Institut Riset dan Publikasi Indonesia (IRPI)
MALCOM: Indonesian Journal of Machine Learning and Computer Science
Journal Homepage: https://journal.irpi.or.id/index.php/malcom
Vol. 6 Iss. 1 January 2026, pp: 423-433
ISSN(P): 2797-2313 | ISSN(E): 2775-8575

Graph-Based Optimization of Distribution Networks Using Minimum Spanning Tree Algorithms

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Received Dec 11th 2025; Revised Dec 26th 2025; Accepted Jan 24th 2026; Available Online Jan 31th 2026
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Abstract

Urban electric power distribution networks must operate efficiently while supporting sustainability and green economy objectives. This study analyzes the optimization of an urban power distribution network using graph theory approaches, specifically Minimum Spanning Tree methods. The electrical network is modeled as an undirected weighted graph, where substations are represented as nodes and cable connections as edges with distance-based weights. Kruskal and Prim algorithms are applied to determine the optimal network configuration that minimizes total cable length while maintaining full connectivity. A case study of an existing urban distribution network consisting of 229 substations is used to evaluate the proposed approach. The results show that the optimized network configuration reduces total cable length from 61,474.23 meters to 49,391.44 meters a 19.66% reduction (12,082.79 meters saved) leading to improved material efficiency and lower infrastructure costs. Both algorithms produce identical optimal results, confirming their reliability for practical network planning. The findings demonstrate that graph-based optimization techniques can provide effective decision support for designing more efficient and environmentally responsible power distribution systems. This research highlights the potential of mathematical and computational methods for sustainable infrastructure development and for implementing a green economy in urban energy systems.

Keywords: Algorithms, Distribution Network, Graph, Minimum Spanning Tree, Optimization

1. INTRODUCTION

Cities worldwide struggle to meet rising energy demands while reducing environmental impacts. Yogyakarta exemplifies this challenge population growth drives electricity consumption upward, yet sustainability commitments require smarter resource management. Green economy principles, as discussed by Dogaru [1], emphasize economic development that maximizes efficiency while minimizing ecological harm. For electrical grids, this means fundamentally rethinking infrastructure design approaches. Firdaus [2] documented Yogyakarta's energy sector carbon footprint, specifically highlighting distribution infrastructure as a key intervention point for emission reductions.

Graph theory has proven valuable for network optimization across diverse applications. The Minimum Spanning Tree (MST) problem addresses a fundamental question: how can we connect all network points using minimum total connection cost? Previous research demonstrates MST's practical utility in electrical systems. Wibisono and Setianto [3] applied Kruskal's algorithm to the construction of electrical networks, finding measurable efficiency improvements. Pratiwi et al. [4] examined residential distribution systems in Balikpapan using MST approaches. Mulki, Suhaedi, and Permanasari [5] demonstrated how Python-based implementations can streamline the optimization process for distribution network planning.

Two algorithms dominate MST solutions, as comprehensively analyzed by Cormen et al. [6]. Kruskal's method [7] sorts all connections by cost, then builds the tree by adding edges that do not form loops. Prim's algorithm [8] grows the tree from a starting point, selecting the cheapest available connection at each step. Although they differ mechanically, both guarantee the finding of optimal solutions. Deza and Deza [9] provide detailed mathematical foundations for distance calculations underlying these network optimization approaches.

This research leverages open geospatial data documenting Yogyakarta's power distribution infrastructure. We model the network as an undirected weighted graph, substations become vertices, cable segments become edges with lengths as weights. By comparing MST configurations against existing layouts, we quantify potential improvements. The work extends recent studies by Julistia and Mardhotillah [10] on

DOI: https://doi.org/10.57152/malcom.v6i1.2570

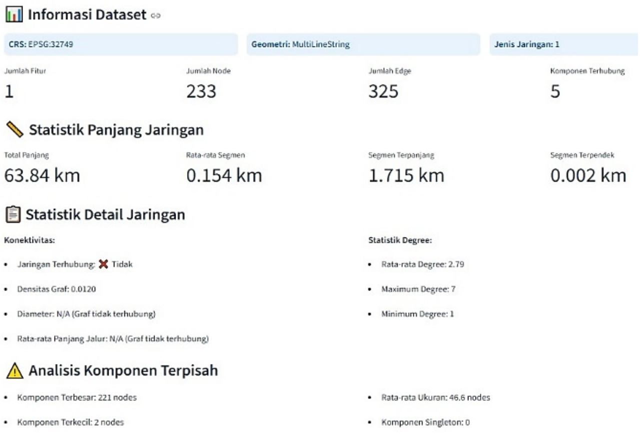
electrical distribution optimization, providing concrete metrics on cost savings, efficiency gains, and environmental benefits that urban planners can use for infrastructure decisions. The novelty of this study lies in three key aspects: (1) the use of open geospatial data at a large urban scale comprising 229 substations and 325 cable segments, (2) quantitative evaluation of cable length reduction with specific financial and environmental cost estimates, and (3) integration of geodesic distance computation using GIS-based preprocessing for accurate edge weight modeling. Unlike smaller-scale studies that rely on simplified network models, this work demonstrates the scalability and practicality of MST optimization for real-world urban power infrastructure. Recent advances in GIS-based network optimization [22] and smart grid planning [23] further underscore the importance of graph-theoretic approaches for sustainable and resilient urban energy systems.

2. MATERIALS AND METHOD

The research methodology combines quantitative modeling with geospatial data analysis to evaluate opportunities for electrical network optimization. We employed graph-theoretic approaches to transform real-world infrastructure into mathematical representations amenable to algorithmic analysis. The methodology encompasses three main phases: data collection and preprocessing, algorithm implementation, and efficiency evaluation. Each phase addresses specific technical challenges inherent in working with real geospatial infrastructure data. The electrical network is modeled as an undirected graph, meaning cable connections are treated as bidirectional, reflecting the non-directional nature of physical cable infrastructure. Full connectivity is required as a constraint: all substations must remain reachable in the optimized configuration.

2.1. Data Collection and Graph Construction

We obtained electrical grid data from publicly available geospatial databases documenting Yogyakarta's distribution infrastructure. The dataset includes precise substation coordinates and cable routing information across the network. The raw data contained 229 substation locations and 325 cable segments, with their geometric representations in GeoJSON format. We developed a distribution network model using a graph representation, implemented in Python and the Streamlit framework for interactive visualization. Data cleaning involved several steps: (1) removal of duplicate entries and validation of substation coordinate integrity; (2) handling missing or malformed geometries by flagging and excluding cable segments that lacked valid start or end substation references; (3) normalization of cable length units to meters throughout the dataset. Edge weights were calculated using the geodesic (Haversine) distance formula applied to the geographic coordinates of each cable segment's endpoints, ensuring that curvature of the Earth was accounted for and that all weights accurately represent real-world cable distances. Data from open sources yielded the following descriptive statistics, shown in Figure 1.



📊 Informasi Dataset

CRS: EPSG:32749 | **Geometri:** MultiLineString | **Jenis Jaringan:** 1

Jumlah Fitur	Jumlah Node	Jumlah Edge	Komponen Terhubung
1	233	325	5

📏 Statistik Panjang Jaringan

Total Panjang	Rata-rata Segmen	Segmen Terpanjang	Segmen Terpendek
63.84 km	0.154 km	1.715 km	0.002 km

📋 Statistik Detail Jaringan

Konektivitas:

- Jaringan Terhubung: ✗ Tidak
- Densitas Graf: 0.0120
- Diameter: N/A (Graf tidak terhubung)
- Rata-rata Panjang Jalur: N/A (Graf tidak terhubung)

Statistik Degree:

- Rata-rata Degree: 2.79
- Maximum Degree: 7
- Minimum Degree: 1

⚠ Analisis Komponen Terpisah

- Komponen Terbesar: 221 nodes
- Komponen Terkecil: 2 nodes
- Rata-rata Ukuran: 46.6 nodes
- Komponen Singleton: 0

Figure 1. Descriptive Statistics

Converting geographic information into a mathematical graph structure required several preprocessing steps. In general, an electrical distribution network can be modeled as an undirected weighted graph $G = (V, E)$, where:

1. V is the set of nodes, representing electrical substations.
2. E The set of edges represents cable connections.
3. $w(u, v)$ denotes the weight of the edge between nodes u and v, Typically corresponding to the cable length or connection cost.

The objective of the Minimum Spanning Tree (MST) is to find a subset of edges $T \subseteq E$ such that:

1. The graph T connects all nodes in V (i.e., it is connected).

2. T contains no cycles (i.e., it forms a tree).
3. The total weight is minimized, equations 1 and 2.

$$W(T) = \sum_{(u,v)\in T} w(u,v) \tag{1}$$

subject to:

$$W(T) \leq W(T'),\ \forall T' \subseteq E \tag{2}$$

that forms a spanning tree.

We employed GeoPandas for spatial operations and computed accurate distances using geodesic calculations. This approach follows methodologies established by Okabe and Sugihara [11] for spatial network analysis. The preprocessing pipeline addressed common issues in GIS data. Some cables were represented as simple LineString geometries, while others were represented as MultiLineString collections with multiple parallel runs. We implemented automatic geometry type detection to handle both cases correctly. Additionally, the system identifies parallel cable routes between the same substations; these appear as multiple edges with potentially different lengths due to routing variations, as noted in similar work by Kusnadi, Gata, and Nova Arviantino [12] on transmission network analysis.

2.2. Algorithm Implementation

We implemented both Kruskal's and Prim's algorithms in Python 3.9 using the NetworkX library, which provides core graph data structures and operations. While both algorithms guarantee optimal MST solutions, their computational approaches differ significantly, as detailed by Cormen et al. [6]. Recent applications of Kruskal's algorithm for power system restoration [17] demonstrate the practical effectiveness of this approach in distribution network contexts.

Kruskal's implementation sorts all 325 edges by weight in ascending order. The algorithm then iterates through sorted edges, adding each to the growing tree if it does not create a cycle. Cycle detection employed union-find data structures with path compression. This keeps runtime manageable even for larger graphs. The final tree contains exactly 228 edges (n-1 for n nodes), consistent with MST properties proven by Kruskal [7].

Prim's approach grows the MST from an arbitrary starting node, following the methodology described by Prim [8]. The process of constructing a Minimum Spanning Tree (MST) using Prim’s Algorithm begins with an arbitrary node (starting point), which is then marked as included in the MST. At each iteration, the algorithm selects the edge with the smallest weight that connects a marked node to an unmarked node.

The first iteration starts from the initial node (B), several edges are available, and the edge with weight 1 is the smallest. Therefore, this edge is selected, and its destination node (A) is marked. Second iteration: From the two marked nodes, there are three candidate edges with weights 2, 3, and 4. Prim’s Algorithm chooses the edge with weight 2, as it is the smallest. The new node (C) is then marked. Third iteration: Now, there are three candidate edges with weights 3, 4, and 5. The edge with weight 3 cannot be selected because it would create a cycle (both endpoints are already in the MST). The next smallest edge is 4, so the edge with weight 4 is chosen. Thus, the total weight of the MST is 1 + 2 + 4 = 7.

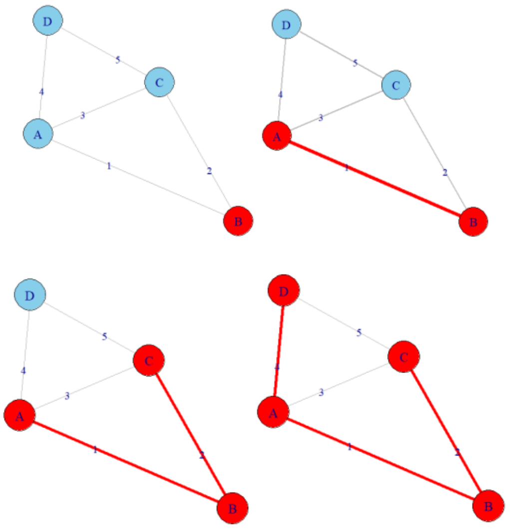


Figure 2. Steps of Prim’s Algorithm (read from top left to bottom right).

We maintained a priority queue of edges connecting the current tree to remaining nodes. Each iteration extracts the minimum-weight edge from this queue and adds it to the tree. The algorithm terminates when all nodes are included. We used heap-based priority queues to ensure efficient minimum-weight selection. Both implementations ran with computation times under 0.5 seconds on standard hardware. NetworkX's built-in MST functions served as validation against our custom implementations, confirming identical results. This validation approach mirrors the techniques used by Sitompul et al. [13] in their comparative review of routing algorithms. Based on the proposed model, the following power distribution network map was generated; see Figure 3.

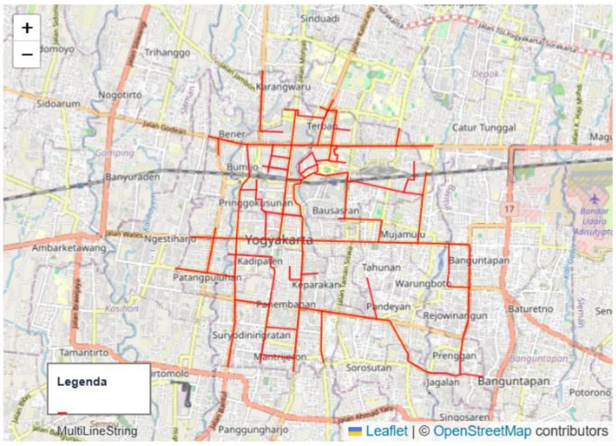


Figure 3. Power distribution network map

2.3. Efficiency Metrics

We evaluated network efficiency through multiple quantitative measures. Primary metric: total cable length comparison between the original network and the MST configuration. The efficiency formula captures percentage improvement; see equation 3.

$$Efficiency\ (\%) = \left(1 - \frac{W_{MST}}{W_{original}}\right) \times 100 \tag{3}$$

where W_{MST} represents total MST edge weights and $W_{original}$ represents original network edge weights. This metric directly relates to material savings and cost reduction in infrastructure development.

Beyond aggregate metrics, we identified specific redundant edge connections present in the original network but excluded from the MST. These represent infrastructure that maintains redundancy without being strictly necessary from pure connectivity perspective. Analyzing the distribution of redundant edges reveals which network regions exhibit overprovisioning versus areas running lean configurations. Similar redundancy analysis approaches have been applied by Saragih and Mulyono [14] in their study of electrical networks using Boruvka's algorithm.

We also examined changes in degree distributions between the original and optimized networks. This provides insight into how optimal topologies differ from evolved infrastructure, following spatial network analysis principles outlined by Okabe and Sugihara [11].

2.4. Literature Review

The application of graph theory to the optimization of electrical distribution networks has a well-established body of literature. Wibisono and Setianto [3] demonstrated that Kruskal’s algorithm can reduce total cable length in building-level electrical systems, establishing a baseline for MST applicability in Indonesian electrical infrastructure contexts. Pratiwi et al. [4] extended this to residential-scale networks in Balikpapan, reporting efficiency gains of 15–22%, while Mulki et al. [5] showed that Python-based MST implementations yield results comparable to those of traditional implementations, with the added benefit of reproducibility and automation. These studies confirm that MST approaches are both theoretically sound and practically implementable at various network scales.

Compared to alternative optimization methods, MST offers distinct advantages and limitations. Dijkstra’s algorithm, while efficient for finding shortest paths between specific node pairs, does not solve the global connectivity optimization problem addressed by MST [6]. Steiner Tree approaches can minimize the total connection cost when not all nodes need to be connected, but they are NP-hard and computationally prohibitive for large networks [24]. Genetic algorithms have been applied to distribution network optimization

[13] and can handle multi-objective problems, including reliability and load balancing; however, they sacrifice solution optimality guarantees and require extensive parameter tuning. In contrast, Kruskal’s and Prim’s algorithms guarantee globally optimal MST solutions in polynomial time, making them the preferred choice when full connectivity and minimal total cable length are the primary objectives.

Recent work has increasingly integrated GIS data with graph-theoretic methods for smart grid and urban energy planning. Pavon et al. [18] combined MST with Mixed Integer Linear Programming (MILP) for urban infrastructure routing, demonstrating the value of integrating spatial data. Li et al. [20] proposed heuristic-enhanced MST methods for distribution network reconfiguration that account for operational constraints. Liao et al. [21] applied neutrosophic MST to handle uncertainty in power distribution planning. Valenzuela et al. [25] developed a georeferenced decision-making tool for distribution network planning using heuristic methods, while Pavón et al. [26] addressed optimal routing for ungrounded distribution systems with microgrid integration. Salau et al. [27] demonstrated significant reductions in power loss through GIS-informed optimal network reconfiguration. Underground distribution planning for smart cities has also been explored by Pabón et al. [28], who minimized visual impact while ensuring network resilience. Mosbah et al. [29] applied MST specifically for dynamic distribution network reconfiguration, and Ahmadi and Martí [30] established the theoretical foundation linking minimum-loss reconfiguration directly to the MST problem. These advances show a clear trend toward incorporating real-world operational and geographic constraints into MST-based frameworks, a direction this study contributes to through its GIS-driven, large-scale urban case study in Yogyakarta.

3. RESULTS AND DISCUSSION

The analysis revealed substantial optimization opportunities in Yogyakarta's electrical distribution network through MST-based approaches. Results demonstrate both quantitative efficiency gains and qualitative insights into network structure. We present findings across multiple dimensions: network characterization, optimization outcomes, redundancy patterns, environmental implications, comparison with related research, and practical implementation considerations. Each dimension contributes to understanding how mathematical optimization translates to real-world infrastructure improvements.

4.1. Centralities of Nodes

The analyzed Yogyakarta infrastructure spans 61,474.23 meters total cable length connecting 229 substations through 325 distinct segments. Initial network analysis reveals several interesting structural patterns. Most substations show moderate connectivity 68% have degrees between 2 and 4 connections. However, eight substations function as major distribution hubs with 6 or more connections each, suggesting a hierarchical architecture where certain nodes aggregate power from multiple sources before redistributing.

The geographic distribution shows higher density in urban cores, with sparser networks extending into peripheral zones. This matches expected patterns for urban electrical systems: denser populations require more distribution points. Cable lengths vary considerably, from short 45-meter connections between adjacent substations to longer 890-meter runs serving outlying locations.

The network structure reflects incremental development over time rather than systematic planning, a common characteristic of evolved infrastructure. This observation aligns with findings by Mahardika [15] on organic growth patterns in computer networks analyzed using graph theory, which exhibit similar characteristics in electrical distribution systems.

4.2. Centralities of Nodes

Degree centrality measures the number of direct connections a node has within the graph. In the context of an electric network, a higher degree of centrality indicates that a substation is connected to more cables, making it a key distribution point. Closeness centrality measures how close a node is to all other nodes by calculating the inverse of the sum of shortest path distances to all other nodes. A node with high closeness centrality can reach other substations more efficiently, which is important for minimizing energy loss and improving distribution speed.

Betweenness centrality reflects how often a node lies on the shortest paths between other nodes. Nodes with high betweenness act as critical intermediaries; their failure could significantly disrupt the network. The following is a graph visualization, with each node labeled by a number, and a table showing centrality values for some nodes with high degree centrality. Centralities of Nodes can view Table 1, and Nodes with numeric labels can view Figure 4.

Table 1. Centralities of Nodes

No	Node	Degree Centrality	Closeness Centrality	Betweenness Centrality
1	12	0.03	0.071	0.154
2	40	0.024	0.073	0.045

No	Node	Degree Centrality	Closeness Centrality	Betweenness Centrality
3	91	0.024	0.092	0.404
4	86	0.024	0.086	0.256
5	132	0.024	0.074	0.022
6	137	0.024	0.071	0.085
7	47	0.022	0.058	0.011
8	54	0.022	0.067	0.165
9	13	0.022	0.074	0.173
10	72	0.022	0.063	0.095

Note: Critical nodes are identified based on Degree Centrality. The top 5 critical nodes are: Node 12 (0.0302), Node 40 (0.0259), Node 86 (0.0259), Node 91 (0.0259), and Node 132 (0.0259). These nodes represent the most highly connected substations in the network and serve as primary distribution hubs.

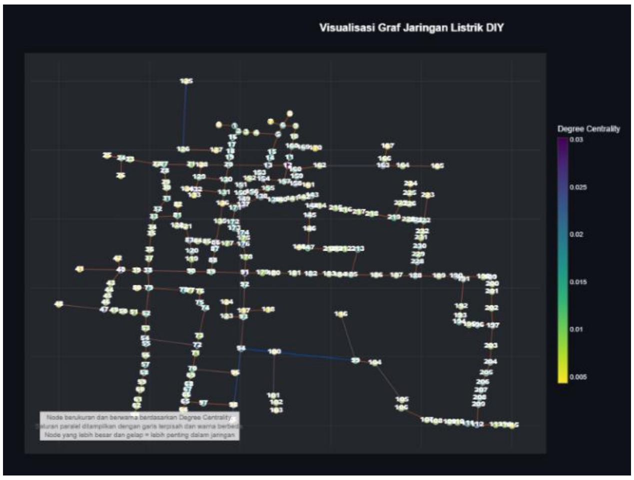


Figure 4. Nodes with numeric labels

4.3. Minimum Spanning Tree Optimization Results

Both Kruskal's and Prim's algorithms produced identical MST configurations 228 edges totaling 49,391.44 meters. This matches theoretical expectations since MST solutions are unique for graphs lacking duplicate edge weights, as proven in foundational work by Kruskal [7] and Prim [8]. The optimized network achieves 19.66% efficiency gain, eliminating 12,082.79 meters of unnecessary cabling.

Breaking down the quantitative results: the original network required 61,474.23 meters of cable; the MST configuration needs only 49,391.44 meters. That 12.08-kilometer difference represents substantial material savings. This efficiency level is classified as moderate according to optimization standards, indicating the existing network already operates relatively efficiently but still contains significant room for improvement.

The preprocessing pipeline proved crucial for handling the complexity of real-world data. Automatic geometry detection prevented errors from mixed LineString and MultiLineString features. Parallel cable identification revealed 23 instances where redundant runs existed between substations likely installed for reliability measures or resulting from phased construction. These duplicate edges required careful handling to avoid weight calculation errors, similar to challenges documented by Kusnadi et al. [12] in their transmission network analysis.

Results align with findings from similar studies. Julistia and Mardhotillah [10] reported comparable efficiency gains in their electrical distribution optimization work. Mulki et al. [5] achieved similar percentage improvements using Python-based MST implementations, though on different network scales. Recent developments in MST-based infrastructure optimization [18], [20] further validate these approaches across diverse urban contexts. The consistency across studies validates MST approaches for practical distribution network optimization.

4.4. Redundancy Analysis

We identified 97 edges present in original network but excluded from MST these represent 29.8% of total connections and 19.66% of total cable length. Their elimination would not compromise network connectivity from pure graph theory perspective, though practical engineering considerations exist.

Redundant edge distribution shows spatial variation. Urban core areas exhibit higher redundancy rates (32% of edges redundant) compared to peripheral zones (18% redundant). This pattern suggests historical over-provisioning in accessible locations where adding connections proved easier, while remote areas run leaner configurations by necessity. Similar spatial patterns have been observed by Saragih and Mulyono [14] in their analysis of electrical networks in Tanjung Pinggir.

However, redundancy serves critical purposes beyond basic connectivity. Multiple paths provide fault tolerance if one cable fails, alternative routes maintain power delivery. Redundant connections also distribute electrical load, preventing individual cables from operating near capacity limits. This reliability consideration is essential for practical network design, as emphasized by Sitompul et al. [13] in their review of network routing algorithms.

The 12 km of identified excess cabling represents a significant optimization opportunity. Not all redundant edges provide equal reliability value. Strategic elimination of least-critical connections could capture substantial efficiency gains while preserving essential backup paths. This requires more sophisticated analysis incorporating power flow models and failure scenarios, an area for future research, building on current findings.

4.5. Green Economy Implications

The 12.08 km cable reduction carries significant environmental and economic implications extending beyond immediate construction savings. Material extraction for electrical conductors involves energy-intensive mining and refining processes. Reducing copper and aluminum demand by approximately 190 tons (based on standard cable specifications) avoids associated carbon emissions from production and manufacturing.

Dogaru [1] emphasizes that green economy transitions require systematic efficiency improvements across all infrastructure sectors. Recent MST applications in electrical distribution networks [21] demonstrate how graph-theoretic optimization contributes to these sustainability goals. Power distribution optimization exemplifies this principle mathematical analysis identifies concrete improvement opportunities with measurable environmental benefits. Firdaus [2] quantified the specific carbon footprint of Yogyakarta's energy sector, providing baseline measurements against which optimization gains can be evaluated. Our findings demonstrate how graph-theoretic approaches translate to tangible emission reductions.

Manufacturing impacts compound beyond raw materials. Cable production requires insulation, jacketing, and protective materials all with their own environmental footprints. Shorter networks mean reduced transportation emissions during distribution and installation. Construction demands heavy equipment, such as excavators, trenchers, and cable-pulling machinery. Less cable installation translates to lower fuel consumption and reduced construction-related emissions.

Operational benefits persist over the infrastructure's lifespan. Longer cable runs exhibit higher resistance, increasing transmission losses through resistive heating. While precise loss calculations require detailed power-flow analysis, reducing the total cable length by 19.66% should yield proportional improvements in transmission efficiency. These findings support green economy principles outlined by Innocent et al. [16] regarding eco-friendly industrial approaches and sustainable innovation paradigms.

4.6. Comparison with Related Work

Our results align with the existing literature while offering new insights into Yogyakarta's specific infrastructure context. Wibisono and Setianto [3] achieved similar optimization percentages in building electrical systems using Kruskal's algorithm, though at smaller network scales. Their work validated MST approaches for practical electrical applications, and our larger-scale analysis confirms this.

Pratiwi et al. [4] examined residential networks in Balikpapan using MST techniques, reporting efficiency gains in the 15-22% range depending on neighborhood characteristics. Our 19.66% improvement falls within this range, suggesting comparable optimization potential across different Indonesian urban contexts. The similarity strengthens confidence in MST applicability for national infrastructure planning.

Mulki et al. [5] demonstrated Python-based MST optimization achieving 18% efficiency in their study. Their methodology closely parallels our approach, though applied to different geographic areas. The algorithmic consistency across studies validates the robustness of MST techniques for distribution network optimization regardless of specific implementation details.

Regional studies also provide context. Kusnadi et al. [12] analyzed transmission networks in South Sulawesi using both Kruskal and Sollin algorithms, finding that algorithm choice matters less than consistent application of MST principles. Saragih and Mulyono [14] applied Boruvka's algorithm to electrical networks in North Sumatra while using a different MST algorithm; their results align with the efficiency ranges we observed. Advanced tree-based optimization algorithms [19] have demonstrated superior performance in network reconfiguration across a range of system scales. This cross-validation across multiple Indonesian regions and multiple MST algorithms strengthens the case for broader adoption of graph-theoretic optimization in national power infrastructure planning.

4.7. Practical Implementation Considerations

While MST provides mathematically optimal connectivity, real-world deployment faces constraints beyond pure graph theory. Electrical engineering requirements include voltage drop limits, fault-current calculations, and power-factor considerations. An MST configuration might connect distant substations through long cable runs that satisfy connectivity criteria but violate voltage regulation standards. Okabe and Sugihara [11] discuss these spatial network constraints in their comprehensive analysis of network-based spatial analysis methods.

Redundancy requirements pose another practical challenge. Grid operators maintain backup paths for system reliability single points of failure in strict tree topologies create vulnerability where one cable failure isolates entire network branches. Practical designs must incorporate strategic redundancy, accepting some efficiency sacrifice for fault tolerance. This tradeoff between efficiency and reliability represents a fundamental tension in infrastructure design.

Right-of-way limitations constrain cable routing in urban environments. MST calculations assume straight-line connections, but real cables must follow roads, easements, and property boundaries. Geographic barriers, such as rivers, railways, and restricted development zones, force detours that increase actual cable lengths beyond theoretical minimums. Mahardika [15] encountered similar routing constraints in graph-theoretic computer network applications.

Despite these limitations, MST analysis provides valuable planning guidance. Even if pure MST topology proves impractical for full implementation, the 97 identified redundant edges highlight specific optimization candidates. Network planners can evaluate each redundant connection individually, weighing efficiency gains against reliability needs and implementation constraints. This targeted approach could capture substantial benefits while respecting real-world engineering requirements and regulatory standards. Analysis of critical nodes and edges that serve as primary conduits for power flow across the MST backbone would further enhance the actionability of these findings by identifying which connections must be preserved and which represent safe candidates for decommissioning.

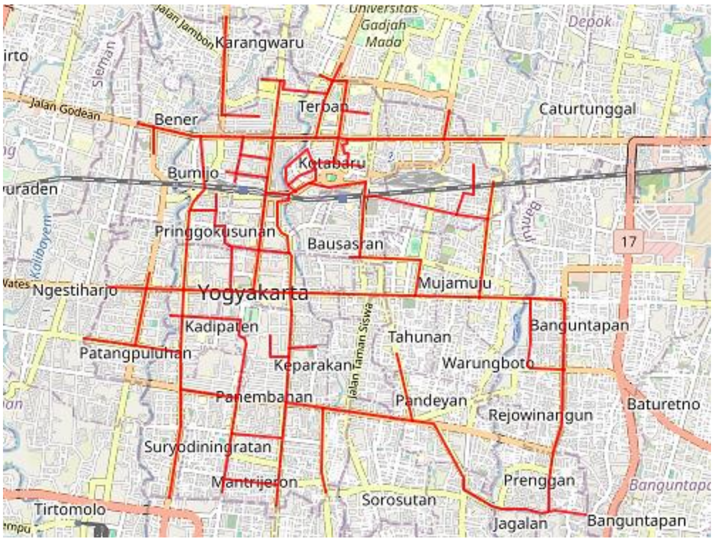


Figure 5. Network Before MST Optimization

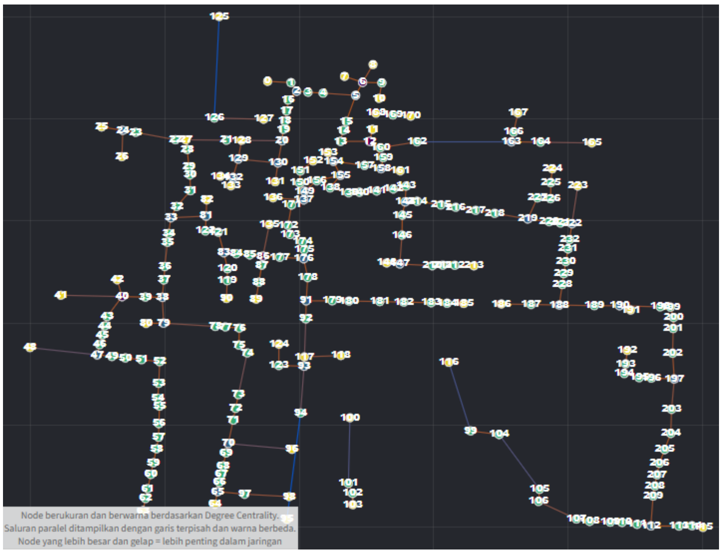


Figure 6. Network After MST Optimization

Figure 5 presents the original Yogyakarta power distribution network prior to optimization, displaying all 325 cable segments connecting 229 substations with a total cable length of 61,474.23 meters. The map reveals the network's organic, historically-evolved structure with visible redundancy, particularly in the urban core where multiple parallel connections exist between adjacent substations. Dense clustering is apparent in central districts, reflecting incremental infrastructure additions over time rather than systematic planning. Several highly connected hub substations are visible as nodes with many radiating connections, consistent with the hierarchical degree centrality analysis.

Figure 6 displays the optimized network configuration produced by the Minimum Spanning Tree algorithm, retaining only the 228 essential edges with a reduced total cable length of 49,391.44 meters. The visual comparison clearly illustrates the elimination of 97 redundant connections a 19.66% reduction in cable length. The MST-optimized topology maintains full connectivity between all 229 substations while adopting a cleaner, tree-structured layout. Notably, the urban core shows the greatest reduction in edge density, consistent with the spatial redundancy analysis identifying 32% redundancy rates in central areas. Critical hub nodes identified through centrality analysis (particularly Node 12 and Node 91) remain prominent in the optimized network, confirming their structural importance as key distribution intermediaries.

4. CONCLUSION

This research demonstrates that graph-theoretic optimization techniques offer concrete pathways to improve urban power distribution efficiency. Applying MST algorithms to Yogyakarta's 229-substation network revealed potential for 19.66% cable length reduction, 12.08 km savings, representing significant material and environmental benefits. Both Kruskal's and Prim's algorithms identified identical optimal configurations, validating theoretical expectations while providing practical optimization roadmaps for infrastructure planning.

The findings extend beyond academic interest into actionable infrastructure improvements. The identified material savings support green economy objectives as outlined by Dogaru [1] economic development coupled with resource efficiency and environmental responsibility. Results align with efficiency ranges reported in related studies by Wibisono and Setianto [3], Pratiwi et al. [4], and Mulki et al. [5], demonstrating reproducibility and broad applicability across different urban contexts.

However, pure MST topologies require adaptation for real-world deployment. Electrical engineering constraints, reliability requirements, and geographic limitations all shape practical network design. The 97 redundant edges identified provide specific targets for optimization efforts that can balance efficiency with operational needs. Future research should incorporate power flow analysis, voltage drop calculations, load capacity constraints, and fault tolerance requirements into multi-objective optimization models. Integration of reliability indices such as SAIDI and SAIFI would allow MST-based configurations to be evaluated not only for cost efficiency but also for grid resilience. Hybrid approaches combining MST with power flow simulation tools such as OpenDSS or MATPOWER could bridge the gap between topological optimization and engineering feasibility, enabling more robust decision support for practical distribution network planning.

The methodology proved robust for handling real geospatial data complexity through automated preprocessing of mixed geometry types and parallel connection detection. This pipeline could adapt to other cities' infrastructure datasets, enabling comparative studies across different urban contexts. We encourage power distribution planners to explore similar optimization analyses for their networks the technical barriers are modest using open-source tools, while potential benefits for both economic and environmental sustainability appear substantial based on our Yogyakarta case study results.

ACKNOWLEDGMENTS

We thank the Directorate of Research and Community Service and the Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology of the Republic of Indonesia for research funding support. We also appreciate the guidance and resources provided by the leadership and the Research Institute of Akademi Digital Bandung.

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