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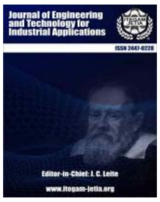

RESEARCH ARTICLE OPEN ACCESS

MODERNIZING ELECTRICAL UTILITY NETWORKS: THE ROLE OF GEOGRAPHICAL INFORMATION SYSTEM IN ENHANCING POWER DISTRIBUTION AND MANAGEMENT

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ABSTRACT

Electrical utility networks, structured as centralized power systems with one-way flow, are undergoing significant transformation. Geographic Information Systems (GIS) have become pivotal in modernizing these networks, enabling spatial analysis, real-time monitoring and optimization of power distribution. Traditional electrical utility networks, reliant on manual operations, struggle with fault detection, load balancing, and integrating renewable energy sources. This study focuses on a comparative analysis of these traditional and modern networks, highlighting the structural evolution, technological advancements, and the critical role of GIS in creating a scalable, future-ready power infrastructure. To increase operational efficiency, modern systems make use of IoT sensors, smart grid technology, and predictive analytics. GIS supports dynamic decision-making by integrating real-time data with geographic context. The transition marks a paradigm shift toward decentralized, data-driven, and resilient energy networks.

I. INTRODUCTION

Traditionally, the electric power grid relied on large central power plants that supplied electricity through a high-voltage (HV) transmission network, which then connected to local distribution systems delivering energy directly to customers [1]. These electrical utility networks have long played a critical role in power generation, transmission, and distribution, ensuring that electricity reaches industries, businesses, and households efficiently. Despite these improvements, conventional grids still face challenges in efficiency and adaptability. Many conventional grids operate on outdated infrastructure, making them inefficient in handling increasing loads and ensuring seamless power distribution [2]. One major issue is high transmission losses, where electricity dissipates as it travels through long-distance power lines. As the electricity demand continues to grow, traditional utility networks are struggling to keep pace with modern requirements. Transmission and distribution (T&D) networks account for energy losses estimated at up to 30% of total generated power. Another key challenge is the lack of flexibility in traditional grids. These systems were designed with rigid, centralized structures, making it difficult to adapt to shifting energy demands and unexpected disruptions.

The electric power industry faces major hurdles in reaching grid parity. While integrating variable energy resources offers the promise of a cleaner environment, it also creates challenges such as greater demands for regulation, ramping, and reserve capacity [1]. Additionally, the absence of real-time monitoring systems means utilities often rely on reactive maintenance, addressing problems only after they occur rather than preventing them in advance. To improve grid reliability and efficiency, utilities must transition to more intelligent and data-driven management systems. By implementing automated controls, predictive maintenance, and advanced analytics, power networks can minimize losses, enhance operational efficiency, and ensure a more stable electrical supply. Modern utility systems demand efficient energy distribution and management to keep up with rising consumption and environmental concerns. With the growing need for sustainable solutions, integrating smart technologies and renewable energy sources has become essential. By enhancing network connectivity and optimizing power flow, utilities can improve reliability, reduce costs, and support a more sustainable energy future. There are different researchers who have explored the applications of Geographic Information System (GIS) in network connectivity, subnetwork management, and smart grids.

As the global energy landscape evolves, electrical utility networks must transition from static, conventional frameworks to dynamic, data-driven infrastructures. Traditional grids often rely on manual operations and reactive maintenance, leading to inefficiencies in power distribution and outage management. In contrast, modernized networks leverage advanced digital technologies to improve real-time monitoring, spatial analysis, and fault detection. Applying digital processing and communications to the power grid places information management at the core of the smart grid concept. This integration of digital technology with power systems unlocks a wide range of new capabilities [3]. Geographic Information Systems (GIS) play a fundamental role in this transformation, providing utilities with enhanced asset tracking, predictive maintenance, and operational efficiency [4], [5]. This study examines the comparative advantages of traditional and modernized networks, highlighting GIS as a key enabler of efficiency and resilience. Currently, power distribution relies heavily on manual processes, such as updating network construction plans, monitoring operations, and maintaining consumer records. This limited oversight reduces the ability to prevent losses and address outages efficiently.

To overcome these challenges, electric utilities are increasingly adopting Geographic Information Systems (GIS), which provide a spatially oriented view of distribution networks and help reduce outages while improving system management [6]. The absence of an integrated mapping system meant that utilities struggled to track infrastructure efficiently, leading to frequent disruptions and maintenance challenges. GIS bridges the gap between utility assets and customer activity. It shows where solar panels are being installed, highlights high-risk parts of the grid, and helps utilities decide which assets to replace first [7]. Additionally, GIS is capable of identifying patterns in network performance, allowing utilities to analyze faults, optimize power distribution, and plan future expansions with greater accuracy.While GIS has proven to be a valuable tool in modernizing electrical utility networks, several research gaps remain. Existing studies primarily focus on GIS applications for asset tracking, outage management, and infrastructure planning, but there is limited research on standardized frameworks for GIS implementation across different utility infrastructures, leading to inconsistent adoption. Additionally, while GIS enhances power distribution and fault detection, its role in optimizing renewable energy integration and improving real-time load forecasting remains underexplored.

There is also a lack of studies analyzing the long-term cost-benefit impact of large-scale GIS adoption, making it difficult for utilities to assess its financial feasibility. Furthermore, research on GIS for grid decentralization and microgrid planning is still in its early stages, limiting its potential use in developing more resilient and adaptive power networks. Addressing these gaps will help maximize GIS's effectiveness in transforming traditional power grids into efficient, modernized systems. The objective of this study is to utilize the power of Geographical Information System (GIS) in building a smart and modernized electrical network, and also to analyze the limitations of conventional grids and the advancements enabled by GIS-driven smart grids [8]. Furthermore, this study explores how GIS supports predictive maintenance, optimizes load balancing, and enables adaptive energy management. With spatial analytics and intelligent automation, GIS plays a crucial role in building a more sustainable and efficient power infrastructure. Given that every country has its own approach to utility management, the challenge of ensuring a reliable and modernized grid becomes even more critical on a global scale. Effective management is essential to address these complexities, and GIS provides a unified framework to enhance collaboration and drive the future of power system modernization.

II. STUDY AREA

The study area chosen for this study is Lisle, Illinois, United States of America. The selected study area, Lisle, Illinois, is a vibrant suburban village in DuPage County, United States, recognized for its strategic energy infrastructure, diverse topography, and evolving power distribution network. Situated within the Chicago metropolitan area, Lisle serves as a critical hub for energy distribution, smart grid integration, and infrastructure optimization. Its blend of urban, suburban, and industrial sectors makes it an ideal location for analyzing network connectivity and renewable energy potential. Figure 1 shows the study area of Lisle, Illinois Lisle's climate, population density, and existing electrical infrastructure directly influence energy consumption patterns, distribution efficiency, and grid stability. The village features a well-established power distribution network, complemented by major transportation arteries such as Interstate 88, U.S. Route 34, and the Metro rail system, which impact energy demands across residential, commercial, and industrial sectors. The area also houses key green spaces, including the Morton Arboretum, providing unique opportunities for sustainable energy planning and environmental impact assessments. Table 1. depicts the description of the study area.

Table 1: Key Features of the Study Area.

Sl. No.	Feature	Details
1.	Location	Lisle, DuPage County, Illinois, USA
2.	Total Area	18.08 km²
3.	Population	23,222 as of 2023
4.	Latitude & Longitude	41.8011° N, 88.0748° W
5.	Elevation	206 meters (676 feet) above sea level
6.	Climate Type	Humid continental

Source: Authors, (2026).

III. DATA COLLECTION AND PROCESSING IN ELECTRICAL UTILITY NETWORKS

Data collection and processing in an electrical utility network involve multiple techniques to ensure accurate mapping, monitoring, and management of both low-voltage (LV) distribution and high-voltage (HV) transmission systems. The process starts with manual surveys and remote sensing technologies, followed by real-time monitoring systems and GIS-based digitalization to convert raw data into actionable insights.

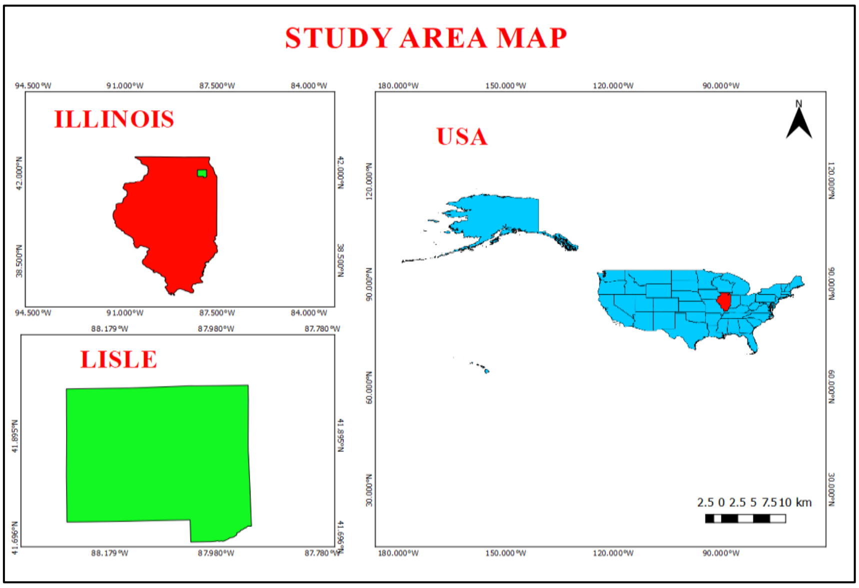


Figure 1: Study Area.
Source: Authors, (2026).

The data collection process involves multiple methodologies, each contributing to the overall accuracy and reliability of network analysis. One of the primary methods includes manual field surveys with GPS mapping, where utilities perform on-site inspections to capture transformer locations, feeder paths, and customer connections [9]. The use of smart meters and Advanced Metering Infrastructure (AMI) further supplements data acquisition by providing real-time energy consumption patterns, voltage fluctuations, and anomaly detection.

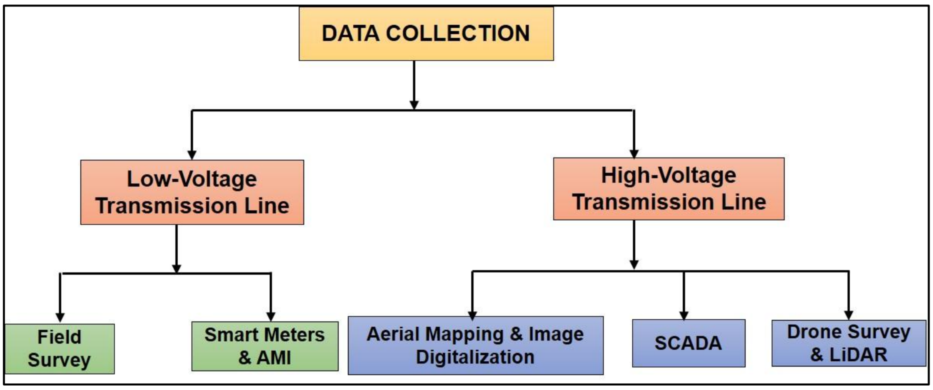


Figure 2: Data collection methods for low & high voltage transmission lines.
Source: Authors, (2026).

These smart grids continuously collect data at predefined intervals, allowing seamless monitoring of the power distribution network [10]. Figure 2 shows the various data collection methods for low & high-voltage transmission lines.

Manual Field Surveys & GPS Mapping: Utilities perform on-site surveys with handheld GPS devices and GIS tools to map transformer locations, feeder paths, and customer connections. Spatial data were collected using a Global Positioning System (GPS), while non-spatial data were obtained through direct field interviews [11].

Smart Meters & AMI (Advanced Metering Infrastructure): Smart meters and AMI provide real-time energy data, detect anomalies, and monitor voltage fluctuations, serving as primary sources for raw utility data collection. Advanced Metering Infrastructure (AMI) serves as the principal source of data, capturing and retrieving information from end-user premises. Measurements are recorded and collected at intervals of 10 to 15 minutes [12].

Aerial Mapping & Image Digitization: Drones, helicopters, and LiDAR-equipped aircraft capture high-resolution aerial images of substations, transmission lines, and distribution networks, which are then processed into 2D and 3D digital models. Remote sensing techniques, including LiDAR and drone surveys, were employed to map transmission and distribution networks, ensuring accurate asset positioning [11]. Satellite Imagery and Remote Sensing technologies are used to capture large-scale infrastructure layouts for terrain analysis, transmission line planning, and right-of-way management. Google Earth imagery from 2021 was used as a data source to analyze maps, road networks, and land use [11].

SCADA & Smart Grid Monitoring: SCADA (Supervisory Control and Data Acquisition) systems contribute significantly to data collection by gathering real-time information from sensors and Remote Terminal Units (RTUs). SCADA collects real-time, raw grid data from sensors and RTU (Remote Terminal Units), providing unprocessed voltage, power flow, and fault alerts for later analysis. SCADA systems integrate with GIS to provide real-time monitoring of voltage levels, power outages, and system faults. [13].

Drone Surveys: Utilizes UAVs equipped with high-resolution cameras and GPS to capture georeferenced imagery and videos for real-time monitoring and fault detection in electrical utilities. The drone-based inspection system captures high-resolution images and videos of power lines, which are then processed using GIS tools to detect potential faults and assess infrastructure conditions [14].

LiDAR: LiDAR employs laser scanning technology to generate high-precision 3D point clouds, enabling detailed modelling of power infrastructure within GIS frameworks [15].

The vast amount of data collected in smart grids undergoes multiple processing stages to ensure accuracy and reliability. Initially, data preprocessing involves filtering out incomplete or erroneous data, a process known as data cleansing. In this phase, the collected data are processed before any analysis is conducted. To address issues of incompleteness and inaccuracy, inconsistencies are removed through a process known as data cleansing [12]. Next, data integration is performed to unify scattered datasets, such as load profiles and weather conditions, to optimize energy distribution. Data collected from different sources are often inconsistent and need to be combined properly before analysis [12]. Once integrated, data storage ensures accessibility for real-time operations, with smart grids requiring high-speed data retrieval for efficiency. In the data storage phase, the data is stored, located, and can be accessed at any instant of time. Finally, data analytics extracts insights for load forecasting, fault detection, and predictive maintenance, enabling smarter decision-making. In smart grid systems, substantial amounts of data are regularly collected. These data support multiple analyses, such as examining end-user behavior, assessing system states, and detecting faults [12].

IV. STRUCTURE OF ELECTRICAL UTILITY NETWORKS

An electrical utility network is a sophisticated system created to effectively produce, transmit, and distribute electricity to customers. It consists of three main components: generation, transmission, and distribution, each playing a crucial role in ensuring a stable and reliable power supply. The first step is production, in which electrical energy is created in the power plant and converted to high-voltage electrical energy in the power station, which is more suited for effective long-distance transportation [16]. Power plants convert primary energy sources such as fossil fuels, nuclear, hydro, solar, and wind into electricity. In the transmission section of the electric power system, high-voltage (HV) power lines effectively move electrical energy over great distances to the places where it is consumed [16]. Transmission networks use high voltages, typically ranging from 110 kV to 765 kV, to reduce energy losses over long distances. Figure 3 shows the typical distribution of an electrical network system.

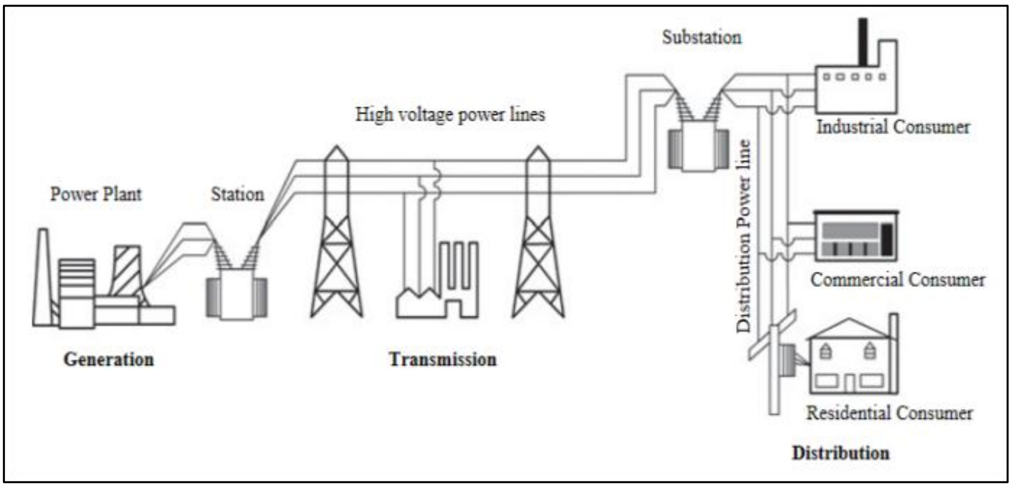


Figure 3: Electrical Network System overview.
Source: [17].

At the substations, voltage levels are stepped down for distribution through distribution networks, which deliver electricity to industrial, commercial, and residential consumers. Remote substations play a critical role in converting high-voltage electricity for delivery over feeder lines optimized for distribution. Subsequently, the electrical energy is further reduced to medium and low voltage to serve residential, commercial, and industrial consumers. The distribution network, including transformers, substations, medium- and low-voltage lines, and metering systems, ensures the reliable delivery of electricity at appropriate voltage levels [16].

V. METHODOLOGY

V.1 CORE FUNCTIONALITIES

This study provides a structured approach to analyzing and comparing traditional electrical utility networks with modernized GIS-based networks. It outlines the key steps involved in data collection, network modeling, and performance evaluation using ArcGIS Utility Network. This section ensures that the research follows a systematic and transparent process, making it easier for utility planners, GIS professionals, and researchers to understand and apply the findings. By using real-world datasets from Lisle, Illinois, this study demonstrates how GIS can transform electrical network management through enhanced connectivity, fault detection, and service expansion planning.

The Public Works Department of the City of Lisle, Illinois, has been using a geometric network to manage its municipal electric network. However, to explore the capabilities of a utility network in ArcGIS, this study utilizes a pre-configured dataset from Esri's Electric Utility Network Foundation. This dataset represents a small subset of the service territory and allows for modelling and analysis of network assets. As part of the study, network tracing was performed to answer key questions about the electrical network, generate reports to identify customer counts, and execute a service line extension to integrate a new customer into the network. This was followed by an update subnetwork operation to incorporate the changes. Figure 4 shows the flowchart of a modernized electric utility network using GIS.

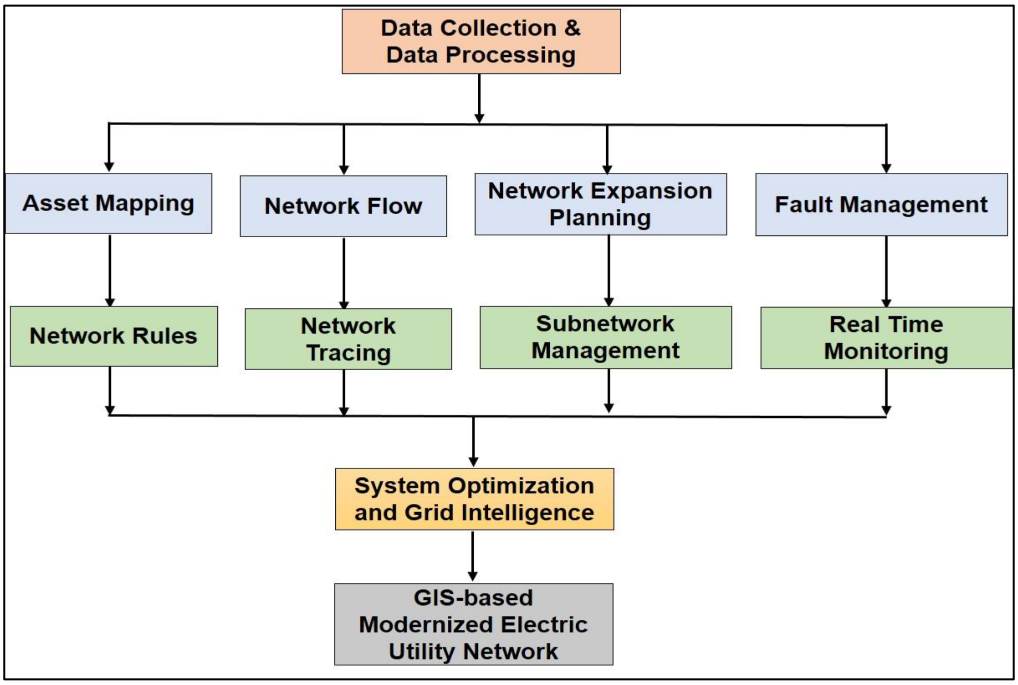


Figure 4: Flowchart of a GIS-driven modernized electric utility network.
Source: Authors, (2026).

V.2 NETWORK RULES IN ELECTRICAL NETWORK

Network rules play an essential role in maintaining the integrity and logical flow of a utility network by defining valid connections between various components. Network rules in ArcGIS Utility Network define valid connections and relationships between network components, ensuring realistic and error-free modelling. They regulate how junctions connect to edges and how assets are contained or structurally attached. These rules help maintain data integrity, optimize power flow, and ensure accurate utility management.

- **Junction:** A junction is a point where electricity flows through or gets distributed. It represents devices like transformers, switches, meters, and fuses.
- **Edge:** An edge is a connection/line that carries electricity between junctions. It represents power lines, cables, or conductors. Junctions and edges work together to form the power grid, ensuring electricity flows efficiently from power stations to consumers [18].

The types of network rules are as follows:

1. Junction-Edge Connectivity Rules
2. Junction-Junction Connectivity Rules
3. Edge-Junction-Edge Connectivity Rules

1. Junction-Edge Connectivity Rules

These rules govern the connections between point features (junctions) and line features (edges). They specify which types of junctions can connect to which types of edges, ensuring logical and valid network configurations [18]. For example, a control valve (junction) connecting to a distribution main(edge) would be governed by such a rule. It is shown in Figure 5.

Figure 5: Junction-edge connectivity in a distribution network.
Source: Authors, (2026).

2. Junction-Junction Connectivity Rules

These rules manage the connectivity between two junction features, whether they are geometrically coincident or associated through connectivity associations. For example, connectivity associations link a fuse, transformer, and breaker to transition power from medium-voltage three-phase to low-voltage single-phase, ensuring efficient and safe electricity distribution [18], and it is depicted in Figure 6.

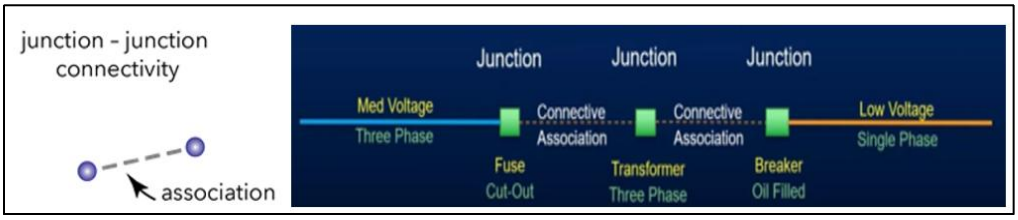


Figure 6: Junction-junction connectivity and associations in a power network.
Source: Authors, (2026).

3.Edge-Junction-Edge Connectivity Rules

These rules control how two edge features connect through an intermediate junction. They ensure that line features can only connect via appropriate junctions, maintaining the integrity of the network's topology. For instance, a medium voltage electrical transition from an above-ground system to a below-ground system at a junction point [18]. Figure 7 shows the edge-junction-edge connectivity in a medium voltage network.

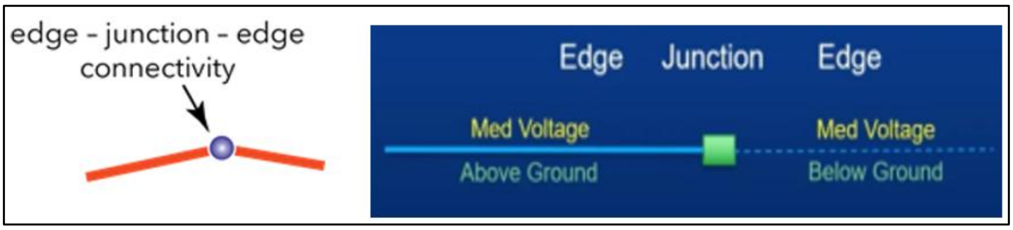


Figure 7: Edge-junction-edge connectivity in a medium voltage network.
Source: Authors, (2026).

V.2.1 Connectivity, Containment, and Attachment in Utility Networks

A well-structured electrical utility network relies on connectivity, containment, and attachment to define the relationships between different infrastructure components, ensuring efficient power flow, accurate network modelling, and streamlined asset management. Figure 8 shows the relationship, such as connectivity, containment, and attachment, in an electrical utility network.

- **Connectivity:** Defines the logical and physical interconnections between network components such as transformers, circuit breakers, transmission lines, and substations. GIS-based connectivity rules ensure that only valid electrical connections exist within the network, allowing utilities to simulate power distribution, detect faults, and optimize routing [19].

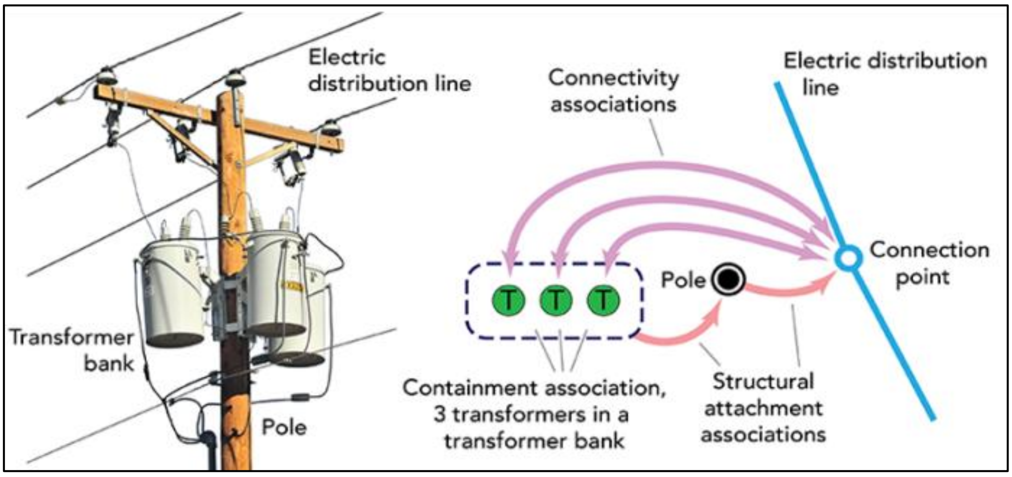


Figure 8: Connectivity, Containment, and Attachment.
Source: [19].

- **Containment:** Enables grouping multiple network features within a single container, such as a substation housing transformer, circuit breakers, and bus bars. This simplifies network visualization, asset tracking, and maintenance scheduling by reducing clutter on GIS maps [19].
- **Attachment:** Represents physical relationships between assets and their supporting structures, such as transformers mounted on poles or switchgear housed in substations. This ensures accurate spatial positioning and improves maintenance planning and network reliability [19]. Connectivity, containment, and attachment ensure efficient network management, accurate modelling, and stable power distribution.

V.3 ELECTRICAL UTILITY TRACING

Tracing is a process used in utility networks to analyse and visualize how different components within a network are connected and interact with each other. In the context of electrical utility networks, tracing helps identify the flow of electricity, determine how assets are linked, and assess the impact of potential faults or outages. By following the connectivity of network elements, tracing provides valuable insights into power distribution, enabling operators to monitor, manage, and optimize the electrical grid efficiently.

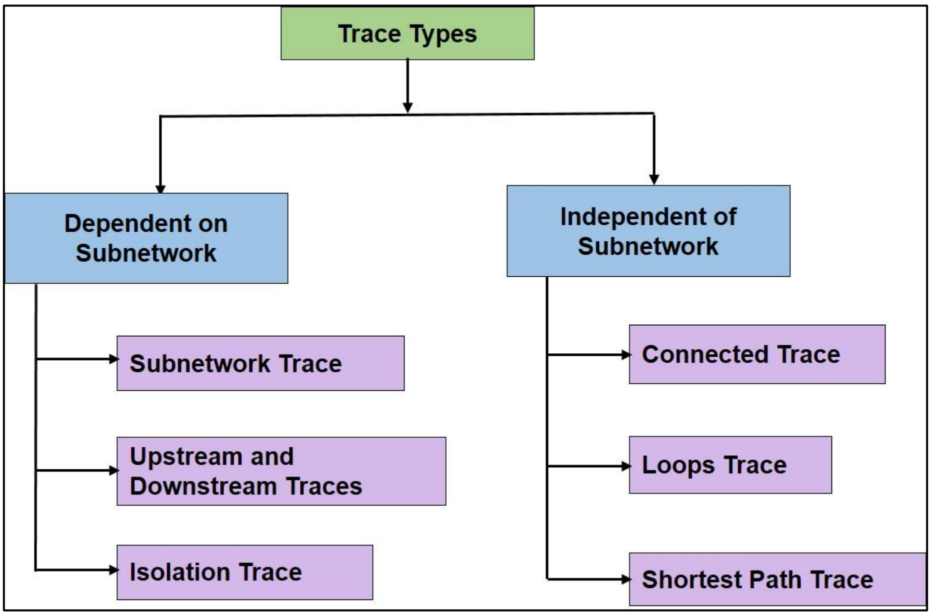


Figure 9: Classification of trace types in network analysis.
Source: Authors, (2026).

Each component in a power grid, such as substations, transformers, or circuit breakers, has a significant role in maintaining an uninterrupted power supply. Tracing serves as an invaluable tool in identifying faults, managing system expansion, and optimizing load distribution. Tracing ensures proper connectivity, identifies misrouted paths, and reduces the likelihood of service failures. In the event of faults such as short circuits or equipment failure, tracing helps quickly identify and isolate the affected sections, improving response time and service reliability. As electrical networks continue to expand, tracing aids in assessing new infrastructure integration and planning optimal locations for substations and feeders. It also helps evaluate the impact of network expansion on overall power flow, ensuring the network remains stable and efficient. Figure 9 shows the classification of trace types in network analysis.

V.3.1 Tracing Methods Dependent on Subnetwork

Figure 10 shows the types of tracing methods based on the dependent on subnetwork type.

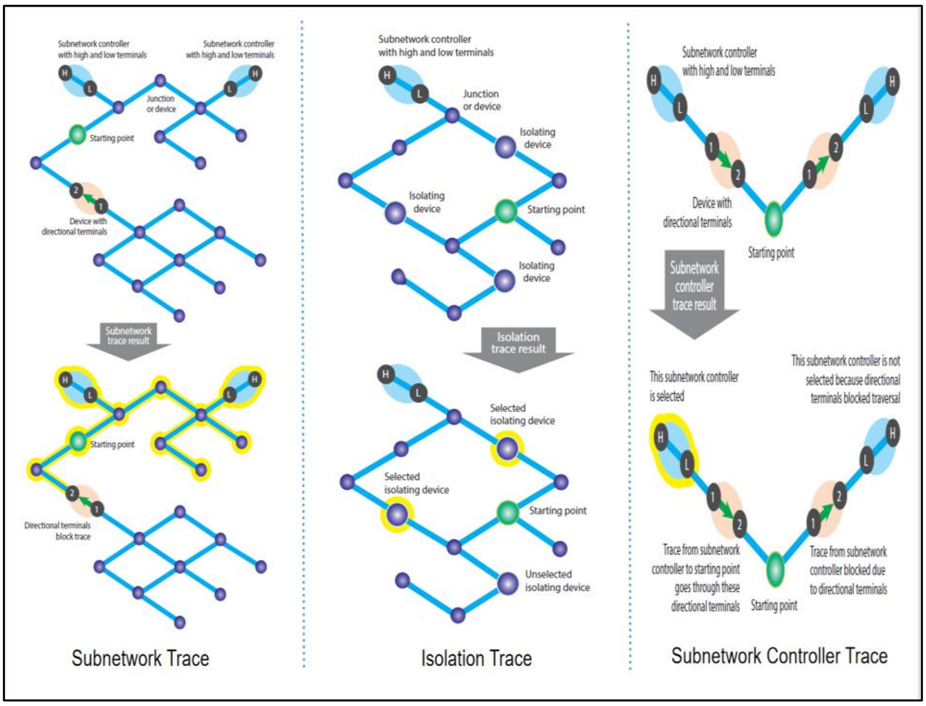


Figure 10: Network traces: subnetwork, isolation, and subnetwork controller.
Source: Authors, (2026).

1. Subnetwork Trace: A subnetwork trace finds every feature that is a part of a subnetwork, including a particular feeder or circuit. This trace relies on the subnetwork definition and requires at least one subnetwork controller to determine flow direction during the trace [19].

2. Upstream and Downstream Traces

- **Upstream Trace:** Identifies the source of resource supply for any network element by tracing against the flow direction toward the origin, such as a power plant or substation. This is useful for locating the origin of a contaminant in a water network or identifying the source of power feeding a particular area.
- **Downstream Trace:** Follows the flow direction away from the source, identifying customers or infrastructure that would be affected by a fault or outage at a specific point. This trace is crucial for outage management and planning maintenance activities to minimize customer impact.

3. Isolation Trace: The Isolation Trace determines the specific switches or valves that need to be operated to isolate a faulty section of the network. This trace is critical for outage management, allowing operators to quickly identify and isolate problem areas, thereby reducing downtime and mitigating the impact on consumers.

V.3.2 Tracing Methods - Independent of Subnetwork

1. Connected Trace: A Connected Trace starts from one or more points and follows connected features, stopping when it reaches a barrier or the end of a path. This trace is particularly useful for verifying that newly edited features are connected as expected, ensuring network integrity. For instance, in maintenance or upgrade scenarios, a connected trace can identify all customers or devices linked to a particular feeder, facilitating efficient planning and execution[19]. Figure 11 shows the types of tracing methods based on the independent on subnetwork type.

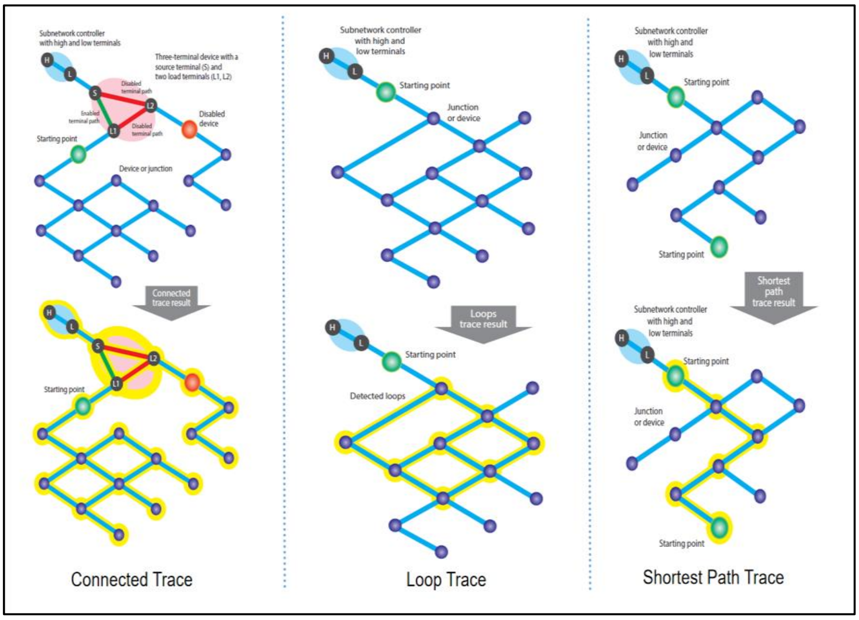


Figure 11: Network traces: connected, loop, and shortest path.
Source: Authors, (2026).

2. Loops Trace: The Loops Trace identifies sections of the network where a path starts and ends at the same location without crossing the same line twice, essentially forming a closed circuit. Detecting loops is crucial, especially in radial networks where unintended loops may indicate errors. In water distribution systems, for example, loops can help maintain consistent water pressure and supply, even if a part of the network is isolated for maintenance.

3. Shortest Path Trace: The Shortest Path Trace calculates the most efficient route between two starting points using a numeric network parameter like shape length. This trace is valuable for determining cost- or distance-based paths, aiding in scenarios like rerouting power due to maintenance or outages to restore service with minimal losses. By applying the appropriate trace type to specific scenarios, operators can proactively manage resources, swiftly respond to issues, and strategically plan for future network developments

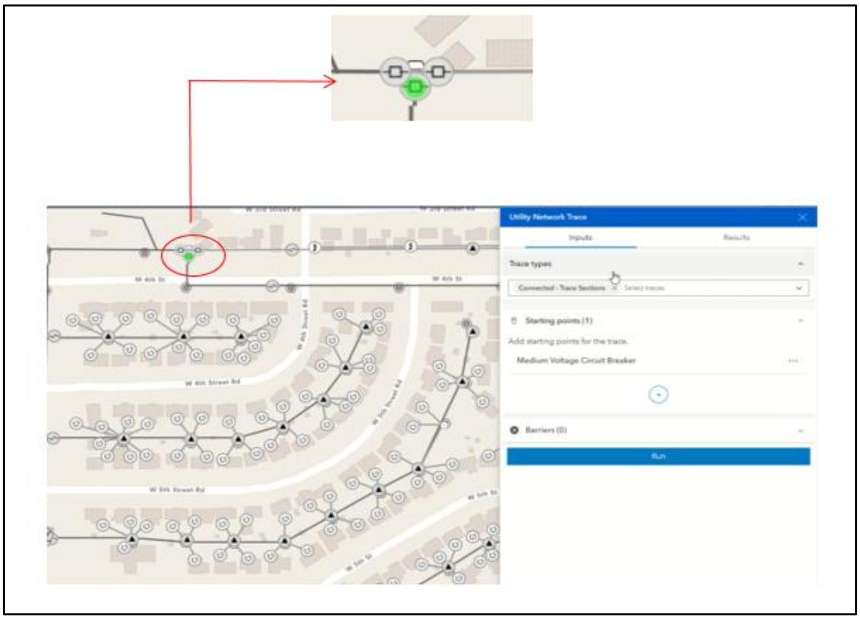
V.4 NETWORK EXPANSION PLANNING

Network Expansion Planning is a vital process in electrical utilities that focuses on upgrading and extending the power grid to accommodate the increasing electricity demand. It involves assessing current network capacity, forecasting future energy needs, and implementing infrastructure such as new substations, transmission lines, and distribution systems. A well-executed expansion plan ensures that electricity is delivered reliably, minimizes power disruptions, and supports sustainable energy development [20]. The rising global electricity demand, driven by urbanization, industrial growth, and household consumption, necessitates strategic grid expansion. [21] Without proper planning, grids risk overloads, blackouts, and increased operational costs. GIS-based network expansion planning enables utilities to manage this growth effectively by analysing substation capacity, forecasting energy needs, and identifying optimal expansion routes [20]. It provides insights into whether existing substations can handle increased loads or if new infrastructure is necessary, thereby preventing power failures caused by overcapacity.

VI. RESULTS AND DISCUSSION

VI.1 WORKFLOW FOR UTILITY NETWORK TRACING

The process of utility network tracing begins by accessing the web-based GIS application that is integrated with the ArcGIS Utility Network or a comparable tracing tool. Prior to initiating any analysis, users must ensure they have the appropriate permissions and roles to perform network tracing operations and that the electrical utility network dataset is properly loaded from the organization's cloud-based GIS or enterprise geodatabase. Once the dataset is available, the next step involves selecting the appropriate tracing type based on the analytical requirements. Common tracing methods include connectivity tracing to verify network connectivity, subnetwork tracing to identify all elements in a feeder or circuit, isolation tracing to locate switches and breakers for fault isolation, and upstream/downstream tracing to analyze power flow direction. In this case, a connectivity trace was selected to evaluate the directly linked elements within the network. Figure 12 show the initialization of a connected trace on a utility network map. After determining the trace type, the user must define a starting point and, if necessary, place barriers to simulate faults, outages, or maintenance constraints. This is typically achieved by interacting with the map interface, where the starting point may represent a substation, transformer, or distribution feeder. For this analysis, a medium-voltage circuit breaker was selected as the trace origin. Once the parameters are established, the trace is executed, prompting the system to perform real-time analysis of the network and highlight all connected elements.

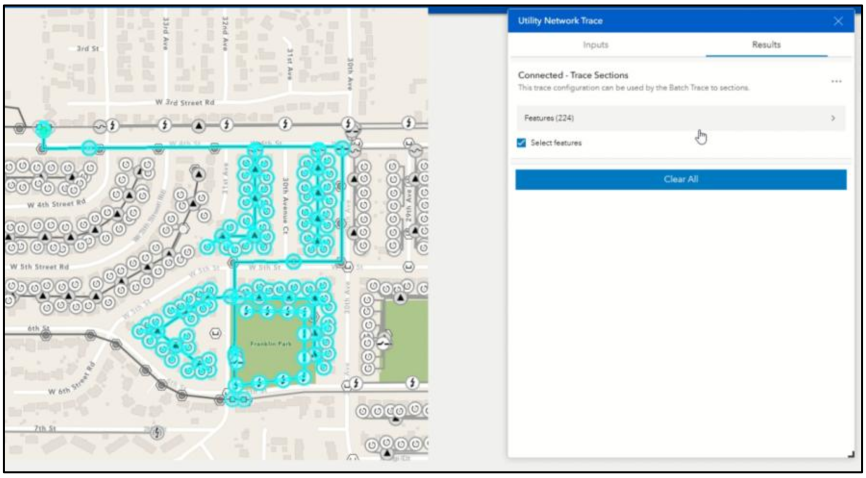


Add starting points for the trace.

Medium Voltage Circuit Breaker

Figure 12: Initiating a connected trace on a utility network map.
Source: Authors, (2026).

The resulting trace revealed that 224 features were directly connected to the selected medium-voltage circuit breaker, with the traced path displayed in blue for clear interpretation and it is shown in Figure 13.



This trace configuration can be used by the Batch Trace to sections.

☑ Select features

Figure 13: Results of a connected trace in a utility network.
Source: Authors, (2026).

Finally, the results of the trace can be exported or visualized using network diagrams, tabular reports, or GIS layers to support further analysis. These outputs enable utility engineers to validate network connectivity, assess fault isolation strategies, and evaluate power flow conditions in both spatial and schematic contexts. Moreover, the visualization and reporting capabilities facilitate integration with enterprise systems, thereby enhancing operational decision-making, outage management, and long-term infrastructure planning [22].

While this study demonstrates the connectivity trace procedure, the same workflow can be applied to other tracing types such as subnetwork, isolation, upstream/downstream, shortest path, loop, or subnetwork controller traces each serving distinct purposes in utility network analysis and management. The working mechanism of GIS-enabled network expansion planning integrates geospatial data with electrical network models to evaluate power flow, connectivity, and demand distribution. Planners can simulate various expansion scenarios and assess their impact on the existing grid, ensuring that new connections do not compromise overall performance. This proactive approach allows utilities to align infrastructure growth with energy demand trends, fostering a resilient, future-ready electrical network.

VI.2 ELECTRICAL UTILITY NETWORK DASHBOARD

The Electric Utility Network Dashboard serves as the nerve centre of the application, offering a real-time, integrated view of network operations. Built using ArcGIS Dashboard, this feature consolidates key performance indicators, asset data, and operational insights into a single, interactive interface and depicted in Figure 14.

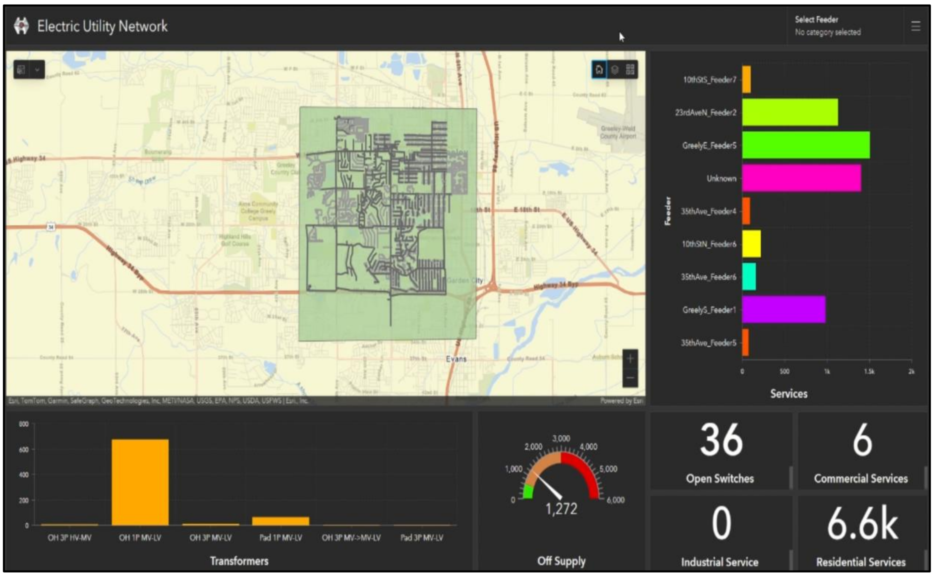


Figure 14: Electric utility network dashboard overview with service statistics.
Source: Authors, (2026).

Utility operators can use the dashboard to monitor network performance, track asset conditions, and assess key metrics such as outage frequency, equipment failures, and maintenance schedules. The dashboard's intuitive design enables quick analysis of network health, allowing decision-makers to respond proactively to potential issues [23]. The ability to visualize network status in real time enhances operational awareness, enabling utility providers to optimize resource allocation and improve service reliability. By integrating various data sources into a centralized dashboard, this feature ensures that stakeholders have access to the information they need to maintain a stable and efficient utility network.

VI.3. ANALYSIS OF TRACING RESULTS AND NETWORK BEHAVIOR

The tracing tools in ArcGIS Utility Network enabled detailed visualization of electrical flow and system behavior. Traces such as upstream, downstream, isolation, and connected traces simulated real-world scenarios like fault detection and route switching. Notably, the Connected Trace from the Medium Voltage Circuit Breaker identified the number of directly linked features (Residential, Commercial, Industrial Service points and Switches), confirming the established connectivity across distribution lines, transformers, and service points. To assess phase performance, Downstream Trace paired with the Summarize tool revealed a critical finding: Phase A was significantly underutilized, while Phase C showed signs of overutilization. This imbalance highlighted the need for load redistribution to ensure better phase management and system efficiency. These insights directly informed network expansion planning. This data-driven approach ensured that new customer connections were aligned with under loaded phases, supporting grid reliability and sustainable expansion.

VI.4 ANALYSIS FOR LOAD BALANCING AND STRATEGIC EXPANSION

The Summarize tool revealed a clear phase imbalance. Phase A was significantly underutilized, presenting an ideal opportunity for load redistribution. This insight guided the strategic allocation of new customer connections to Phase A in the Jonquil Avenue expansion zone of the Essential 001 Feeder, improving overall load balance across phases. Using the Create Features tool, new assets such as transformers, service points, and low-voltage conductors were digitized. Snap functionality ensured precise spatial alignment, and network associations, both connectivity and structural attachments were established to preserve logical flow and physical realism in the network. Following integration, network topology validation confirmed compliance with connectivity rules and junction-edge relationships. Initially, new features were not included in any Subnetwork, so the Subnetwork / Feeder name is set to 'Unknown'. Using the Update Subnetwork tool, assigning them to the appropriate Feeder 'Essential 001' was done. A final downstream trace verified successful resource flow across the newly added components, with no breaks or topological errors, validating a smooth and efficient network expansion.

VII. CONCLUSION

This research explores the application of Geographic Information Systems (GIS) in the modernization of electrical utility networks. As energy infrastructure evolves to meet increasing demand and complexity, GIS plays a pivotal role in improving network connectivity, asset mapping, and subnetwork management [24]. Through advanced functionalities such as tracing, utilities can simulate real-world scenarios like fault detection, load flow analysis, and isolation planning, enhancing the system's responsiveness and efficiency. The study addresses limitations in conventional grids and demonstrates how GIS supports data-driven operations and efficient network planning. Network expansion was planned and executed using GIS tools to ensure spatial accuracy and logical connectivity. The implementation of upstream, downstream, and connected traces provided valuable insights into power flow, load distribution, and structural integrity across the network [25]. The modernization of electrical utility networks requires a paradigm shift from conventional grid management practices toward data-driven, intelligent systems, with Geographical Information Systems (GIS) serving as a critical enabler [26]. GIS facilitates advanced asset mapping, load flow analysis, outage management, and fault location detection, all of which are essential for efficient power distribution [27]. By integrating GIS with Supervisory Control and Data Acquisition (SCADA) systems [28] and Distribution Management Systems (DMS), utilities can achieve real-time situational awareness, improve demand forecasting, and minimize technical and non-technical losses.

This enhances not only the operational efficiency of the grid but also its resilience against faults and peak demand pressures[29].Moreover, the integration of GIS with emerging smart grid technologies allows for greater interoperability, predictive maintenance, and renewable energy integration [30]. For example, spatial data analytics can optimize the placement of distributed energy resources (DERs), support microgrid development, and improve restoration strategies during natural disasters. By enabling utilities to model, simulate, and manage complex network interactions, GIS contributes to a more adaptive and sustainable power distribution framework. Ultimately, its role in modernizing electrical utility networks is pivotal in ensuring that the grid evolves into a more intelligent, flexible, and customer-focused system aligned with global energy transition goals. Hybrid aloe vera/hemp fibre composites showed better strength and thermal stability, making them suitable for lightweight engineering use [31]. ANSYS-based optimisation improved the performance and durability of two-wheeler suspension systems [32]. Solar photovoltaic–based cogeneration was found to support efficient energy and water management [33]. The use of vortex generators improved airflow characteristics and reduced aerodynamic drag in vehicle models [34]. IoT-based systems enabled real-time monitoring and improved operational efficiency [35-36].

VI. AUTHOR'S CONTRIBUTION

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