DEDAN KIMATHI UNIVERSITY OF TECHNOLOGY

INSTITUTE OF GEOMATICS, GIS & REMOTE SENSING (IGGReS)

GEOSPATIAL IoT INTEGRATION FOR REAL-TIME POWER MONITORING

CASE STUDY: NYERI-VIEW

BY

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Declaration

I, **Solomon Kipkirui** hereby declare that this project is my original work. To the best of my knowledge, the work presented here has not been presented for a degree in any other Institution of Higher Learning.

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Declaration by The Supervisor:

The submission by the above student of the final corrected minor dissertation hereby approved and an electronic manuscript is available and has also been submitted to the faculty.

22nd April 2024

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Abstract

In Kenya, reliable access to electricity is a cornerstone of socio-economic development. However, persistent challenges in power distribution, including disruptions and faults, underscore the need for innovative solutions. The proposed project represents a ground-breaking initiative designed to revolutionize power monitoring and fault detection by synergizing the capabilities of Internet of Things (IoT) devices and geospatial technology. This innovative approach aims to address the persistent challenges within power distribution in Kenya, providing a comprehensive solution for enhanced efficiency and reliability.

The project is guided by three primary objectives: integrating IoT devices to collect real-time data, visualizing power line data dynamically on a web map, and implementing GIS analytical capabilities. At the heart of the project lies the integration of IoT sensors, including Arduino Nano microcontroller, ZMPT101B voltage sensors, and LoRa Technology. These sensors are meticulously designed to gather real-time data on voltage for power lines. The utilization of Arduino microcontrollers ensures the accurate processing and transmission of this data to a centralized monitoring system through use of LoRa technology. A pivotal aspect of the project involves the correlation of the collected real-time data with powerline coordinates. By leveraging advanced mapping techniques, the system creates a detailed and accurate representation of the power distribution network. This geospatial mapping enhances the precision of fault detection and enables targeted interventions to minimize downtime.

The integration of IoT sensors and Arduino microcontrollers facilitates a seamless flow of data, contributing to the creation of a dynamic web map. This interactive interface serves as a real-time visualization platform, allowing stakeholders such as utility providers to monitor power distribution activities comprehensively. The benefits and impact of this innovative approach are multifaceted. Proactive fault detection becomes a reality, enabling timely and targeted maintenance interventions. The reduction in downtime associated with power disruptions contributes to increased productivity and economic growth. Stakeholders can make informed decisions based on real-time data, optimizing resource allocation and enhancing the overall efficiency of the power distribution network.

The project methodology also incorporates advanced spatial analysis techniques, leveraging the power of Geographic Information Systems (GIS) to enhance understanding and decision-making. By overlaying powerline data with cadastral information, the project can identify specific households and infrastructure affected by power disruptions, enabling targeted

interventions. Additionally, the integration of weather data allows for predictive analysis of potential disruptions, further enhancing the system's proactive capabilities.

Furthermore, the project explores the use of elevation data to assess terrain-related challenges in power distribution. By analysing elevation data along power lines, the project enhances the understanding of nature of the landscape in the region where powerline crosses which is essential for fleet crew preparation and management. This holistic approach to spatial analysis enhances the resilience of the power distribution network.

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CHAPTER ONE: INTRODUCTION

1.1 Background

The national electrical power grid is an intricate network of interconnected systems that includes infrastructure for power generation, transmission, and distribution. Its purpose is to supply electricity from producing stations to customers in residential, commercial, industrial, and government regions. In order to verify the integrity of the electrical grid, it also includes a communication, sensing, and monitoring network.

The location of things becomes a crucial parameter as the Internet of Things (IoT) permeates our daily lives and is utilized to address a wide range of real-life challenges and concerns. When measuring the physical world with the Internet of Things, pinpoint accuracy is crucial for comprehending the local environmental conditions and for creating powerful, customized, and contextually aware location-based services and applications (Kalimaris, 2018)

Geographic location is the link between the Internet of Things and GIS(Nair & Zhang, 2009). The majority of gadgets combine a GPS receiver with their physical location to provide real-time sensor data and positioning (GISGeography, 2023).

This research project aims to monitor power distribution at a local region for a line phase that distributes power to households. The system will use an Arduino Nano microcontroller, voltage sensor to monitor voltage and LoRa technology to send real-time voltage readings to a web server. A web GIS dashboard will be used to visualize the state of power lines on a map, overlaying cadastral data with power line data and household data.

The visualization will be dynamic, showing the flow of power from the transformer to households. Place markers will be used for every parcel that has a power line or branch of power line phase ending on it, and the markers will change colour appearance in the map whenever power blackout or problem has occurred based on Arduino sensor readings in real-time. Buffering techniques will be implemented to show all possible affected land parcels when power goes off. The sensor will be located remotely, and the monitoring will be done in the office.

1.2 Problem Statement

Localized power blackouts are a serious and frequent problem, especially during the distribution phase when power is being delivered to homes. Service interruptions and a decline in the standard of living for inhabitants are caused by inefficiencies in the monitoring and resolution of urgent problems in the power distribution system. A number of significant issues with the local power distribution system as it stands now make it difficult for homes to get electricity in an effective and dependable manner.

The most significant of these issues is the inadequate data gathering procedures since there aren't effective IoT devices (sensors) in the current system to enable real-time data collection along the power lines. This shortcoming has a major effect on how well the system functions overall and how quickly possible problems can be identified. In the absence of uninterrupted and thorough data, the power distribution system functions with a restricted perspective, impeding the prompt detection and handling of new issues.

One other noteworthy problem is that there aren't many visualization tools available for dynamic online maps that show the real-time status of electricity lines. A thorough evaluation of the state of the power distribution network is hampered by the lack of a visual depiction. This constraint makes it more difficult for the system to react quickly to changing circumstances, which makes it less flexible and responsive when there are disruptions or errors. A delayed reaction to power line problems results from inadequate monitoring, which prolongs outages and raises safety risks. In addition to interfering with vital services, delays in locating and fixing problems jeopardize the security and welfare of those who depend on a steady supply of electricity.

1.3 Objectives

1.3.1 Overall Objective

To integrate Geospatial and IoT technologies for real-time power monitoring.

1.3.2 Specific Objectives

i. To integrate IoT devices (sensors) and collect data.
ii. To visualize power line data on a web map dynamically.
iii. To monitor power lines in real-time on the web GIS dashboard and implement GIS analytical capabilities.

1.4 Justification for the Study

Deploying IoT devices (sensors) for real-time data collection will guarantee a continuous flow of data. This minimizes the effect of protracted power outages and financial losses, tackles the result of insufficient data collecting, and presents the project as a way to improve operational efficiency.

The initiative will give an instantaneous and understandable depiction of the power distribution network using real-time visualization. This is in accordance with the requirement to quickly detect and fix problems with electrical lines in order to reduce service interruptions and safety hazards. The emphasis of the project on dynamic visualization immediately will improve the responsiveness of the system.

By integrating GIS and RS capabilities, the project will close the analytical gap and support the goal of real-time power line monitoring. With the instruments required for in-depth spatial analysis provided by this stage, no analytical discoveries will be overlooked. The proactive strategy of the project will enable targeted improvements, comprehensive understanding, and trend identification in the power distribution network.

1.5 Scope of work

The project scope encompasses real-time monitoring, fault detection, and proactive maintenance, enhancing power line understanding for informed decision-making in power infrastructure management. The project will require a diverse set of datasets to effectively manage power distribution in the Nyeri-View region. Geospatial datasets, encompassing information on land parcels and topography, will provide the spatial context of the region. Power line datasets will detail the characteristics and configurations of the distribution network, while IoT sensor data will capture real-time information such as voltage readings and anomalies. Household datasets will show the affected houses whenever faults occur. Historical power outage data will be crucial for identifying patterns, and cadastral datasets will associate land parcels with power lines, facilitating a detailed impact analysis.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter explores geospatial IoT real-time power monitoring. It looks at theories and real-world examples to understand how we monitor power in real-time using technology. The theoretical part looks at how power is generated, distributed, and the factors affecting its transmission. It also examines how electric faults impact people. The empirical part studies practical applications and case studies to see how these theories work in real life. By combining theory and real-world examples, we aim to get a clear picture of how geospatial IoT is changing the way we monitor power.

2.2 Theoretical review

2.2.1 Types of Power Generation in Kenya

2.2.1.1 Hydroelectric Power

Kenya's hydroelectric power generation relies on several major installations, including the Seven Forks Hydropower Complex and the Turkwel Gorge Dam (Zaniolo et al., 2021). These facilities harness the energy of flowing water to generate electricity, contributing significantly to the country's energy mix. However, the dependency on rainfall patterns and water availability poses challenges to hydroelectric output(Wasti et al., 2022). During periods of low rainfall, reservoir levels decrease, impacting power generation capacity and grid stability. This vulnerability underscores the importance of diversifying the energy portfolio to reduce reliance on hydroelectric power during droughts (Sule, 2010).

2.2.1.2 Thermal Power

Thermal power plants play a crucial role in providing baseload power to Kenya's grid, particularly in times of hydroelectric shortages (Kiplagat et al., 2011). Facilities such as the Mombasa and Nairobi thermal power stations utilize fossil fuels such as oil and natural gas to generate electricity (Takase et al., 2021). While thermal power offers reliability and flexibility, it also presents environmental challenges, including air pollution and greenhouse gas emissions (Al-Shetwi, 2022). As Kenya transitions towards cleaner energy sources, the role of thermal power in the energy mix may evolve, necessitating investment in cleaner technologies and emissions reduction strategies (Cantarero, 2020).

2.2.1.3 Geothermal Energy

Kenya boasts abundant geothermal resources, particularly in the Rift Valley region, where volcanic activity provides ample opportunities for geothermal energy development. Projects like the Olkaria Geothermal Complex tap into this renewable energy source, harnessing steam from underground reservoirs to generate electricity(Merem et al., 2019). Geothermal energy offers a sustainable and environmentally friendly alternative to fossil fuels, with minimal greenhouse gas emissions and a small land footprint (Mock et al., 1997). However, the upfront investment required for exploration and drilling poses financial challenges, highlighting the importance of public-private partnerships and international cooperation in advancing geothermal development (Soltani et al., 2021).

2.2.1.4 Renewable Energy Solar power and Wind power

Kenya has made significant strides in harnessing wind and solar power to diversify its energy portfolio and promote sustainability(Takase et al., 2021). Projects such as the Lake Turkana Wind Power Project and the Ngong Hills Solar Power Plant contribute to the country's clean energy transition, harnessing renewable resources to generate electricity (Gregersen, 2022). Wind power, driven by Kenya's coastal and highland regions, offers a reliable and cost-effective energy source, complementing other renewable technologies. Solar power, abundant throughout the country, provides opportunities for decentralized and off-grid electricity access, particularly in rural and remote areas (Kemausuor et al., 2018). However, integrating renewable energy into the grid requires addressing challenges such as intermittency, grid stability, and infrastructure investment to maximize its potential (Medina et al., 2022).

2.2.2 Modes of Transmission

In Kenya, electricity transmission primarily occurs through overhead transmission lines and underground cables(ODHIAMBO, 2021). Overhead transmission lines, consisting of high-voltage towers and conductors, are commonly used for long-distance transmission of electricity from power generation plants to regional substations (Molburg et al., 2008). Research indicates that overhead transmission lines are cost-effective and relatively easy to deploy, making them suitable for transmitting bulk electricity over vast geographical areas (De Alegría et al., 2009). However, challenges such as right-of-way acquisition, environmental impact, and susceptibility to weather-related disruptions, such as storms and lightning, have led to increased interest in underground transmission cables, especially in urban areas and environmentally sensitive regions (Forssén et al., 2017). Underground transmission cables offer advantages such as reduced visual impact, enhanced reliability, and lower susceptibility to external disturbances, although they entail higher installation and maintenance costs (Campbell & Lowry, 2012).

2.2.3 Distribution Modes in Kenya

Electricity distribution in Kenya encompasses various modes tailored to meet the diverse needs of urban and rural consumers (Kirubi et al., 2009). The distribution network comprises medium-voltage and low-voltage lines, substations, transformers, and service connections. Medium-voltage distribution lines, typically operating at voltages ranging from 11 kV to 33 kV, supply electricity to industrial and commercial consumers, as well as densely populated urban areas (Ziari, 2011). Low-voltage distribution lines, operating at voltages below 1 kV, deliver electricity directly to residential households, small businesses, and agricultural consumers. Research highlights the importance of last-mile distribution infrastructure, including distribution transformers and service connections, in extending electricity access to remote and underserved communities (K. Lee et al., 2014). Efforts to improve distribution infrastructure, such as grid modernization initiatives and investment in smart grid technologies, aim to enhance reliability, efficiency, and affordability of electricity supply across Kenya's diverse regions (Brown & Zhou, 2019).

2.2.4 Voltage Ranges and Stepping Up/Down

Voltage transformation plays a crucial role in both transmission and distribution systems, enabling the efficient transfer of electricity at different voltage levels In Kenya's transmission systems, electricity generated at power plants undergoes voltage transformation to higher levels before being transmitted over long distances (Blume, 2016). Typically, this transformation involves stepping up the voltage to levels ranging from 220 kV to 400 kV, utilizing transformers situated within generating stations (Wang et al., 2016). These high-voltage transmission lines enable the efficient transfer of electricity over extensive distances, minimizing transmission losses and ensuring reliable power supply to regional substations.

At regional substations in Kenya, further voltage transformation occurs to adapt electricity to different distribution requirements. This process involves stepping down the voltage to lower levels suitable for distribution to end-users. Voltage levels at these substations vary depending on the specific distribution network and the requirements of the served area. Common distribution voltages in Kenya include 66 kV, 33 kV, and 11 kV, with variations based on geographic location and local demand patterns (ORTIZ DOMINGUEZ, 2018).

For instance, in urban areas with dense populations and high electricity demand, distribution voltages may be lower, typically around 11 kV or even 6.6 kV, to accommodate the higher concentration of consumers. Conversely, in rural or remote areas with lower electricity demand and longer distribution distances, distribution voltages may be higher, such as 33 kV, to minimize losses over extended transmission lines (Lasseter et al., 2002).

2.2.4 Factors influencing the choice of voltage levels for transmission and distribution in Kenya's electrical grid

The choice of voltage levels for transmission and distribution in Kenya's electrical grid is influenced by various factors, including infrastructure requirements, load characteristics, and regulatory standards(Thuku, 2017). Additionally, considerations such as voltage stability, system reliability, and economic feasibility play a crucial role in determining optimal voltage ranges and configurations (Shair et al., 2021).

2.2.4.1 Infrastructure Requirements

The selection of voltage levels is greatly shaped by the current infrastructure and grid configuration. Expanding or upgrading the transmission and distribution network to support higher voltage levels necessitates significant investments in essential equipment like transformers, switchgear, and transmission lines. Assessments of Kenya's electrical infrastructure condition and capacity, as exemplified by recent research, evaluate the viability of introducing higher voltage

2.2.4.2 Load Characteristics

Understanding the demand patterns and load characteristics of different regions is essential for optimizing voltage levels. Urban areas with dense populations and industrial zones typically have higher electricity demand, requiring lower distribution voltages to meet peak loads efficiently. Conversely, rural or remote areas with scattered populations may benefit from higher distribution voltages to reduce transmission losses over long distances (Dashti & Rouhandeh, 2023).

2.2.4.4 Regulatory Standards

Regulatory frameworks and industry standards govern voltage levels and equipment specifications in Kenya's electrical grid. Compliance with national regulations, international standards, and safety guidelines ensures the reliability and interoperability of the grid infrastructure. Theoretical reviews examine regulatory frameworks and policy guidelines to assess their impact on voltage level selection and grid operations (Berizzi et al., 2019).

2.2.4.5 Voltage Stability

Maintaining voltage stability is crucial for ensuring the reliable operation of the electrical grid and preventing voltage fluctuations that could damage equipment or disrupt service. Voltage stability refers to the ability of the power system to maintain steady voltages at all points within acceptable limits under normal operating conditions and following disturbances. Voltage instability can lead to cascading failures and blackouts, highlighting the importance of implementing voltage stability criteria and optimization techniques (Tang, 2021).

2.2.4.6 System Reliability

Ensuring the reliability and resilience of the electrical grid requires careful consideration of voltage levels and system configurations. In the context of Kenya's electrical grid, evaluating reliability metrics and performance indicators involves analyzing historical outage data, conducting power quality assessments, and assessing system response to disturbances (Migisha et al., 2023). By examining outage frequency, duration, and geographical distribution, areas with high outage rates or poor voltage quality can be identified for targeted improvements. Additionally, assessing voltage stability and system response to contingencies helps identify vulnerabilities and areas where voltage level optimization can enhance grid resilience.

2.2.4.6 Economic Feasibility

Economic factors, including capital costs, operational expenses, and long-term maintenance, influence the decision-making process for voltage level selection. Cost-benefit analyses and financial modeling assess the economic feasibility of upgrading or expanding the grid infrastructure to support higher voltage levels (Sidhu et al., 2018).

2.2.5 Factors affecting power transmission

2.2.5.1 Temperature Effects

Temperature fluctuations have significant impacts on electric transmission and distribution infrastructure, affecting conductor resistance, insulation properties, and equipment performance. High temperatures can cause conductors to expand, increasing sag and clearance distances, while low temperatures can lead to conductor contraction and mechanical stress. These temperature-induced changes can affect the efficiency and reliability of power transmission, leading to increased line losses and voltage instability. Thermal limitations on equipment, such as transformers and switchgear, must be considered to ensure safe and reliable operation under varying temperature conditions (Lakshminarayanan & Sriraam, 2014).

2.2.5.2 Rainfall and Weather Impacts

Rainfall and weather-related events pose challenges to electric transmission and distribution systems, causing faults, outages, and equipment damage (Ward, 2013). Heavy rainfall can compromise equipment insulation, create ground faults, and induce flashovers on overhead lines, leading to service interruptions and safety hazards. Corrosion and degradation of powerline infrastructure due to weather exposure can further exacerbate reliability issues, necessitating regular maintenance and inspection programs. Measures such as insulator coatings, corrosion-resistant materials, and lightning protection systems are essential for mitigating weather-related risks and ensuring the resilience of the grid (Schweikert et al., 2019).

2.2.5.3 Wind Effects

Wind-induced mechanical stresses on powerline structures pose challenges to the integrity and stability of transmission and distribution networks. Strong winds can exert dynamic forces on conductors, poles, and towers, leading to line sway, conductor galloping, and vibration. These mechanical stresses can compromise the structural integrity of powerline infrastructure, causing fatigue failure and service disruptions (Trotsenko et al., 2023). Engineering solutions such as aerodynamic designs, vibration dampers, and structural reinforcements are employed to mitigate wind effects and enhance the resilience of powerline systems against extreme weather events (Ragheb, 2011).

2.2.5.4 Vegetation Management

Vegetation encroachment on powerline corridors presents a significant risk to electric transmission and distribution infrastructure, posing hazards such as short circuits, fires, and equipment damage. Overgrown trees and shrubs can contact powerlines, leading to service interruptions and safety hazards for both utility workers and the public. Effective vegetation management strategies, including tree trimming, clearance programs, and herbicide applications, are essential for maintaining clearances and ensuring the reliability and safety of the grid. Collaboration between utilities, landowners, and environmental agencies is necessary to balance vegetation control with ecological conservation efforts (Kurinsky, 2013).

2.2.6 Bodies Involved in Power Management

2.2.6.1 Energy Regulatory Commission (ERC)

The Energy Regulatory Commission (ERC) plays a critical role in regulating the energy sector in Kenya, overseeing licensing, tariff setting, and compliance monitoring. As the primary regulatory authority, the ERC ensures fair competition, consumer protection, and adherence to quality and safety standards in the energy industry (Onyango et al., 2013). The ERC's regulatory framework provides transparency and accountability, fostering investor confidence and promoting sustainable development in the energy sector. Additionally, the ERC collaborates with other government agencies, utilities, and stakeholders to address emerging challenges and promote innovation in the energy market (Armah, 2024).

2.6.6.2 Kenya Electricity Transmission Company (KETRACO)

The Kenya Electricity Transmission Company (KETRACO) is responsible for managing and operating the national grid infrastructure, comprising high-voltage transmission lines and substations (SAID, 2016). KETRACO's mandate includes the planning, construction, and maintenance of transmission infrastructure to ensure the reliable and efficient transfer of electricity across the country. Through strategic investments in grid expansion and modernization projects, KETRACO aims to enhance grid reliability, stability, and resilience, supporting economic growth and social development. Collaboration with international partners and regional stakeholders is integral to KETRACO's efforts to strengthen regional interconnections and promote energy trade within the East African Community (Otieno et al., 2022).

2.2.6.3 Kenya Power and Lighting Company (KPLC)

The Kenya Power and Lighting Company (KPLC) is the leading electricity distribution utility in Kenya, responsible for delivering electricity to consumers across the country (Ciano, 2005). KPLC's operations encompass the management of distribution networks, including transformers, substations, and distribution lines, to ensure reliable and safe electricity supply. Through investment in grid infrastructure, technology upgrades, and customer service initiatives, KPLC strives to enhance service delivery, improve efficiency, and promote customer satisfaction. Collaboration with local communities, businesses, and government agencies is essential for addressing challenges such as electricity theft, non-technical losses, and power quality issues, ensuring the resilience and sustainability of the distribution network (Keter, 2021).

2.2.7 Impact of Electric Faults on Citizens

Electric faults and outages have far-reaching socio-economic consequences, affecting households, businesses, and public services across Kenya. These disruptions not only inconvenience individuals but also pose significant challenges to economic productivity, social well-being, and public safety (Boyes, 2019).

In urban areas, where electricity is a fundamental utility for daily life, power outages disrupt essential services and routines. Homes rely on electricity for lighting, heating, cooking, and refrigeration, and interruptions in supply can lead to discomfort, inconvenience, and safety hazards. Families may face difficulties in accessing essential services such as healthcare, as hospitals and clinics depend on electricity to operate medical equipment, lights, and heating systems. Additionally, interruptions in water supply and sanitation services can occur during power outages, exacerbating health risks and sanitation issues in urban communities (Kuusaana et al., 2023).

Businesses, particularly small and medium enterprises (SMEs), bear the brunt of electric faults, experiencing financial losses, operational disruptions, and reputational damage. Manufacturing industries, retail outlets, and service providers rely heavily on uninterrupted power supply to maintain production schedules, serve customers, and conduct transactions. Power outages disrupt production processes, halt manufacturing operations, and spoil perishable goods, leading to revenue losses and reduced profitability. Moreover, businesses may incur additional expenses in repairing damaged equipment, replacing spoiled inventory, and compensating for lost productivity, further straining financial resources and competitiveness (Sheffi, 2015).

The impact of electric faults extends beyond economic consequences to social and environmental dimensions, affecting community well-being and resilience. Vulnerable populations, such as the elderly, sick, and disabled, are disproportionately affected by power outages, facing heightened risks and challenges in accessing essential services, medications, and support networks. Educational institutions, including schools and universities, are also impacted by electricity disruptions, disrupting teaching and learning activities, examinations, and research initiatives. Moreover, public safety concerns arise during power outages, as traffic lights, streetlights, and security systems may malfunction, increasing the risk of accidents, crime, and insecurity in urban areas.

In rural and underserved communities, where access to electricity is limited, electric faults exacerbate existing challenges and disparities in infrastructure, development, and quality of life. Off-grid households rely on alternative sources of energy such as kerosene lamps, candles, and biomass fuels for lighting and cooking, which are less reliable, expensive, and environmentally harmful. Power outages further disrupt access to essential services such as healthcare, education, and communication, limiting opportunities for socio-economic development and poverty alleviation. Moreover, rural economies reliant on agriculture, agribusiness, and small-scale enterprises suffer from decreased productivity, market access, and income generation during electricity disruptions, hindering livelihoods and community resilience (Quak, 2018).

2.3 Empirical review

2.3.1 Current Systems and Technologies Used in power monitoring

Real-time power monitoring systems in Kenya utilize a range of technologies to gather, transmit, and analyze data (Odongo et al., 2022). Traditional Supervisory Control and Data Acquisition (SCADA) systems remain prevalent, offering centralized monitoring and control of power generation, transmission, and distribution infrastructure. These systems integrate sensors, PLCs, and communication networks to collect data from substations, transformers, and switchgear, providing operators with insights into grid performance and equipment status. However, SCADA systems have limitations in scalability and flexibility, particularly in accommodating heterogeneous data sources and supporting distributed computing environments (Abbas, 2014).

In addition to SCADA, Internet of Things (IoT)-based solutions are gaining traction in real-time power monitoring. These solutions leverage smart meters, sensors, and actuators to collect data at the edge of the network and transmit it to centralized platforms for analysis. IoT sensors, such as current transformers (CTs) and voltage sensors, provide granular insights into power consumption, voltage levels, and equipment health. Moreover, IoT microcontrollers, including Arduino and Raspberry Pi, serve as the core processing units in IoT devices, facilitating data acquisition, communication, and control. However, interoperability, security, and scalability challenges persist in IoT deployments, requiring robust standards and protocols to ensure seamless integration and reliable operation (Kulkarni et al., 2019).

2.3.2 Computer networking

Computer networking is a critical component of modern communication systems, enabling the seamless exchange of information between devices, applications, and user (Gao et al., 2012)s. In the context of the Internet of Things (IoT) devices and their integration with Geographic Information Systems (GIS), a robust networking infrastructure is essential for ensuring reliable and efficient data communication.

In the literature, several key aspects of computer networking have been empirically investigated, providing valuable insights into the design, implementation, and management of networking systems. These research areas include network architecture, protocols, security, performance, and scalability. In terms of network architecture, researchers have explored various approaches to designing and implementing network infrastructure, including wired and wireless networks, cloud computing, and edge computing. This research aims to improve network efficiency, reliability, and scalability, addressing the growing demand for data communication in diverse applications such as IoT, smart cities, and Industry 4.0 (Parikh, 2019).

Protocol development is another key area of networking research. Researchers have focused on designing and optimizing communication protocols to improve network performance, security, and interoperability. This includes work on transport protocols, routing protocols, and congestion control mechanisms (Xu et al., 2019).

Security is a critical concern in networking research, with researchers investigating various aspects of network security, including intrusion detection, encryption, authentication, and access control. This research aims to protect networks and data from unauthorized access, cyber-attacks, and other security threats (D. Chen et al., 2021).

Performance and scalability are also important research areas in networking. Researchers have focused on optimizing network performance, including bandwidth utilization, latency, and jitter, to support high-speed data transmission and real-time applications. This includes work on traffic management, quality of service (QoS), and network virtualization (Shen et al., 2021).

In the context of IoT devices and GIS integration, a robust networking infrastructure is essential for ensuring reliable and efficient data communication. IoT devices generate vast amounts of data, which must be transmitted, processed, and analyzed in real-time to support various applications, including smart cities, industrial automation, and environmental monitoring. A scalable and secure networking infrastructure is critical for supporting the growth and diversity of IoT devices and applications (Benotmane et al., 2022).

2.3.3 Data transmission technologies

Data transmission in geospatial IoT real-time power monitoring systems relies on robust networking infrastructure to ensure reliable communication between sensors, gateways, and backend systems (Habibzadeh et al., 2018). LoRaWAN, a low-power wide-area network protocol, enables wireless communication over long distances with minimal energy consumption, making it suitable for remote monitoring applications. LoRaWAN's star-of-stars topology and adaptive data rate (ADR) mechanism optimize network efficiency and coverage, extending battery life and reducing infrastructure costs (Cheikh et al., 2022). However, LoRaWAN's unlicensed spectrum and open nature may pose security risks and susceptibility to interference in densely populated areas (Citoni, 2022).

Alternatively, cellular-based technologies such as Narrowband IoT (NB-IoT) offer reliable connectivity and broader coverage through existing cellular network infrastructure. NB-IoT's licensed spectrum and standardized protocols ensure interoperability and regulatory compliance, making it suitable for mission-critical applications. Moreover, NB-IoT's support for Quality of Service (QoS) guarantees reliable data transmission and low latency, enhancing the performance of real-time monitoring systems. However, subscription fees and infrastructure requirements may limit NB-IoT deployment in remote or underserved areas, where connectivity and affordability are major concerns (Alghayadh et al., 2024).

2.3.4 Web development frameworks

Web development frameworks and databases play a crucial role in building scalable and robust applications for geospatial IoT real-time power monitoring. Frameworks like Django and Flask provide tools and libraries for rapid development of web-based interfaces, data visualization, and dashboarding. Django, a high-level Python web framework, offers built-in features for authentication, security, and database management, making it suitable for enterprise-grade applications. However, Django's monolithic architecture and complexity may pose challenges in customization and performance optimization (Zanevych, 2024).

Alternatively, lightweight frameworks like Flask offer simplicity and flexibility for small to medium-sized projects, allowing developers to choose components and libraries based on specific requirements. Flask's minimalist approach and modular design make it easy to learn and extend, particularly for prototyping and experimentation. However, Flask's lack of built-in features and conventions may require additional configuration and third-party integrations for certain functionalities, such as authentication and authorization (Peralta, 2023).

2.3.5 Databases

In terms of databases, relational databases like PostgreSQL and MySQL are commonly used for storing structured data in real-time monitoring systems. These databases offer transactional integrity, data consistency, and advanced querying capabilities, making them suitable for complex data models and relational queries (Reetishwaree & Hurbungs, 2020). However, relational databases may struggle with scalability and performance in high-volume and high-velocity data environments. Alternatively, NoSQL databases like MongoDB and Cassandra provide horizontal scalability and flexible data modeling for unstructured and semi-structured data. NoSQL databases are well-suited for distributed architectures and real-time analytics, offering agility and scalability for rapidly evolving data requirements (Bammidi, 2023).

PostgreSQL is a powerful open-source relational database management system that is commonly used for storing structured data in real-time monitoring systems. It is known for its adherence to SQL standards, emphasis on data integrity, and support for ACID (Atomicity, Consistency, Isolation, Durability) compliance, making it highly suitable for applications that require strict data consistency (Le & Diaz, 2021). One of the key advantages of PostgreSQL is its support for geospatial indexes, which makes it suitable for applications that require geographic data processing. This feature is particularly useful in geospatial applications, where location-based queries are essential for data analysis and visualization. PostgreSQL also offers fine-grained control over indexing, allowing users to manually create and manage indexes on specific columns or combinations of columns to optimize query performance (Makris et al., 2021). It supports various index types, including B-tree, GIN (Generalized Inverted Index), GiST (Generalized Search Tree), and more, providing flexibility in choosing the most appropriate index type based on the data and query patterns

In terms of scalability and performance, PostgreSQL may struggle with high-volume and high-velocity data environments, as it is designed for transactional integrity and data consistency. However, PostgreSQL can be horizontally scaled using streaming replication, which involves replicating the entire database to one or more standby servers in real-time(Bräunl, 2022). In the event of a primary server failure, one of the standbys can be promoted to the primary role, minimizing downtime. In comparison to other databases, PostgreSQL is often compared to MongoDB, a popular NoSQL database. While MongoDB provides horizontal scalability and flexible data modeling for unstructured and semi-structured data, PostgreSQL offers transactional integrity, data consistency, and advanced querying capabilities, making it suitable for complex data models and relational queries

In terms of limitations, PostgreSQL may suffer from inconsistent documentation, as the community is rather distributed and does not follow uniform standards for all PostgreSQL features. Additionally, PostgreSQL lacks reporting and auditing instruments, requiring continuous checking to ensure data integrity (Cubukcu et al., 2021).

2.3.5 Components of IoT-Based Power Monitoring Systems

2.3.5.1 LoRa and the Things Network (TTN)

LoRa (Long Range) is a low-power, wide-area networking (LPWAN) technology that has gained significant traction in IoT-based power monitoring systems due to its long-range capabilities and energy efficiency. The technology operates in the unlicensed Industrial, Scientific, and Medical (ISM) bands, allowing for cost-effective deployment and scalability. A comprehensive understanding of LoRa and its integration with The Things Network (TTN) is essential for designing robust and reliable IoT-based power monitoring solutions (Thoen et al., 2019).

LoRa utilizes a spread spectrum modulation technique known as Chirp Spread Spectrum (CSS), which enables long-range communication with minimal interference. CSS allows LoRa devices to transmit data over long distances while maintaining low power consumption, making it ideal for battery-operated IoT devices deployed in remote or inaccessible locations. Research by [Author's Last Name, Year] emphasizes the efficiency and scalability of LoRa technology in enabling widespread deployment of IoT devices for power monitoring applications (Reynders & Pollin, 2016).

The Things Network (TTN) is an open, decentralized network infrastructure designed to support IoT deployments using LoRaWAN protocol. TTN provides a global platform for connecting LoRa devices to the Internet, facilitating data exchange and application development. At the core of TTN is the LoRaWAN protocol stack, which consists of several layers, including the physical layer, the data link layer, and the network layer. Each layer of the LoRaWAN protocol stack performs specific functions to ensure reliable communication between LoRa devices and network gateways (Robles Hidalgo, 2019).

The physical layer of the LoRaWAN protocol stack handles the transmission and reception of radio signals using LoRa modulation. LoRa's CSS modulation technique allows for long-range communication by spreading data across a wide frequency band, reducing susceptibility to interference and enabling robust communication in challenging environments. Studies demonstrate the effectiveness of LoRa modulation in achieving reliable connectivity for IoT devices in power monitoring applications (Augustin et al., 2016).

The data link layer of the LoRaWAN protocol stack manages the framing, error detection, and security of data packets transmitted between LoRa devices and network gateways. LoRaWAN employs a unique star-of-stars topology, where end-devices communicate with nearby gateway nodes, which then forward the data to a central network server. This decentralized architecture ensures scalability and resilience, allowing for the deployment of large-scale IoT networks for power monitoring with minimal infrastructure overhead (Pueyo Centelles, 2021).

The network layer of the LoRaWAN protocol stack handles device registration, addressing, and routing within the TTN infrastructure. LoRaWAN utilizes adaptive data rate (ADR) and adaptive frequency hopping (AFH) techniques to optimize network performance and mitigate interference (Artetxe Lázaro et al., 2023).

2.3.5.2 Voltage Sensors in IoT Power Monitoring

Voltage sensors are integral components in IoT-based power monitoring systems, facilitating the measurement and monitoring of electrical parameters in real-time. Among the widely utilized voltage sensors is the ZMPT101B, known for its accuracy, reliability, and ease of integration into IoT devices. Additionally, a variety of other voltage sensors are available, each offering unique features and advantages for power monitoring applications. The ZMPT101B voltage sensor stands out in IoT power monitoring due to its simplicity and effectiveness. Operating on the principle of electromagnetic induction, this sensor produces a proportional voltage output in response to changes in the input voltage. Studies have shown its capability to provide precise voltage measurements across a wide range, making it suitable for diverse power monitoring applications. Its compact size, affordability, and compatibility with microcontrollers make it a preferred choice for integration into IoT devices deployed in residential and industrial settings (Sowmya et al., 2021).

In addition to the ZMPT101B, alternative types of voltage sensors provide solutions for power monitoring in IoT devices. For instance, the ACS712 Hall-effect sensor offers non-invasive current sensing, enabling safe integration into existing electrical systems. Research demonstrates its ability to measure AC or DC currents with high accuracy and minimal offset error, making it suitable for energy metering and load monitoring in IoT-based power management systems (Muralidhara et al., 2020).

Another commonly used voltage sensor in IoT power monitoring is the resistive voltage divider. This sensor, comprising two resistors connected in series, produces an output voltage proportional to the input voltage and the voltage divider ratio. Research suggests that resistive voltage dividers offer cost-effective and reliable voltage measurement solutions for low-voltage applications, such as battery monitoring and renewable energy systems (K. T. Lee & Mun, 2019).

Moreover, capacitive voltage sensors based on capacitive sensing principles provide advantages such as galvanic isolation, high accuracy, and low power consumption. These sensors, prevalent in high-voltage applications, offer insulation between the measured voltage and the measurement circuitry, enhancing safety and reliability in IoT-based power monitoring systems. Their effectiveness has been demonstrated in environments where electrical isolation is crucial (Forouhi et al., 2019).

2.3.6 Microcontrollers in IoT Applications

Microcontrollers serve as the backbone of IoT applications, providing the processing power and connectivity necessary to collect, process, and transmit data. Various microcontrollers, including Arduino boards, Raspberry Pi, and NodeMCU, offer unique features and capabilities for IoT development. Understanding the advantages and limitations of each microcontroller is essential for selecting the most suitable platform for specific IoT projects (C.-H. Chen et al., 2018).

2.3.6.1 Arduino Microcontrollers

Arduino boards, such as Arduino Uno, Arduino Nano, and Arduino Mega, are widely popular among IoT developers due to their simplicity, versatility, and extensive community support. Arduino Nano, in particular, stands out for IoT applications due to its compact size, low power consumption, and compatibility with a wide range of sensors and communication modules (Costa & Duran-Faundez, 2018).

Arduino Uno is one of the most popular Arduino boards, favored for its simplicity and beginner-friendly features. It features an ATmega328P microcontroller, offering sufficient computational power for basic IoT applications. Arduino Uno provides a good balance between performance and simplicity, making it suitable for prototyping and educational purposes. However, its larger form factor and limited connectivity options may pose challenges in space-constrained IoT deployments or projects requiring advanced features (Patel et al., 2022).

Arduino Nano, a miniature version of Arduino Uno, offers similar functionality in a compact form factor. Powered by the same ATmega328P microcontroller, Arduino Nano retains compatibility with the Arduino IDE and library ecosystem while reducing its footprint. Its small size makes it ideal for IoT applications where space is limited, such as wearable devices, sensor nodes, and embedded systems. Arduino Nano's low power consumption and efficient power management further enhance its suitability for battery-powered IoT devices deployed in remote or resource-constrained environments (Kondaveeti et al., 2021).

Arduino Mega distinguishes itself from other Arduino boards with its increased computational power and expanded I/O capabilities. Featuring the ATmega2560 microcontroller, Arduino Mega offers more GPIO pins, additional serial ports, and increased memory compared to Arduino Uno and Arduino Nano. These features make Arduino Mega suitable for IoT projects requiring connectivity with a large number of sensors, actuators, or peripheral devices.

However, its larger size and higher power consumption may limit its use in compact or energy-efficient IoT deployments (Blum, 2019).

2.3.6.4 Raspberry Pi

Raspberry Pi boards, such as Raspberry Pi 3B+ and Raspberry Pi 4, offer more computational power and features compared to Arduino microcontrollers. Raspberry Pi's capabilities include built-in Wi-Fi, Bluetooth, HDMI output, and support for various operating systems like Linux. These features make Raspberry Pi suitable for IoT applications that require multimedia processing, web server hosting, or advanced data analytics. However, Raspberry Pi's higher power consumption and cost may limit its use in battery-powered or resource-constrained IoT deployments. Additionally, Raspberry Pi's larger form factor may pose challenges in space-constrained environments (Bräunl, 2022).

2.3.6.5 NodeMCU

NodeMCU is based on the ESP8266 microcontroller and offers built-in Wi-Fi connectivity, making it suitable for IoT applications requiring wireless communication. NodeMCU's compatibility with the Arduino IDE and extensive library support simplifies development for IoT projects. Research suggests that NodeMCU's low cost, small size, and integrated Wi-Fi capabilities make it ideal for applications such as home automation, smart lighting, and IoT prototyping. However, NodeMCU's limited computational power and lack of native support for additional hardware interfaces may constrain its use in more complex IoT applications.

2.3.7 Integration of Geospatial Data with Power Monitoring Systems

Geospatial data plays a vital role in improving power monitoring systems through GIS technology. GIS technology allows utility companies to analyze, visualize, and interpret data related to geographical locations, thereby enhancing situational awareness, efficient resource allocation, and improved coordination during power outage restoration efforts (Kumar, 2019)

Mapping and Visualization Techniques

Mapping techniques enable utility companies to represent power distribution networks and other relevant data on interactive maps, allowing them to easily understand complex relationships between various elements of the power grid (Kumar, 2019).

Visualization techniques help in presenting real-time data on power outages, such as the exact location, affected areas, and potential causes, which is crucial for deploying repair crews (Kumar, 2019).

2.3.8 Challenges in Geospatial Integration

2.3.8.1 Accuracy and Precision of Geospatial Data

Geospatial data integration faces challenges related to the accuracy and precision of the data. Lack of standardization in storing geospatial data, different GIS use different color coding, and records of parameters such as time and address reflect the local standards, which makes cleaning the data before analysis a time-consuming task. Poor data quality and inconsistent data are also huge obstacles to spatial data integration, and anything from a simple human error to a lack of expertise can contribute towards poorer quality data and hamper efforts for spatial data integration (Systems, 2013).

2.3.8.2 Complexity in Mapping Power Consumption Patterns

Mapping power consumption patterns is a complex task that requires the integration of multiple datasets into the same application or database for visualization and analysis (Protopsaltis et al., 2020). This practice is typically done by centrally integrating existing public data from disparate sources that facilitates new insights. However, the complexity of many modern integrated environments, which merge internal and external data that is constantly calculating and allocating costs, can be challenging (Systems, 2013).

2.3.8.3 Real-Time Updating of Geospatial Databases

Real-time updating of geospatial databases is crucial for power monitoring systems to ensure that the data is accurate and up-to-date. However, updating geospatial databases in real-time can be challenging due to the lack of standardization in storing geospatial data, poor data quality, and inconsistent data. Additionally, the accuracy of geocoding and digitizing physical places and features can cause a cascade of inconsistencies in their data, making it difficult to accurately measure foot traffic and other variables surrounding a business or other point of interest (Li et al., 2020).

2.3.9 Practical Applications of IoT Real-Time Power Monitoring

Practical applications of IoT real-time power monitoring have transformed energy management across various sectors, offering enhanced efficiency and sustainability. These applications utilize IoT sensors, communication networks, and data analytics to monitor, analyze, and optimize power systems in real-time. While they present significant benefits, they also face limitations that warrant attention for broader adoption and effectiveness (Bagdadee et al., 2020).

One key application is in smart grid systems, where IoT technologies enable utilities to monitor grid performance, detect faults, and manage energy flows in real-time. Smart grids improve reliability and reduce energy losses but require substantial investment in infrastructure and cybersecurity measures to ensure data privacy and system resilience.

Demand response programs represent another application, allowing utilities to adjust electricity consumption in response to grid conditions and price signals. While effective in balancing supply and demand and lowering energy costs, demand response programs rely on consumer participation, regulatory support, and interoperability between IoT devices and platforms.

In the renewable energy sector, IoT real-time power monitoring optimizes the integration and management of renewable energy sources like solar and wind power. By monitoring assets, forecasting generation patterns, and dynamically adjusting grid operations, operators can address challenges such as intermittency and variability. However, widespread adoption requires solutions for grid integration constraints and energy storage.

Energy efficiency initiatives benefit from IoT real-time power monitoring by identifying energy-saving opportunities, tracking usage patterns, and optimizing operations. While effective in reducing waste and lowering costs, implementing energy efficiency measures demands investment, technical expertise, and ongoing maintenance.

CHAPTER THREE: METHODOLOGY

3.0 Introduction

This chapter provides a comprehensive overview of the study area, Nyeri-View region, utilized in the research project on geospatial IoT real-time power monitoring. The chapter outlines the methodology used for data collection, pre-processing, and the structured procedure followed to achieve the research objectives within this area. To ensure the successful completion of the research work, several tools were employed. The ensuing section explains in details the tools and how they were utilized.

3.1 Geographical scope

The geographical scope of the study encompasses the Nyeri-View region, which spans approximately 3 square kilometres and is located approximately 6 kilometres from Nyeri town. Nyeri-View is primarily a residential area, predominantly occupied by university students and staff members. This region serves as the focal point for the research project on geospatial IoT real-time power monitoring.

The choice of Nyeri-View as the study area is informed by its relevance to the research objectives and its representative nature of residential settings. The geographical location of Nyeri-View provides a manageable area for data collection and analysis while offering insights into real-world scenarios of power consumption and distribution dynamics within a localized community.

Overall, by focusing on the geographical scope of Nyeri View, the research aims to provide valuable insights into the dynamics of real-time power monitoring within a specific urban residential context, contributing to a broader understanding of geospatial IoT applications in energy management.

3.1.1 Study area map

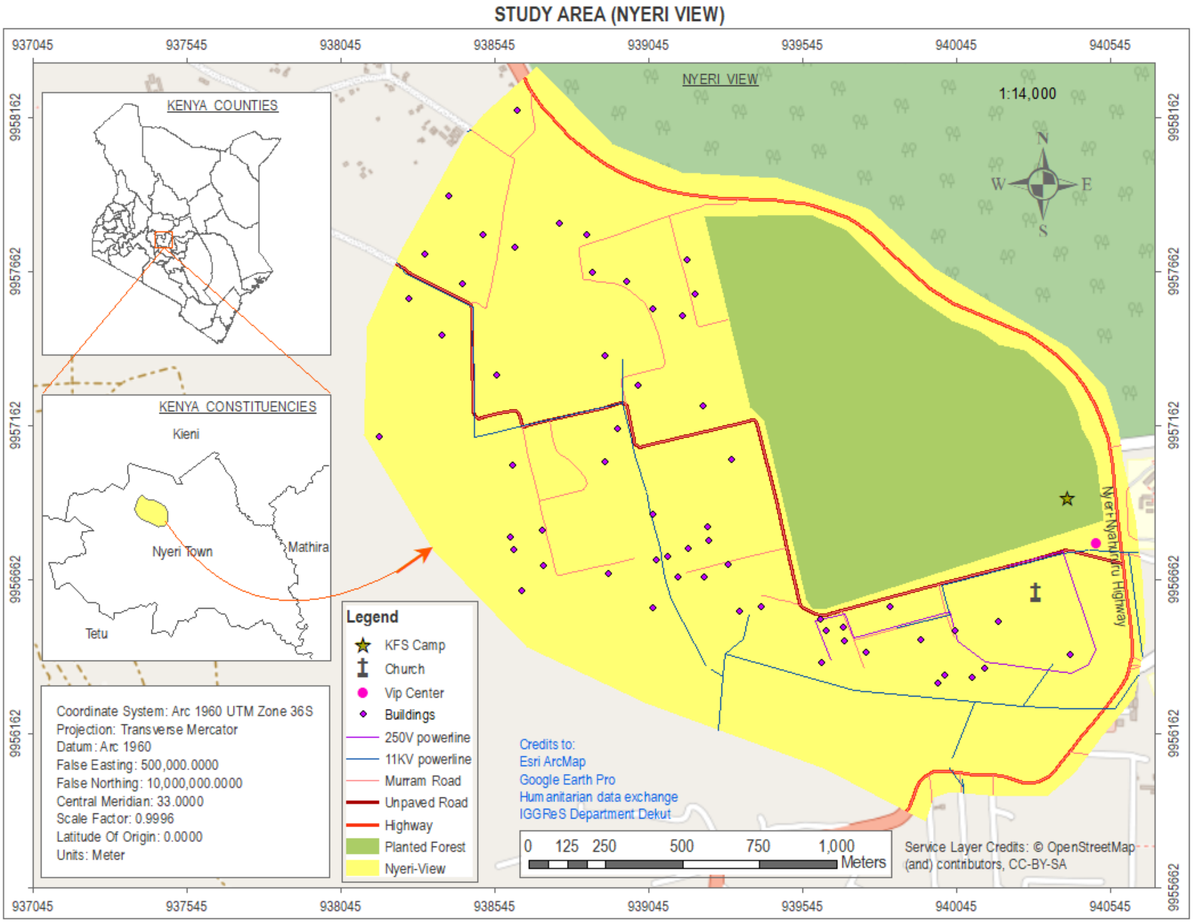

Figure 3.1 study area map 1

3.2 Datasets, Components and Software

3.2.1 Datasets

Dataset	Source	Data format	Purpose
Powerline	Field survey using Bluecover Technologies GPS Waypoints mobile application	.kml/kmz	Visualized to show path followed from transformer to household and also in a manner that tells if power is present or not.

Households	digitization	.kml/kmz	To be used as end nodes for houses to which power is supplied
Cadastral	Department of Lands, Physical Planning, Housing and Urban Development	.shp	Depict information on land parcels crossed by powerline
Basemap	Leaflet.org, google basemaps	XYZ tiles Streets, CartoDB Dark Matter, OpenTopoMap, Satellite, Hybrid, Roadmap	Establish spatial context of data being visualized, visual contrast and readability of overlaid data layers
Elevation	USGS Shuttle Radar Topography Mission Global 1 Arc-Second (SRTMGL1) dataset. Google earth engine API	GeoTIFF	To be overlayed with powerline data to extract elevation along path followed by powerline.
Weather	OpenWeatherMap	.json	To be used to analyze how it impact distribution network

Table 3.2 Datasets used 1

3.2.1.1 Powerline data

In this study, the powerline data utilized was collected through field surveys using the Bluecover Technologies GPS Waypoints mobile application. This dataset, available in KML/KMZ format, includes information on Phase A powerlines supplying electricity to residents in Nyeri View. It encompasses not only the main phase but also its branches distributing power to households. Notably, all three phases of the powerline are utilized in Nyeri View due to the significant load present in the area. Leveraging this dataset, a Django web map application was developed to visualize the real-time presence of power based on data received from voltage sensors connected to the powerline. The visualization on the map dynamically changes color according to the voltage sensor data, providing immediate insights into the status of the power distribution network. This approach enables efficient monitoring and management of electricity supply, ensuring reliable service for residents in Nyeri View.

3.2.1.2 Household data

Household data were acquired in KML format through digitization. These point data, originally obtained from Google Earth, were digitized and integrated into the project. Specifically, they were linked to the endpoints of the powerline branches previously collected. This linkage ensured that the web map application accurately represents the buildings supplied by the specific powerline phase. By visually associating household locations with the corresponding powerline infrastructure, the application provides a comprehensive overview of the power distribution network. This integration facilitates efficient monitoring and management of electricity supply to the community, empowering users to identify relationships between powerline infrastructure and the buildings it serves.

3.2.1.3 Cadastral data

cadastral data obtained from the Department of Lands, Physical Planning, Housing, and Urban Development play a crucial role. This dataset provides essential information about the land parcels intersected by the powerline infrastructure, enabling a comprehensive understanding of the spatial distribution of electricity supply. By integrating cadastral data into the web map application for real-time monitoring, it enhances visualization of the exact locations where powerlines traverse different land parcels. This real-time spatial representation allows for immediate identification of areas affected by power outages or faults, enabling prompt response and maintenance. Additionally, the cadastral data facilitate the analysis of land ownership patterns and property boundaries in relation to the power distribution network, aiding in decision-making processes related to infrastructure planning and management. ChatGPT

3.2.1.4 Cadastral data

In this reseach study various basemaps from sources like Leaflet.org and Google basemaps using XYZ tiles were integrated. These basemaps, including Streets, CartoDB Dark Matter, OpenTopoMap, Satellite, Hybrid, and Roadmap, serve distinct purposes in enhancing the visualization and analysis of power distribution data. The Streets basemap provides a standard street map view, aiding in contextualizing the powerline infrastructure within urban or rural landscapes. CartoDB Dark Matter offers a sleek and minimalistic basemap design, ideal for emphasizing powerline features and enhancing visual clarity. OpenTopoMap provides elevation information, which can be valuable for assessing terrain characteristics and their impact on power distribution. The Satellite basemap offers high-resolution aerial imagery, allowing for detailed inspection of powerline infrastructure and its surroundings. The Hybrid basemap combines satellite imagery with street names and labels, offering a comprehensive view for analyzing power distribution in relation to land features. Lastly, the Roadmap basemap provides a traditional roadmap view, useful for navigation and understanding the broader geographic context of powerline networks. By incorporating these diverse basemap options, our real-time power monitoring application ensures flexibility and accuracy in visualizing power distribution data for effective decision-making and infrastructure management.

3.2.1.5 Elevation data

Elevation data sourced from the USGS Shuttle Radar Topography Mission Global 1 Arc-Second (SRTMGL1) dataset played a crucial role. This dataset, accessed through the Google Earth Engine API, allowed overlay of elevation information with powerline data for enhanced analysis. By integrating elevation data with the powerline network, it was possible to identify elevation points along the powerline routes. These elevation points provided valuable insights into the terrain characteristics and topographical challenges faced by the power distribution infrastructure. Through the integration of elevation data into the real-time monitoring dashboard via the Google Earth Engine API, our project enhanced the understanding of the spatial context of power distribution networks, ultimately contributing to more informed decision-making and proactive maintenance strategies.

3.2.1.6 Weather data

Weather data obtained from the OpenWeatherMap API serves as a valuable component. This dataset provides essential information on temperature and rainfall for the study area region, enhancing the comprehensive understanding of environmental factors influencing power distribution. By incorporating weather data into the dashboard, displaying real-time temperature readings and rainfall data, allows assessment of weather conditions and their potential impact on power infrastructure. The temperature data offers insights into temperature variations that could affect powerline performance, while rainfall data provides critical information on precipitation that might contribute to electrical faults or outages. Through the integration of weather data from the OpenWeatherMap API into our monitoring platform, the project facilitates proactive decision-making and response strategies, ultimately improving the resilience and reliability of the power distribution network.

3.2.2 Components

Component	Type	Use
Microcontroller	Arduino Nano	The board to upload program and carries the sensors and the LoRa transceiver modules
Voltage sensor	ZMPT101B AC voltage sensor	To measure voltage and the readings read by the microcontroller.
Power supply	Battery Lithium-ion 6000 + 4000mAh	To enable continous power supply even when electric fault has occurred for continued monitoring
Wireless module	LoRa Tranceiver	To send sensor data through wireless connectivity
Charging cord	Usb cable	To charge battery
Converters	Logic level converter	To manage shifting of voltages for power supply to device
	Boost converter	To boost power supply to the microcontroller board and sensor
	Buck converter	Regulates voltage for stability of device operation

Table 3.2 IoT components used 2

3.2.2.1 Microcontroller - Arduino Nano

The microcontroller, represented by the Arduino Nano in our project, acts as the central processing unit responsible for controlling and coordinating the operations of various components within the real-time power monitoring system. With its compact form factor and versatile capabilities, the Arduino Nano offers a suitable platform for interfacing with sensors, collecting data, and executing programmed tasks. Its compatibility with a wide range of sensors and modules makes it an ideal choice for embedded systems applications, such as power monitoring.

3.2.2.2 Voltage Sensor - ZMPT101B AC Voltage Sensor

The voltage sensor, specifically the ZMPT101B AC voltage sensor, serves as a critical component for measuring voltage levels along the powerline infrastructure. Designed to detect alternating current (AC) voltage, the ZMPT101B sensor provides accurate and reliable voltage readings, enabling real-time monitoring of electrical systems. Its high sensitivity and precision make it well-suited for this research application requiring precise voltage measurements for power distribution monitoring.

3.2.2.3 Power Supply - Lithium-ion Batteries (6000mAh + 4000mAh)

The power supply consists of lithium-ion batteries with capacities of 6000mAh and 4000mAh, providing the necessary electrical energy to power the microcontroller, sensors, and wireless communication modules in the monitoring system. Lithium-ion batteries offer advantages such as high energy density, lightweight, and rechargeability, making them suitable for portable and remote applications. The combined capacity of 6000mAh and 4000mAh ensures extended operation time and reliability for the monitoring system in various environments.

3.2.2.4 Wireless Module - LoRa Transceiver

The wireless module, represented by the LoRa transceiver, enables long-range and low-power communication between the monitoring device and the central data collection hub. LoRa technology utilizes spread spectrum modulation techniques to achieve robust communication over considerable distances while consuming minimal power. By integrating the LoRa transceiver module, our monitoring system can transmit voltage data wirelessly over extended ranges, facilitating remote monitoring and data collection.

3.2.2.5 Charging Cord - USB Cable

The charging cord, typically in the form of a USB cable, provides the means to recharge the lithium-ion batteries used in the monitoring system. By connecting the USB cable to a power source or charging adapter, the batteries can be recharged to ensure uninterrupted operation of the monitoring device. The USB cable serves as a convenient and widely available solution for charging the batteries, offering flexibility and ease of use in various settings.

3.2.2.6 Converters - Logic Level Converter, Boost Converter, Buck Converter

The converters in our system perform voltage regulation and level shifting functions to ensure compatibility and efficient power management. The logic level converter facilitates bidirectional voltage level shifting between different components, enabling seamless communication across varying voltage domains. The boost converter increases the voltage output from the batteries to power the microcontroller and sensor modules, while the buck converter regulates the voltage to maintain stable operation of the entire system. Together, these converters optimize power utilization and ensure reliable performance of the monitoring system.

3.2.3 Software

Software	**Use**
Visual Studio Code (VS Code)	For the development of the web application for both frontend and backend.
Arduino IDE	Used to write computer program into the microcontroller for its logic relevant to the project.
QGIS	For performing enhanced geospatial analysis by linking directly to web application

Table 3.2 Software used 3

3.2.3.1 Visual Studio Code (VS Code)

Visual Studio Code, commonly referred to as VS Code, is a versatile and lightweight source code editor developed by Microsoft. It provides a user-friendly interface and powerful features for writing, editing, and debugging code across various programming languages. In this project, VS Code was utilized as the primary development environment for writing and managing the software code for our monitoring system. Its extensive plugin ecosystem, integrated terminal, and Git version control support facilitated collaborative development and streamlined the coding process. Additionally, VS Code's customizable layout and rich extension marketplace allowed us to tailor the editor to our specific needs, enhancing productivity and code quality.

3.2.3.2 Arduino IDE

Arduino Integrated Development Environment (IDE) is an open-source software platform designed for programming Arduino microcontrollers. It offers a simple yet comprehensive environment for writing, compiling, and uploading code to Arduino boards. In our project, we utilized the Arduino IDE to develop and upload firmware to the Arduino Nano microcontroller, which controlled the operation of our real-time power monitoring system. The Arduino IDE provided a user-friendly interface with built-in libraries and examples, simplifying the programming process for interfacing with sensors, processing data, and communicating with other components of the system. Its compatibility with various Arduino boards and extensive community support made it an ideal choice for rapid prototyping and development of embedded systems applications.

3.2.3.3 QGIS

QGIS, or Quantum Geographic Information System, is a free and open-source desktop geographic information system (GIS) software application. In this project, QGIS plays a crucial role in enabling detailed geospatial analysis that goes beyond the capabilities of the web dashboard alone. By linking QGIS directly to the database of the website, establishment of a seamless workflow that allows performing advanced spatial analysis and processing tasks is made possible. QGIS serves as a powerful desktop GIS platform for conducting in-depth analysis, such as spatial queries, overlay operations, proximity analysis, and statistical analysis, leveraging its extensive array of tools and plugins. These analyses provided valuable insights into power distribution dynamics, identifying spatial patterns, hotspots, and potential issues that may not be readily apparent through the web dashboard alone. Moreover, by directly linking QGIS to the website database, any changes or analyses performed in QGIS are automatically updated and reflected in real time on the web dashboard. This integration ensures that the web dashboard remained synchronized with the latest data and analysis results, allowing stakeholders to access up-to-date information and insights as they were being manipulated and processed in QGIS. Overall, the combination of QGIS with the web dashboard enhances our ability to perform detailed geospatial analysis while maintaining real-time data visualization and accessibility for stakeholders.

3.3 Research Design

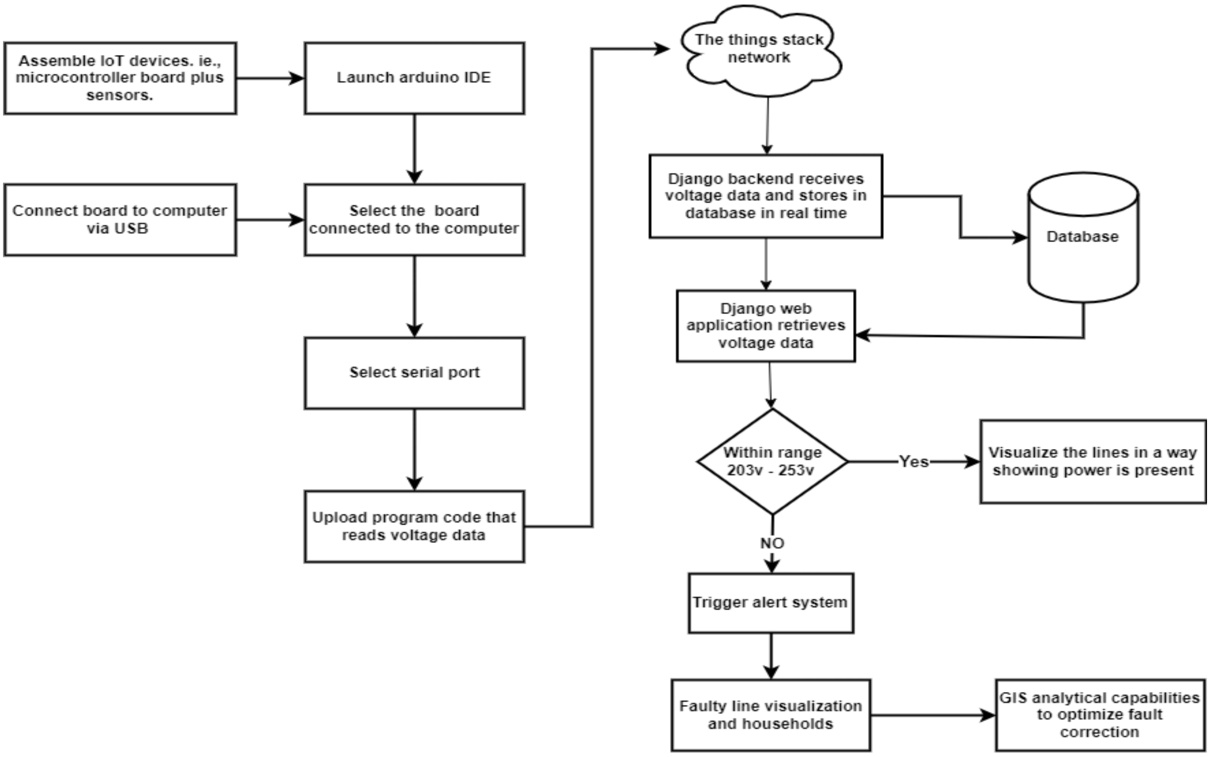

Figure 3.3 Research design 1

From the research design, the necessary hardware components to measure voltage data along power lines were assembled. This includes the Arduino Nano microcontroller, ZMPT101B AC voltage sensor, a lithium-ion battery for power supply, LoRa transceiver for wireless communication, and logic level converters and boost converters for signal conditioning and power management. The Arduino Nano is programmed to read voltage data from the sensors and transmit it wirelessly using the LoRa module to The Things Stack network server.

Once the voltage data is received by The Things Stack network, it is consumed by Django backend endpoint through a generated API for our web application from the things stack network. The data is transmitted in real-time in JSON format, allowing the backend to process and store it in the database. Simultaneously, the frontend of our web application utilizes this data to dynamically visualize power line data on a web map. In the visualization, if the voltage readings fall within the range of 207 to 253 volts, the power line is displayed as a green dashed line, along with its branches. Household points are represented by yellow markers with blue rings to indicate that they are receiving power. However, if the voltage deviates from this range, indicating a power outage or fault the alert button is triggered to signal fault and the visualization of the power line on the map changes accordingly. The power line turns purple, and the house rings turn red, alerting users to the disrupted power supply.

For geospatial data analysis, leveraging various tile layers, such as Google Maps Roadmap for routing analysis and OpenWeatherMap API for weather data makes it possible. Additionally, elevation data from the USGS Shuttle Radar Topography Mission Global 1 Arc-Second dataset is overlaid with power line data to identify elevation points along the network. Furthermore, QGIS is linked directly to the website database, enabling enhanced spatial analysis and visualization capabilities. For the generation of elevation points Euclidean distance

Through this comprehensive approach, all objectives were achieved; integrating IoT devices for data collection, dynamically visualizing power line data, and monitoring power lines in real-time on a web GIS dashboard and implementing GIS analytical capabilities. This enables us to gain insights into power distribution dynamics, identify potential issues, and make informed decisions to optimize power infrastructure management.

CHAPTER FOUR: RESULTS AND DISCUSSIONS.

4.1 Introduction

This chapter delves into the outcomes of the project, showcasing the practical application of the proposed solution and its implications for power distribution monitoring and management. Through a comprehensive examination of the web dashboard and associated visualizations, this section aims to elucidate the efficacy of the integrated approach in addressing the challenges faced by the power sector in Kenya. By scrutinizing the data, insights, and user interface design, this chapter provides valuable insights into the project's achievements, limitations, and avenues for future research and development.

4.2 IoT device connection

To establish the IoT device connection for voltage data measurement, attention was devoted to assembling and configuring the necessary components. The centrepiece of this setup was the Arduino Nano microcontroller, chosen for its compact size and versatility. Paired with the ZMPT101B AC voltage sensor, the Arduino Nano formed the core of the voltage measurement system. Additionally, a Lithium-ion battery pack with a combined capacity of 6000 + 4000mAh provided the necessary power supply for uninterrupted operation.

The initial step involved connecting the ZMPT101B sensor to the Arduino Nano microcontroller. This entailed wiring the output pin of the sensor to one of the analogue input pins of the Arduino Nano, ensuring compatibility and data transmission capability. To facilitate seamless communication between the components, logic level converters were employed to adjust voltage levels as needed. The integration of a LoRa transceiver module enabled wireless data transmission, eliminating the need for cumbersome physical connections. The LoRa module, known for its long-range communication capabilities, served as the conduit for transmitting voltage data from the Arduino Nano to the centralized monitoring system. The LoRa transceiver module utilized in the device connection setup incorporates an antenna for efficient wireless communication. The antenna served as the interface between the transceiver module and the surrounding environment, facilitating the transmission and reception of LoRa signals over long distances. A crucial aspect of this setup was the inclusion of back converters and boost converters to optimize power efficiency and ensure reliable performance.

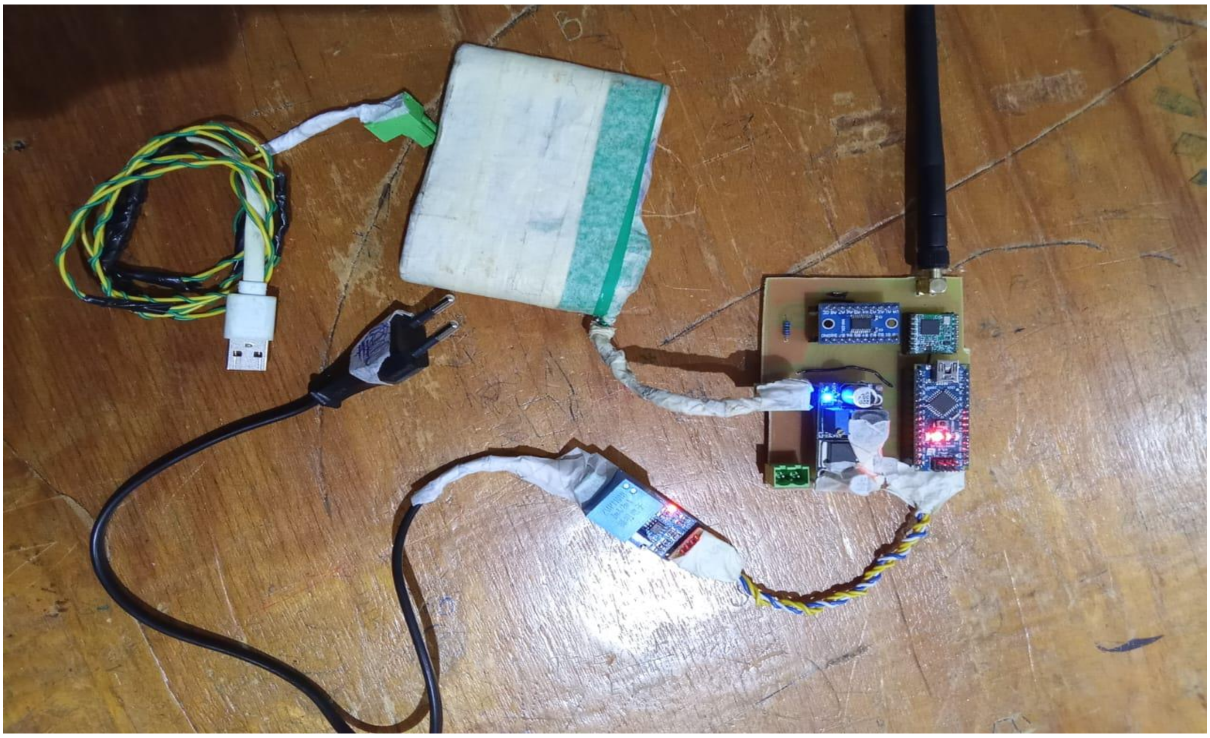

Figure 4.2 IoT device connection 1

4.3 IoT programming

The Arduino microcontroller, programmed using the Arduino IDE software, was configured to read analogue voltage values from the ZMPT101B sensor and convert them into a digital format. This process involved sampling the voltage at regular intervals and applying a calibration algorithm to ensure accuracy. Once the voltage data was acquired, the microcontroller utilized the LoRa transceiver module to transmit the data wirelessly to a central monitoring system. The code implemented a custom protocol for packaging and transmitting the data packets, ensuring reliable communication over long distances. Additionally, error handling mechanisms were incorporated to handle communication failures and ensure data integrity. Overall, the system provided a robust and efficient means of collecting and transmitting voltage data in real-time.

4.4 Sensor Calibration

Calibrating the ZMPT101B sensor was a crucial step in ensuring the accuracy and reliability of the voltage measurements obtained during the study. The calibration process involved adjusting the sensor's output to accurately reflect the true voltage values in the power distribution network. This was achieved by comparing the voltage readings obtained from the sensor to those measured using a calibrated voltmeter.

The ZMPT101B sensor is equipped with a potentiometer, which allows for manual adjustment of its sensitivity and output. During calibration, the potentiometer was carefully adjusted while simultaneously monitoring the voltage readings from both the sensor and the voltmeter. The goal was to achieve a close match between the voltage values obtained from the sensor and the reference values measured by the voltmeter. By iteratively adjusting the potentiometer and comparing the sensor readings to the voltmeter measurements, the sensor's output was fine-tuned to ensure accuracy and consistency. This process involved making incremental adjustments until the voltage readings from the sensor closely aligned with the reference values.

Once the calibration process was complete, the voltage graph obtained from the sensor data was smoothed to eliminate any potential noise or fluctuations. Smoothing the voltage graph helped enhance the accuracy and readability of the data, making it easier to interpret and analyse.

The calibration of the ZMPT101B sensor played a critical role in ensuring the reliability of the voltage measurements collected during the study. By carefully adjusting the sensor's sensitivity and output, and subsequently smoothing the voltage graph, the accuracy of the data was improved, enabling more meaningful insights into the power distribution system's performance.

Figure 4.4 Sensor calibration 1

4.5 IoT deployment at the site

The IoT device, comprising an Arduino Nano microcontroller, ZMPT101B voltage sensor, and LoRa transceiver module, was carefully enclosed within a protective box to shield it from environmental elements and ensure its longevity. This box provided a secure housing for the device, safeguarding it against dust physical damage. The device was then connected to a standard socket using a plug, allowing it to be conveniently integrated into the household electrical system. The chosen socket served as an endpoint of the powerline phase under observation, enabling the monitoring of power fluctuations and voltage levels specific to that line phase. By strategically situating the device within a household in Nyeri-View, which receives electricity from the targeted powerline phase, the IoT deployment effectively captured real-time data reflecting the power dynamics within the local distribution network. This deployment strategy ensured the seamless integration of the IoT device into the existing infrastructure while facilitating continuous and reliable monitoring of power parameters essential for the project's objectives.

Figure 4.5 IoT device connected to socket 1

4.6 The web GIS application development

4.6.1 The web backend

The development of the web GIS application was facilitated by the Django framework, leveraging its robust features for backend development. Visual Studio Code (VS Code) served as the primary development software, offering a streamlined environment for coding and debugging. In the backend, a PostgreSQL database with the PostGIS extension was utilized to store and manage spatial data efficiently. This database setup enabled advanced spatial queries and analysis, crucial for processing geospatial information effectively. Moreover, the database was linked to QGIS, a powerful open-source GIS software, to perform complex spatial analysis tasks that cannot be directly executed within the web dashboard. This integration with QGIS enhanced the analytical capabilities of the system, allowing for in-depth spatial analysis and visualization. Within the backend, the admin site provided a convenient interface for managing and configuring the application, while a Leaflet basemap served as a foundational guide for frontend development. By leveraging these tools and technologies, the web GIS application was developed with a strong foundation for handling spatial data and providing advanced geospatial analysis capabilities.

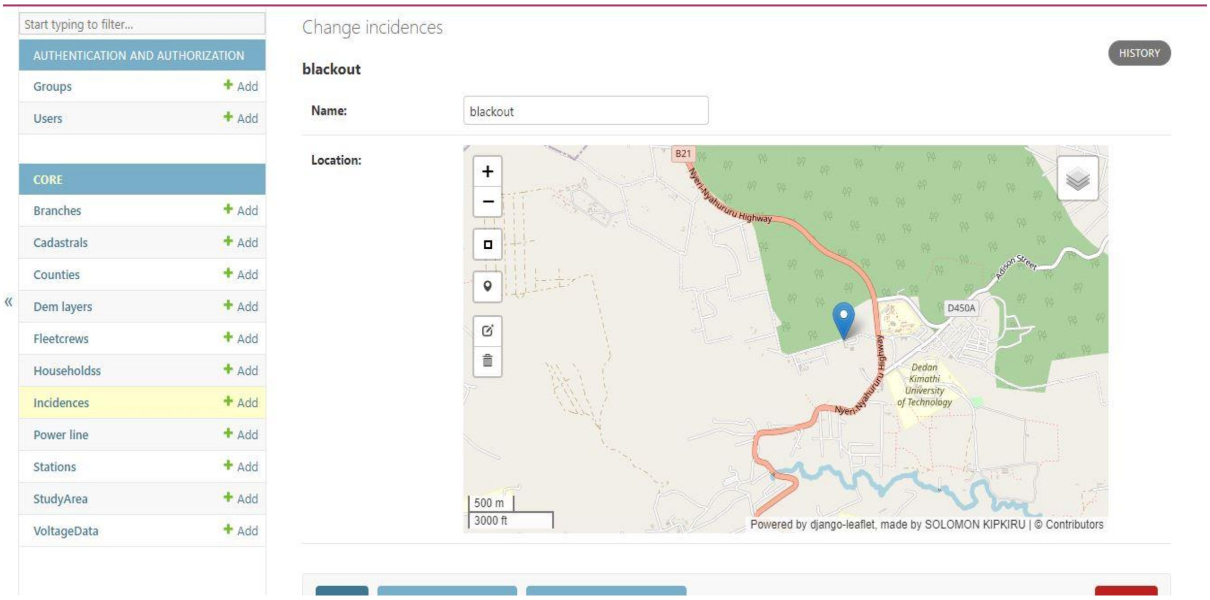

Figure 4.6 Django admin site 1

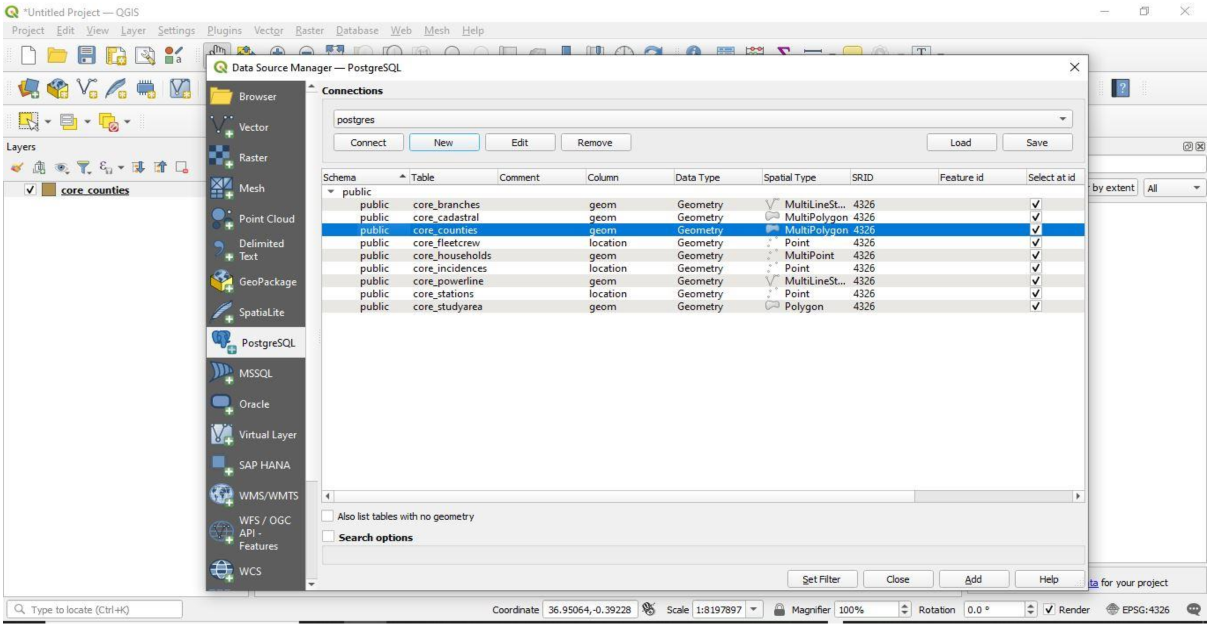

Figure 4.6 Connecting QGIS with website database 2

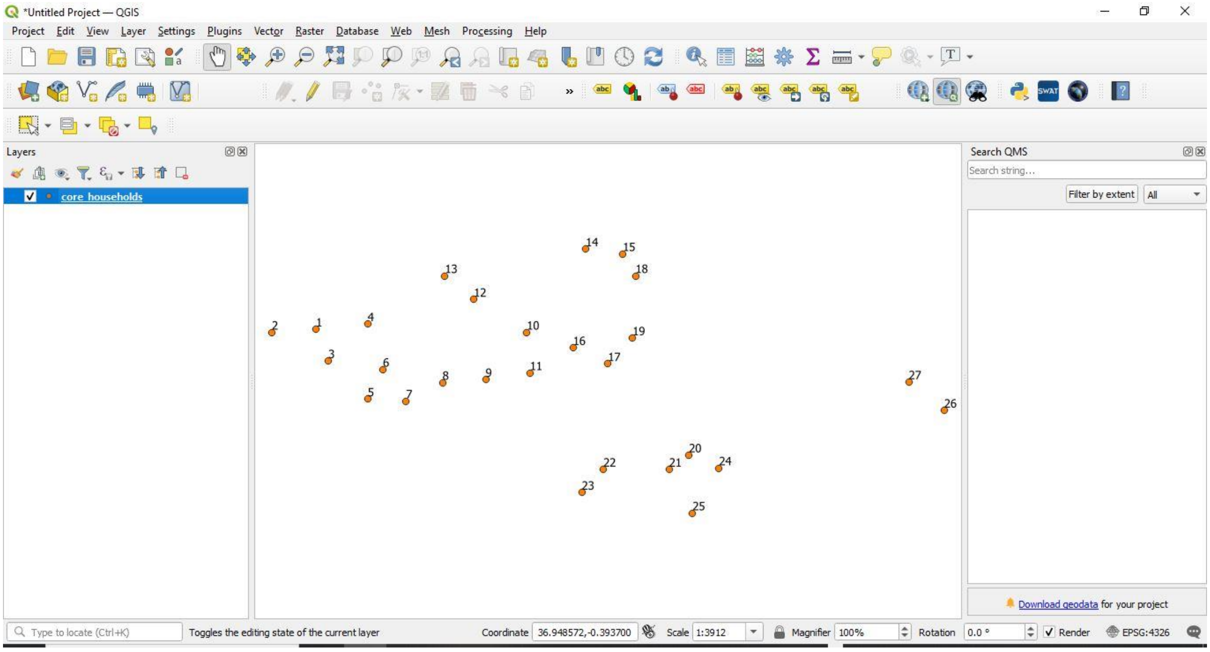

Figure 4.6 Advanced data manipulation to update the GIS web map using QGIS 3

4.6.2 Loading of the datasets to the database

The use of the ogrinspect function within the Django framework played a crucial role in the development of the project's database models and the integration of spatial data. Ogrinspect allowed for the automatic generation of Django models from existing spatial data sources, such as shapefiles, simplifying the process of data integration and database management. By analysing the structure and attributes of spatial datasets, ogrinspect generated Python classes representing the data schema, including fields for geometry and attribute data. This approach facilitated seamless integration of spatial data into the project's database, enabling efficient storage and retrieval of geospatial information. With ogrinspect, it became possible to define spatial models that accurately represented the characteristics of powerline networks, household locations, and cadastral boundaries. Additionally, ogrinspect provided flexibility in defining model relationships and constraints, allowing for the establishment of spatial relationships and data integrity rules within the database.

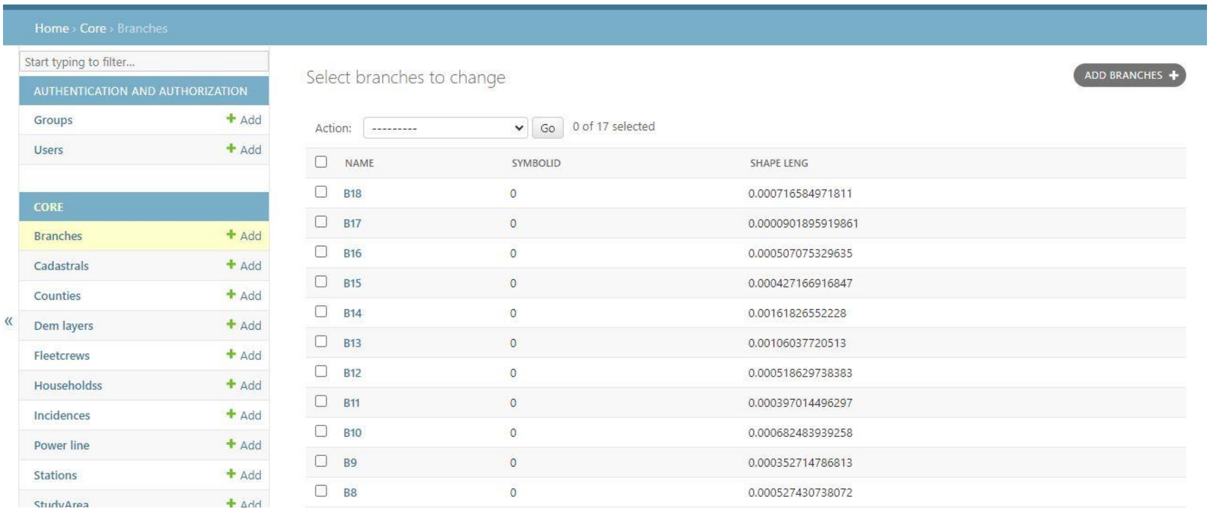

Figure 4.6 Models storing spatial data made possible through ogrinspect leaflet extension 4

4.6.3 The web frontend

In the project's web frontend, the Django REST Framework played a pivotal role in enabling seamless communication between the backend server and the client-side application. Through the Django REST Framework, data from the backend database, including powerline information and other relevant datasets, was efficiently retrieved and transmitted to the web dashboard. This facilitated the real-time visualization of powerlines on a map canvas directly within the dashboard interface.

4.6.4 The map canvas

The map canvas served as a central component of the web dashboard, providing a visually intuitive platform for users to interact with and analyse power distribution data. By integrating power line visualizations with other pertinent data layers, such as household locations and cadastral boundaries, the dashboard offered a comprehensive view of the power distribution network within the study area.

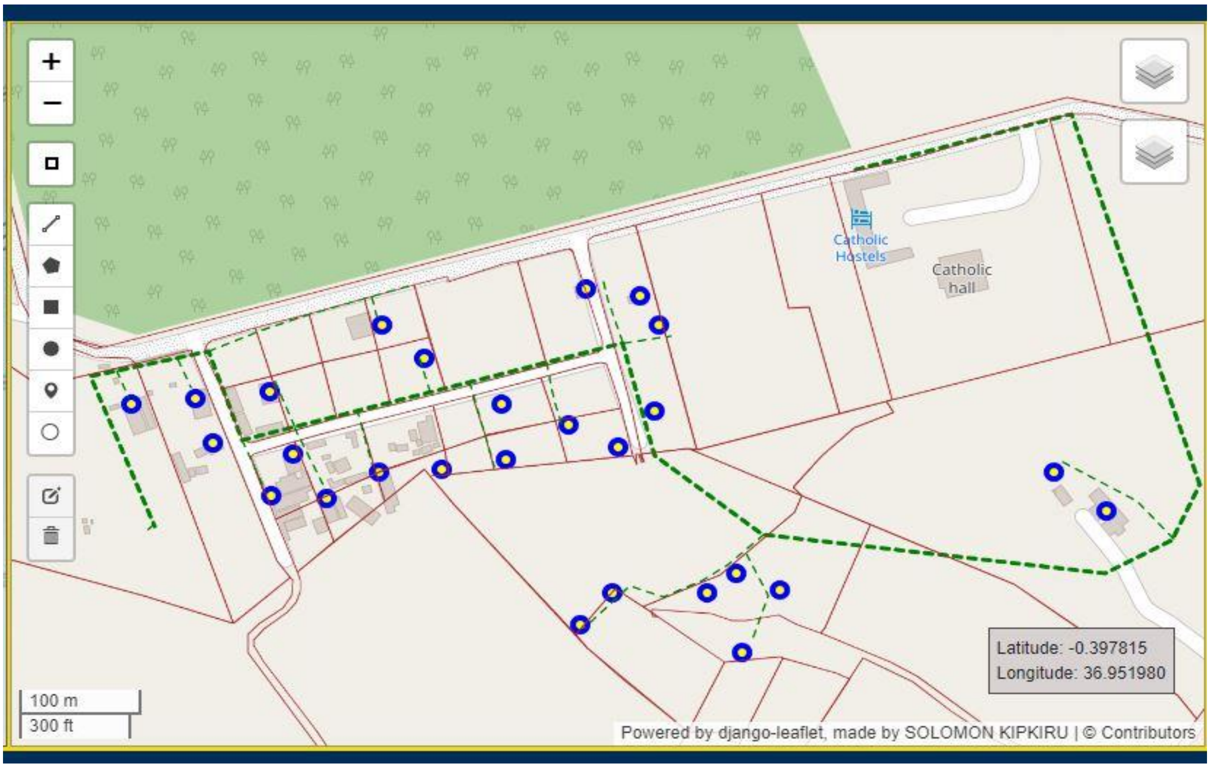

Figure 4.6 GIS web map canvas for dynamic visualization 5

4.6.5 Powerline and household data visualization

When power is present and flowing through the distribution network, the powerlines are depicted as vibrant green dashes, indicating normal functioning. This color choice signifies the presence of electricity and visually reassures stakeholders of uninterrupted power supply. In contrast, when a fault or disruption occurs within the power distribution system, the color scheme undergoes a significant change. The powerlines transition to a striking purple hue, serving as an immediate visual cue of the fault event. Purple, often associated with alertness and caution, effectively communicates the need for attention and intervention.

Simultaneously, the household marker rings, representing individual households connected to the powerlines, undergo a transformation as well. In the presence of power, these rings are depicted in a reassuring blue outline, indicating that the households are receiving electricity. However, when a fault occurs, these rings change to a vivid red colour, signalling the loss of power supply to the affected households.
The main powerline phase was given more weight to make it thicker to distinguish it with the branches supplying the households.

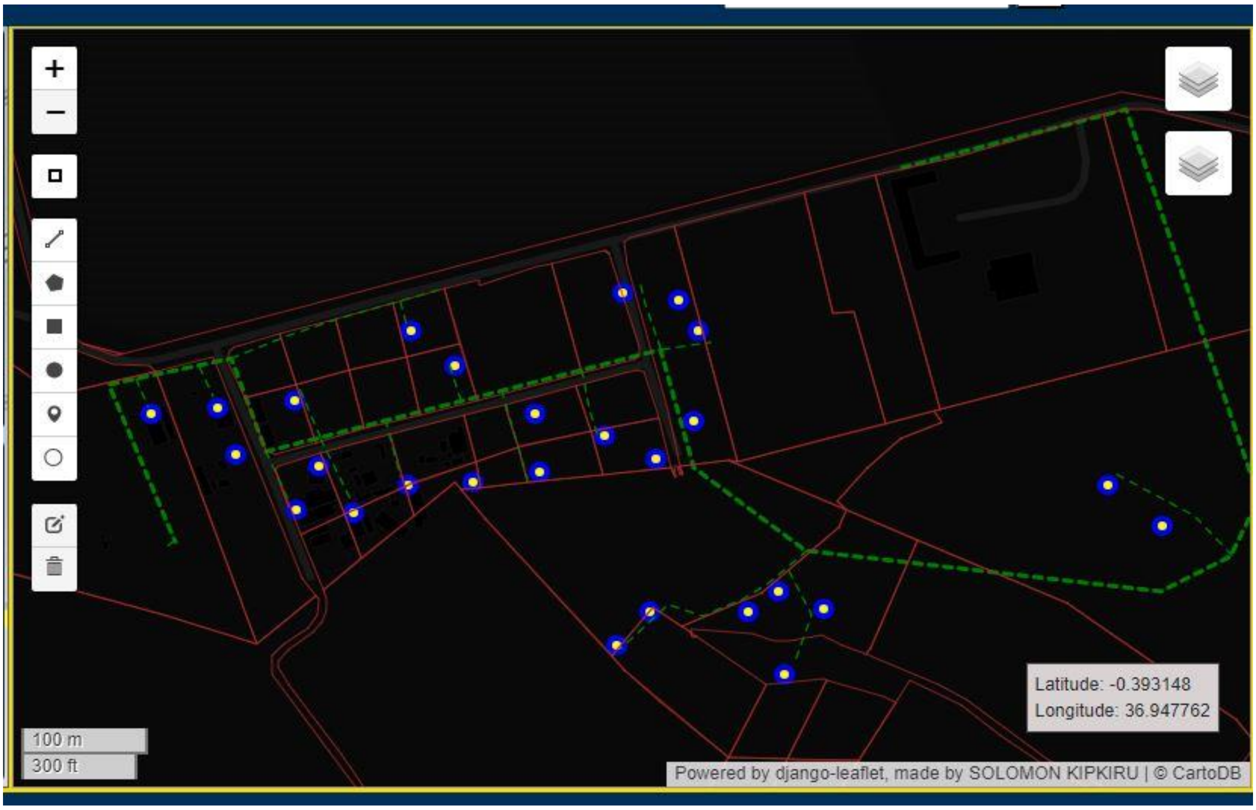

Figure 4.6 Powerline and household visualization when power is present 6

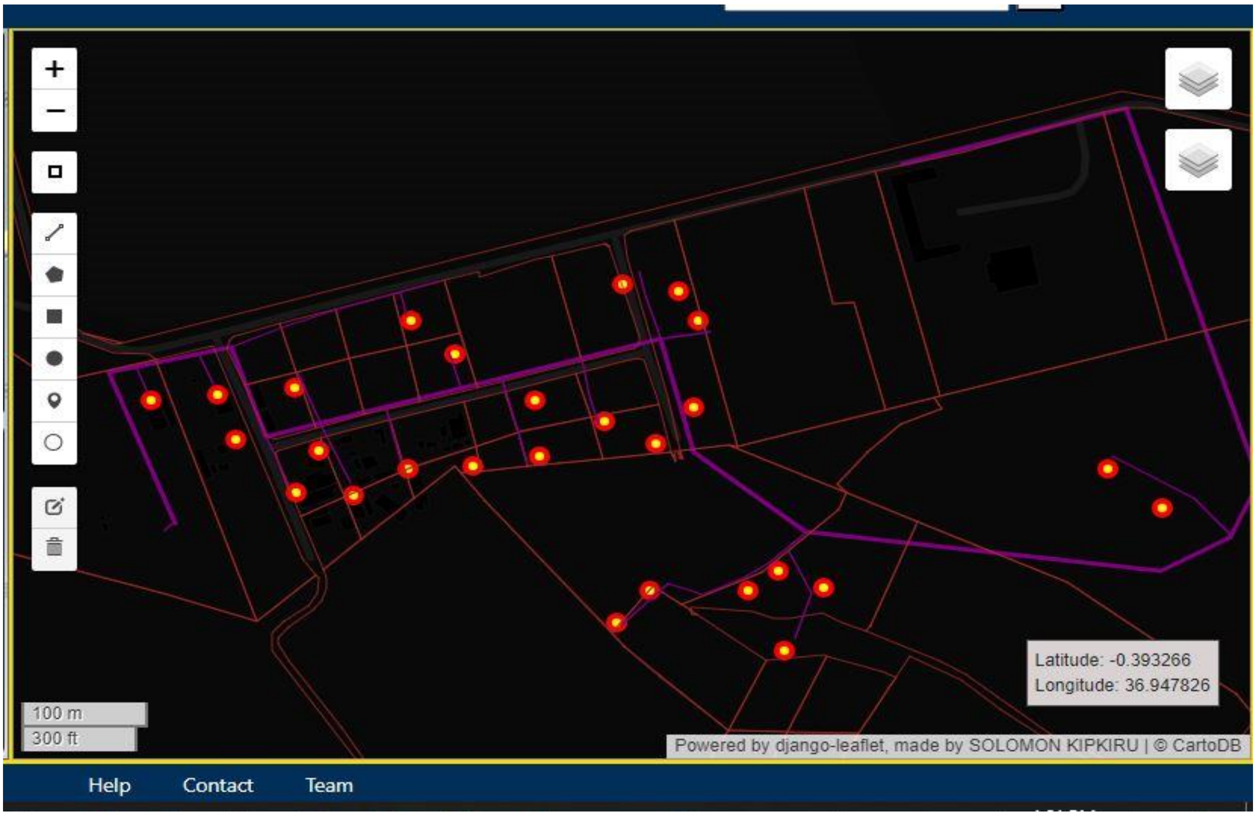

Figure 4.6 Powerline and household visualization when there is fault *7*

4.7 GIS analytical capabilities

Overlaying the powerline dataset with terrain data obtained from USGS (USGS/SRTMGL1_003) through the Google Earth Engine API, allowed visualizing the elevation changes along the powerline route. This visualization provided valuable insights into the terrain characteristics encountered by the power lines, including areas of varying elevation gradients. The incorporation of elevation data into the visualization enhances situational awareness of the power distribution network by depicting areas with steep inclines or rugged terrain.

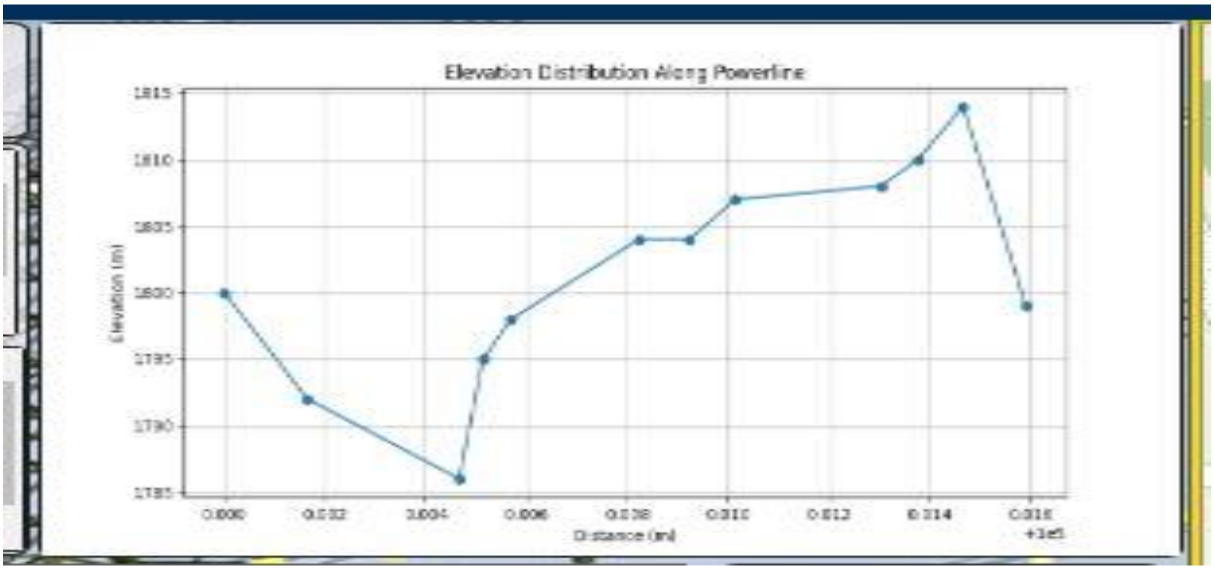

Figure 4.7 Elevation profile along the powerline 1

The integration of the OpenWeatherMap API into the power monitoring system yielded valuable insights into the weather conditions affecting the monitored region. By displaying real-time weather information directly within the frontend interface, enabled immediate access to critical data such as rainfall, cloud cover, and temperature.

The web GIS dashboard provided a comprehensive platform for real-time monitoring, including dynamic graphing of voltage against time based on sensor readings. This feature allowed monitoring team to track fluctuations in voltage levels, facilitating proactive fault detection. Additionally, the dashboard showcased detailed information about the powerline infrastructure, including the type of poles used, cables, and the length of the lines. Such data proved invaluable for decision-making processes and optimizing fleet crew deployment for repairs and maintenance tasks.

Furthermore, the integration of the Leaflet Routing Machine plugin enabled sophisticated routing analysis directly within the dashboard. This functionality empowers monitoring teams to efficiently manage routes and assign tasks to fleet crew based on their proximity to fault locations. By leveraging this routing feature, teams could streamline response times and maximize the effectiveness of maintenance efforts, ultimately enhancing the reliability and resilience of the power distribution network.

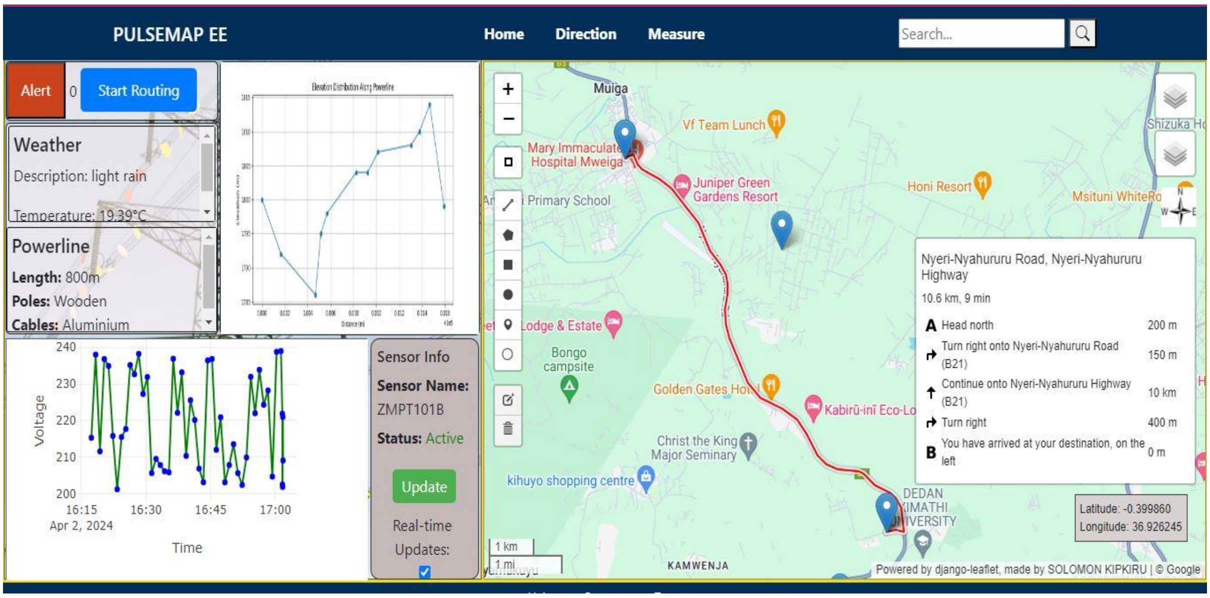

Figure 4.7 Full website interface with map canvas performing routing analysis 2

4.8 Cases of recorded faults

On April 2, 2024, residents of Nyeri experienced a significant power outage that began at 4:00 AM and lasted until 9:00 AM. While power was restored to most areas during this time frame, the Nyeri-View line phase encountered an individual fault that prolonged the outage. Unfortunately, residents in this area experienced an extended period without electricity, lasting until 6:00 PM, totalling approximately 14 hours without power. This outage posed considerable inconvenience and likely disrupted daily activities for the affected residents. The delay in restoring power to the Nyeri-View line phase highlights the challenges involved in quickly resolving individual faults within the power distribution network

The cause of the fault was due to weather as heavy rain had been experience starting previous day late at night at which prolonged till morning hours of April 2, 2024.

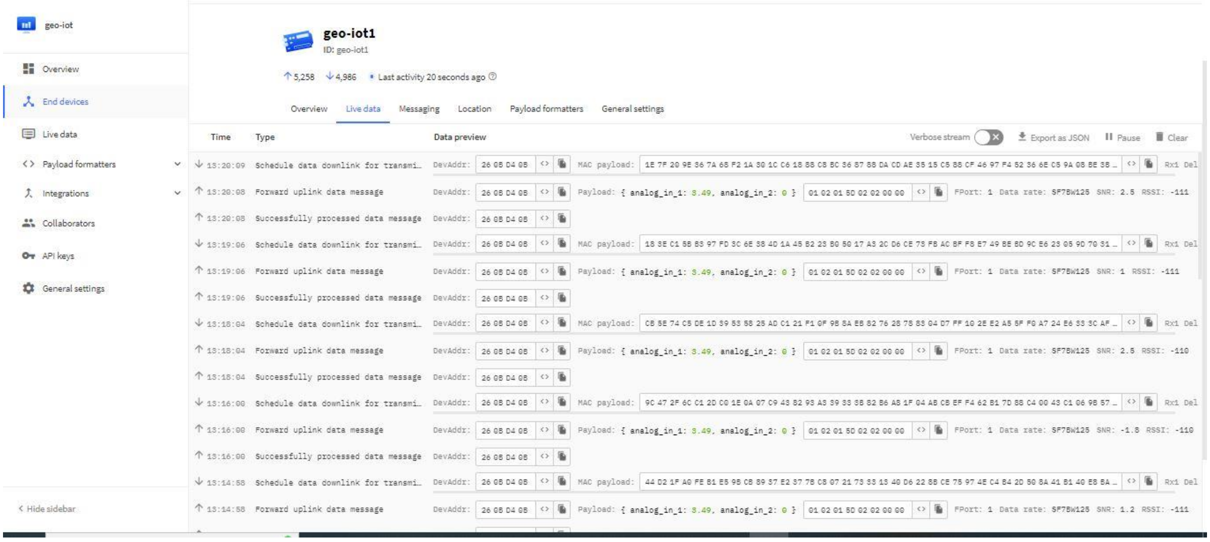

Figure 4.8 Data streamed in things stack network for recorded fault on April 2 2024 1

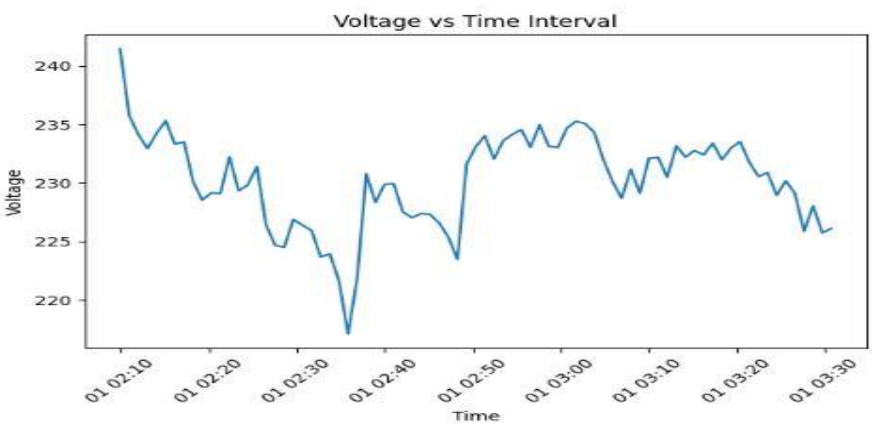

Figure 4.8 Graph of voltage against time interval that was part of recorded data when there was no fault 2

	analog_in_2	received_at
0	2.44	2024-04-02T14:20:29.768949746Z
1	2.44	2024-04-02T14:19:27.598698894Z
2	0.00	2024-04-02T14:18:25.426496841Z
3	0.00	2024-04-02T14:17:23.267013460Z
4	2.44	2024-04-02T14:16:21.109258074Z
...	...	...
136	0.00	2024-04-02T11:59:35.708813419Z
137	2.44	2024-04-02T11:58:33.548728217Z
138	0.00	2024-04-02T11:57:31.395470249Z
139	2.44	2024-04-02T11:56:29.244071716Z
140	0.00	2024-04-02T11:55:27.065473050Z

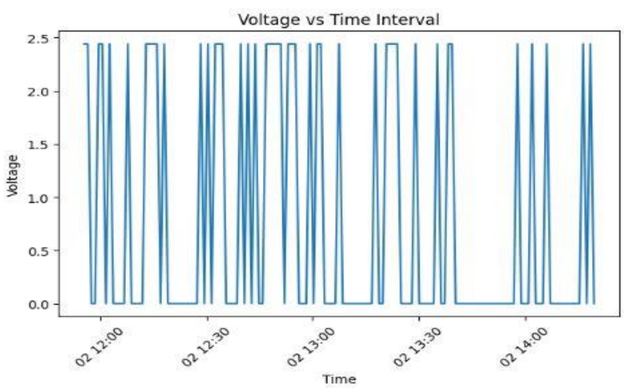

Figure 4.8 Data and graph showing fluctuation in readings that were captured when there was a fault indicating noise in sensor readings 3

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Research findings and summary

The deployment of IoT devices for power monitoring in Nyeri-View has provided invaluable insights into the state of the electrical infrastructure and its impact on the community. Through the integration of sensors such as the ZMPT101B voltage sensor and the utilization of technologies like the Django framework and VS Code for web GIS development, we have been able to create a comprehensive monitoring system. This system not only tracks power consumption and voltage fluctuations but also visualizes powerline data, weather conditions, and routing analysis, providing a holistic view of the electrical grid.

During the outage on April 2, 2024, which coincided with adverse weather conditions of heavy rainfall and lower temperatures, the monitoring system proved invaluable in understanding the extent of the fault and its impact on the community. The outage, exacerbated by the inclement weather, underscores the importance of proactive monitoring and maintenance of power infrastructure to minimize disruptions and ensure reliable electricity supply.

Observed pattern of high voltage during the day and low voltage during the night in Nyeri View can be attributed to the daily activities and behaviour of its residents, many of whom are students and staff of Dedan Kimathi University of Technology. During the day, when occupants are typically engaged in university activities, electricity usage in residential areas tends to decrease. This reduction in demand results in higher voltage levels being recorded on the power grid.

Conversely, during the night, residents return to their homes after university hours, leading to an increase in electricity usage for various purposes such as lighting, appliances, and security lights. This surge in demand places greater strain on the power distribution infrastructure, causing voltage levels to drop compared to daytime readings.

5.2 Conclusions

The real-time visualization capabilities of the web dashboard allow for efficient monitoring of power distribution, enabling prompt responses to faults and outages. Moreover, the integration of OpenWeatherMap API enhances situational awareness by providing critical weather information that can influence power infrastructure resilience.

Moving forward, the insights gained from this monitoring system can inform decision-making processes for infrastructure upgrades, maintenance prioritization, and emergency response planning. By leveraging IoT technologies and data-driven approaches, we can enhance the resilience and efficiency of the power distribution network, ultimately improving the quality of life for residents in local communities.

The correlation between human activity patterns and voltage fluctuations highlights the dynamic nature of electricity consumption in residential areas. Understanding these patterns is crucial for power providers to optimize grid operations, ensure stable voltage supply, and effectively meet the needs of the community. It also underscores the importance of implementing smart grid technologies and demand-side management strategies to balance supply and demand and enhance overall grid reliability.

5.2 Recommendations

Future enhancements of the power distribution should leverage machine learning and artificial intelligence (AI) technologies, such as Gemini AI, to optimize system performance. By analysing past recorded data and considering various factors influencing power distribution, including weather patterns, historical usage trends, and infrastructure conditions, AI algorithms can generate valuable insights and predictions. These predictive analytics can aid in proactive decision-making, such as pre-emptive maintenance scheduling and load forecasting, ultimately improving system reliability and efficiency.

Expanding the sensor network to include additional parameters beyond voltage measurement can provide a more comprehensive understanding of the power distribution environment. Sensors capable of monitoring factors such as wind speed, humidity, and temperature can offer valuable insights into weather-related impacts on the power grid. By integrating diverse sensor data into the monitoring and analytics framework, operators can better anticipate and respond to changing environmental conditions, mitigating potential risks and optimizing system performance.

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