municipalities which exist in the public domain should be revised to include futureproof solutions, and progress from planning to implementation, to allow South African metropolitan municipalities to become more resilient against climate change.

5.5 Consistency table

Table 9: Consistency table highlighting key differences between research propositions and study findings.

RO #	Research Objective	Literature-based Proposition	Conclusion or answer from current study	Key differences between findings and initial propositions
1	Evaluate electricity infrastructure development and best practice maintenance techniques in developing countries.	Electricity infrastructure resilience techniques and policies must be developed to improve maintenance efforts and prevent climate-related vulnerabilities.	Climate change resilience of electricity distribution infrastructure in metropolitan municipalities is dependent upon several factors, with aging infrastructure, insufficient revenue, and poor data management in the form of condition monitoring being the most critical. Electricity infrastructure in metropolitan municipalities is not underperforming for a lack of technical expertise, but rather the joint impact of network vandalism, technical and non-	The initial proposition of this research hinged upon the need to develop electricity infrastructure maintenance practices to build resilience, particularly against climate change. What the study found suggests that maintenance is not an isolated challenge, and neither is the threat of climate change. Instead, the gaps which exist in the management of electricity distribution infrastructure and electricity delivery at

RO #	Research Objective	Literature-based Proposition	Conclusion or answer from current study	Key differences between findings and initial propositions
2			technical losses, and unpredictable weather conditions undermine the operations and maintenance practices which are in place.	the municipal level are connected to other factors such as planning, income or revenue collection and the availability of technical and administrative expertise within the municipality. Resilience is built from within and must be forward-looking.
2	Identify the common causes of electricity infrastructure failure both locally and globally.	The interdependent nature of electricity infrastructure is a major cause of failure, underpinned by extreme weather events caused by climate change, vandalism, and neglect by human beings	Ageing electricity infrastructure, vandalism, illegal connections, and theft are the largest causes of infrastructure failure across metropolitan municipalities. The impact of extreme weather conditions such as heat waves, floods, and lightning strikes compound the issue, resulting in a greater need for financial investment to resolve the	Different types of environmental conditions caused by climate change and the danger they pose for electricity infrastructure were highlighted throughout the study, alongside other common types of network failures which are inherent to power distribution systems. This research considered the interdependent nature of power

RO #	Research Objective	Literature-based Proposition	Conclusion or answer from current study	Key differences between findings and initial propositions
			challenges and maintain electricity access for customers.	distribution systems as a key cause of electricity infrastructure vulnerability. The study then found that the technical configuration of electricity distribution networks in metropolitan municipalities is on par with industry standards, and that the main things which weaken the system are rather poor asset management, infrastructure neglect, and a lack of financial resources and in-house skills to keep up good maintenance practices. The study outcomes shed greater light on the role of financial investment and stability, in the efforts to build

RO #	Research Objective	Literature-based Proposition	Conclusion or answer from current study	Key differences between findings and initial propositions
				electricity infrastructure resilience.
3	Propose a development and maintenance solution to enhance the resilience of electricity infrastructure in the South African context	Proactive and future-focused design, manufacturing, and maintenance techniques should be deployed, alongside early fault or disaster detection and decentralisation of electricity service delivery infrastructure	Modern technology coupled with capacity building efforts are required, as well as network strengthening techniques such as redundancy and undergrounding of existing infrastructure, to build resilience. Robust plans and budgets should be put into place to allow for proactive response to climate change related electricity infrastructure failures.	As it pertains to the final research proposition, the key difference between the literature and the findings, was the need for resilience building techniques to be holistic, proactive, and future-focused, rather than merely theoretical, and responding to past or prevailing trends in the changing climate and the performance of electricity infrastructure in metropolitan municipalities. The objective of the research was to

Source: Author's adaptation (2025)

RO #	Research Objective	Literature-based Proposition	Conclusion or answer from current study	Key differences between findings and initial propositions
				propose possible techniques for building the resilience of electricity against climate change. It was consistently found that there needs to be a thorough condition assessment, an allocation of a budget dedicated to responding to climate change impacts on electricity infrastructure specifically, and the gradual adoption of modern technologies to enhance the performance of electricity distribution infrastructure in metropolitan municipalities.

Source: Author's adaptation (2025)

5.6 Proposed techniques for electricity infrastructure climate change impact resilience

Having considered the existing literature and the findings of the study, this section will provide the proposed interventions to enhance the resilience of electricity infrastructure against climate change.

i. Management of existing infrastructure

The equipment and components that encompass the electricity transmission and distribution network require regular and focused maintenance throughout their useful life cycle. To maximise the efficiency and useful life of various elements of the network, metropolitan municipalities should embark on establishing asset registers that are current and accurate, where detailed condition assessments are recorded periodically. This will assist with eradicating obsolete materials from the municipality's network and minimise electricity supply disruptions caused by aging infrastructure. Additionally, keeping an inventory of the materials that are used throughout their supply area will allow the municipality to be wiser when procuring spare materials such as underground cables, steel or wooden poles, street light luminaires, medium and low voltage circuit breakers, and other protection components, as the inventory or asset register will be a true reflection of what is installed, levels of depreciation, and which elements are due not only for replacement but for technological upgrades. Modernising critical components such as medium voltage circuit breakers, circuit isolators, protection relays, and Supervisory Control And Data Acquisition (SCADA) systems for substations may require a significant capital investment, however, it may be more economically feasible when it is conducted gradually or in a phased approach. Intelligent fault detection and condition assessment technology should be explored to enhance electricity infrastructure management. Electricity infrastructure is designed for long-term use, and financial investment strategies should be applied with this in mind. The gist of this proposal is that improved asset management leads to improved electricity infrastructure performance, and in turn, greater resilience against unexpected environmental or technical conditions.

ii. Prioritisation and allocation of electricity infrastructure maintenance budget

This study found that the quality and reliability of municipal electricity transmission and distribution infrastructure is deteriorating largely due to the inadequacy of financial resources required to carry out the necessary maintenance. In addition to the establishment of asset registers and condition assessment reports, metropolitan municipalities should prioritise the allocation of a sufficient budget dedicated to the maintenance of electricity infrastructure. It is important for an electricity infrastructure maintenance budget to be established, such that various types of maintenance may be prioritised and executed with urgency throughout the metropolitan municipality. When an adequate budget is available, metropolitan municipalities will be better able to maximise the useful life of the transmission and distribution network equipment, thereby increasing the electricity infrastructure resilience.

iii. Accelerated implementation of existing climate action plans and investment into climate impact early warning systems

To enhance the resilience of electricity infrastructure against climate change, it is important for the existing climate action plans to progress from planning or publication to implementation. Where a climate change adaptation and mitigation strategy has been compiled and approved, a metropolitan municipality should endeavour to execute those parts of the strategy which are concerned with electricity infrastructure procurement, protection, and performance. This process should include the raising or allocation of funds as well as community engagement in the form of information campaigns. This way the complete value chain of electricity distribution is involved in the resilience-building efforts. Moreover, trustworthy progress-tracking mechanisms should be put in place at various levels of public service leadership to encourage the execution of climate change action plans. In addition, dedicated investments towards early warning systems for climate change impact are required, to ensure that the electricity infrastructure within metropolitan municipalities is responsive to climate risk management and thus more resilient. The existing early warning system efforts in South Africa are managed by the SAWS, however, there is an opportunity for metropolitan municipalities to proactively invest and participate in strengthening the early warning system and enhancing the localised communication of critical information prior to the occurrence of hazardous climate conditions. An investment into climate impact early warning systems at the metropolitan municipal level would enhance the resilience of electricity infrastructure while preserving the lives of citizens and minimising the climate disaster impact.

iv. Future electricity infrastructure development

New electrification projects within the municipality's area of supply should be designed with greater consideration of environmental and climate conditions. The standard environmental assessments that precede electricity infrastructure construction projects should be expanded to understand both the prevailing climate trends and the anticipated or expected conditions relevant to the area. Material procurement and manufacturing processes should advance to include the use of materials with characteristics such as fire-retarding, heat-resistance, waterproofing, moisture sealing, and intelligent security mechanisms. Original Equipment Manufacturers (OEMs) and component suppliers adhere to national electricity industry standards and the specifications of supply authorities. Climate change resilience should be included when these guidelines are reviewed.

Final recommendations for electricity infrastructure climate change resilience techniques are outlined in the closing chapter.

CHAPTER 6: RECOMMENDATIONS

6.1 Recommendations

The success of the electricity distribution industry in South Africa is a matter of great concern for the customer, the technical staff who plan, operate, and maintain metropolitan municipality electricity networks, and the various arms of local government and national leadership who are the joint custodians of the electricity distribution industry. In this section, recommendations are given to stakeholders of the electricity distribution industry based on the findings of this study.

i. Metropolitan municipality management teams

It has been revealed throughout this study that climate change is a major risk factor to electricity infrastructure performance, service delivery, and the wellbeing of both customers and the assets which serve them. Recurring issues such as poor financial health, budgetary constraints, limited skilled resources, poor asset management practices, and corruption have become the unintended by-products of population growth and the growing demand for electricity access in metropolitan municipalities and their surrounding areas. This study recommends that metropolitan municipalities take inventory of the electricity distribution network and its wellbeing, identify the areas which need attention, as outlined in this report, as well as the financial investment required to resolve recurring challenges, and endeavour to progress from planning of solutions to the determined implementation thereof.

A further recommendation for metropolitan municipalities is to establish an effective manner of including communities in their endeavours to take better care of electricity infrastructure and raise climate change awareness. Many of the infrastructure challenges ascribed to human beings are rooted in customer behaviour. Metropolitan municipalities should embark on educating communities about the infrastructure which serves them, to foster a sense of ownership and responsibility, rather than neglect or entitlement.

ii. National and local government stakeholders who play a role in the electricity distribution industry.

Building on the recommendation made in i this study concludes with a call for greater collaboration among the stakeholders of the electricity distribution industry of South Africa, specifically, between metropolitan municipalities and the various branches of local and national government which are concerned with electricity, infrastructure, service delivery, and climate change.

This recommendation is put forth with an appreciation of the existence of various bodies within the government of the country, whose aim is to improve electricity distribution among other public services. As an example, the National Treasury's Cities Support Program exists to help metropolitan municipalities reduce poverty and become more sustainable, with 'Infrastructure Planning and Climate Responsiveness' listed among their priorities. This sub-department within the National Treasury has published numerous discussion papers and working documents to address social, economic, and environmental challenges in the metropolises of the country, including climate resilience and sustainability plans and projects. The Municipal Infrastructure Support Agency, which falls under the Department of Cooperative Governance is another entity which exists specifically to support the effective planning, operation, and maintenance of municipal infrastructure (which includes electricity transmission and distribution). This sub-department has declared the importance of holistic intervention in the quest to make all levels of municipality more resilient in terms of financial wellbeing, governance, and infrastructure procurement. Taking these two examples into consideration, it is recommended that greater collaboration be undertaken to maximise the necessary efforts of such organisations, to enhance the resilience of metropolitan municipality electricity infrastructure, both technical and climate related.

6.2 Suggestions for further research

To conclude this study, suggestions for further research are shared in this section.

i. Redundancy

Electricity distribution networks are designed according to the universal principles of safety, reliability, and efficiency. Throughout this research, the question of network firmness arose as a resilience-building technique. A study of electricity distribution network redundancy as a method of building network resilience would be a worthwhile exercise, as this study found that the universal concept of “N-1,” which is employed to maintain power system reliability must be adjusted to suit the context of an electricity distribution network.

ii. Power supply and power service standards and specifications

This study revealed that the electricity transmission and distribution industry in South Africa subscribes to different types of guidelines to maintain good service delivery and to protect the wellbeing of infrastructure, such as the National Rationalised Specifications. This specification consists of several parts which are periodically reviewed, such as number 047, which deals with electricity service quality, and number 048, which is mainly concerned the with quality of supply, load reduction practices and system restoration after a fault. Further research may be conducted to determine the suitability of the specifications for the rural, informal, or peri-urban contexts, as these types of geographical locations have an impact on electricity network configuration and stability. Many electrical standards were compiled for a highly industrialised context. Simultaneously, many customers who are more profoundly impacted by the slightest interruption to electricity supply, are not found in industrialised or urban areas. In the South African context, it is worth exploring the unique circumstances of rural, informal, and peri-urban settings, to determine how best they can be served. Such studies may consider investigating the different energy needs of geographical locations with a higher concentration of elderly citizens, or regions which are both remote and more exposed to climate hazards. Developing electricity transmission and distribution standards and specifications unique to these contexts may further contribute to resilience-building techniques.

iii. From planning to implementation

There is a global trend of governmental departments working independently to one another or in silos, despite having shared goals and mandates to achieve. There is a need to explore mechanisms which would foster effective collaboration and thereby accelerate the successful implementation of strategic plans such as a National Development Plan 2030 or a municipality-specific Integrated Development Plan.

Expanding on the above may contribute greater knowledge in the area of electricity infrastructure climate change resilience in various geographical contexts. Finally, there is a need to further investigate how South African metropolitan municipalities can learn from each other since various municipalities are exposed to varying climate change risks.

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APPENDICES

APPENDIX (A): Participant Information Sheet

Participant Information Sheet (PIS)

Dear Sir / Madam

My name is Busisiwe Matshonyonge, and I am a Master student in the Master of Management in Energy Leadership programme, under the Wits Business School, at the University of the Witwatersrand, Johannesburg. My supervisor is Dr Stanley Semelane. I am conducting a research study about energy infrastructure resilience. The study title is Energy Infrastructure Climate Change Resilience Techniques – A Case Study of the South African Metro Municipalities.

I am inviting you to take part in a virtual interview. If you decide to take part, your participation in this research study will last between 30 – 45 minutes. The interview will take place through Microsoft Teams or similar platform, at a time which will be agreed between the researcher and the participant.

With your permission, I would like to keep an audio and video recording of the interview, by keeping the recording and transcription of the virtual interview. This data will be stored in a password-secured personal computer for a maximum of 2 years and will be deleted once the research study is completed and submitted to the University for examination. Only the researcher will have access to the data.

During the research activity, I will need to ask for some personal information about you, including the name of your organisation and your role therein.

The interview will be confidential and research participants will be anonymous to one another. When I share the results of the research study, I will not include your name or anything else that could personally identify you.

Your decision to take part in this research should be completely voluntary. You do not have to take part. You can stop being in the study at any time. You do not have to answer any questions if you do not want to. You will not get any direct benefits if you choose to join the research study. You will not lose any services, benefits or rights you would normally have if you decide not to join. Taking part in the research study will not cost you anything. You will not be paid for being in this research study.

The risks for this research study are no more than what happens in everyday life OR some of the questions asked may make you feel sad or upset.

This research study will be written up as an academic research report. The report may or may not be published in relevant academic and industry journals. If you would like to receive a summary of this report, I will be happy to send it to you.

If you have any questions during or afterwards about this research study, feel free to contact me or my supervisor on the details listed below. If you have any concerns or complaints about the ethical procedures of this research study, you are welcome to contact the University Human Research Ethics Committee (Non-Medical), telephone +27(0) 11 717 1408, email hrecnon-medical@wits.ac.za.

Yours sincerely,

Researcher: Tlanale
Busisiwe Matshonyonge, 706958@students.wits.ac.za

Supervisor:
Dr. Stanley Semelane, semelanes@gmail.com.

APPENDIX (B): Participant Consent Form

Wits Business School

Participant Consent Form

Title of project: Energy Infrastructure Climate Change Impact Resilience Techniques – A Case Study of the South African Metropolitan Municipalities

Name of researcher: Busisiwe Matshonyonge (née Manabe)

I, ……………………………………….., agree to participate in this research project.

I agree to the following:

(Please circle the relevant options below)

The research study was explained to me. I understand what this study is about.	YES	NO
I understand that I can volunteer to take part in the study.	YES	NO
I agree that the interview may be audio and video recorded.	YES	NO
I agree that direct quotations from my interview may be used by the researcher in their research report.	YES	NO
I agree that my participation will remain anonymous (my name or other identifying data will not be used by the researcher in their research report).	YES	NO

Participant:

…………………………………… (Signature)
…………………………………… (Name of participant)
…………………………………… (Date)

Researcher:

I agree that the participant has given clear and voluntary consent to take part in the study.
…………………………………… (Signature)
…………………………………… (Name of researcher/person seeking consent)
…………………………………… (Date)

APPENDIX (C): Research Instrument – Interview Guide

Research Instrument – Interview Guide

1. Introduction
   - 1.1.1. Formal introduction by researcher.
   - 1.1.2. Participant introduction, including name, age, gender, organisation, and role.
   - 1.1.3. Researcher to thank participant for their time and request permission to record the session, as per participant information sheet (PIS).
   - 1.1.4. Ask participant whether there is anything they would like to ask or confirm before the interview commences.

2. Background
   - 2.1.1. Describe your role and duties within the organisation.
   - 2.1.2. How long have you been working with electricity infrastructure?
   - 2.1.3. How long have you been working for this organisation?

3. Electricity Infrastructure
   - 3.1. Describe the elements of electricity transmission and distribution infrastructure that you work with.
   - 3.2. Describe the work which you do related to the electricity infrastructure mentioned in the previous question.
   - 3.3. What electricity infrastructure challenges is the metropolitan municipality facing attributed to vandalism, theft, illegal connections, lack of frequent maintenance?

4. What is your understanding of the phrase "climate change disaster?"
   - 4.1. Do you perceive climate change as one of the forthcoming major risks for the municipal electricity infrastructure?
   - 4.2. Have you encountered electricity infrastructure failures related to climate change (e.g. extreme heat, flooding, drought, lightning strikes, wildfires etc.)?
   - 4.3. Does the municipality have a budget dedicated to climate change mitigation and adaptation measures for electricity infrastructure?

4.4. What measures do you believe the municipality *should* have in place to protect electricity infrastructure against climate change risk?
4.5. How have municipal electricity infrastructure failures affected the municipal revenue?

There is a lack of electricity infrastructure maintenance in some metropolitan municipalities.

5. Resilience
   5.1. How can routine maintenance be improved to ensure optimal performance of electricity assets?

Climate change poses an additional risk to electricity infrastructure.

   5.2. How can electricity infrastructure be resilient to climate change impacts such as floods, drought, lightning strikes, wildfire risk etc?
   5.3. Describe the typical weather of the region in which you conduct your work?
   5.4. Have you observed any drastic changes in the weather patterns of the region?
   5.5. In your opinion and / or experience, which elements or components of electricity infrastructure are the most vulnerable to failure or damage?

6. If the municipality were to encounter faults and failures disruptions related to climate change, how long do you think it will take to restore electricity infrastructure?
7. What is your understanding of the term "resilience" in the context of electricity infrastructure?
8. Having reached this point of conversation, would you describe the electricity infrastructure in the care and control of your organisation as resilient against climate change, please substantiate your response?
9. Do you have any additional thoughts, questions, or comments on the topic of electricity infrastructure climate change resilience?
10. Closing
    10.1. Word of thanks from the researcher to the participant.

10.2. Researcher to remind the participant of how the data will be stored and used beyond the interview without divulging personal details of the respondent.

APPENDIX (D): Ethics Clearance Certificate

Graduate School of Business Administration
University of the Witwatersrand, Johannesburg

Wits Business School Ethics Committee
Constituted under the University Human Research Ethics Committee (Non-Medical)

Ethics Clearance Certificate

Ethics protocol number: WBS/EL706958/127

This certificate is only valid with a legitimate ethics protocol number and signed by the Researcher (below).

This certificate is only valid if accompanied by formal permission from the relevant stakeholder(s).

Project title	Energy infrastructure climate change impact resilience techniques - a case study of the South African Metro Municipalities
Investigator / Researcher	Ms Busisiwe Manabe
Nature of Project	MM (Energy Leadership)
Decision of the Committee	Approved, provided stakeholders and participants are advised that anonymity and confidentiality cannot be guaranteed.
Issue Date of Certificate	07/10/2024
Expiry date	Date of submission of the project / research report
Chairperson	Dr Ayanda Magida ☎ +27 11 717 3953 ayanda.magida@wits.ac.za