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(REVIEW ARTICLE)

Development of gas-insulated substations for urban areas

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Abstract

Gas-Insulated Substations (GIS) have emerged as a critical solution for efficient and reliable power distribution, particularly in urban environments where space constraints and environmental concerns limit the deployment of traditional Air-Insulated Substations (AIS). GIS technology leverages compact, high-voltage components encapsulated in gas-insulated enclosures, providing enhanced operational efficiency, safety, and reliability. This paper explores the technological advancements in GIS, including improvements in insulation materials, monitoring and diagnostic systems, and sustainable designs aimed at reducing greenhouse gas emissions. A comparative analysis of GIS and AIS is conducted, evaluating key factors such as space optimization, installation and maintenance costs, reliability under extreme environmental conditions, and overall environmental impact. The paper also highlights the integration of digital technologies, such as IoT-based condition monitoring, predictive maintenance algorithms, and AI-driven fault detection, which enhance the performance and longevity of GIS installations. Furthermore, the study addresses challenges associated with GIS technology, including the high initial investment, potential risks related to SF_6 gas emissions, and strategies for developing eco-friendly alternatives. Emerging trends, such as the adoption of SF_6-free insulation solutions, advancements in compact modular designs, and hybrid GIS-AIS configurations, are explored to assess the future viability of GIS in modern power networks. By analyzing recent research developments, case studies, and industry best practices, this paper provides insights into the evolving landscape of gas-insulated substations, emphasizing their role in ensuring sustainable, resilient, and efficient power distribution for the growing energy demands of urban and industrial applications.

Keywords: Gas-Insulated Substation (GIS); Air-Insulated Substation (AIS); SF_6 Gas; Urban Power Distribution; Compact Substations; High Reliability; Smart Monitoring; Predictive Maintenance

1. Introduction

The increasing urbanization and rising energy demands necessitate compact and reliable power distribution solutions that can efficiently operate in densely populated areas. Traditional Air-Insulated Substations (AIS) require significant space for installation and maintenance, making them less suitable for urban environments where land availability is limited and costly. In contrast, Gas-Insulated Substations (GIS) offer a more space-efficient alternative, utilizing advanced insulation technology to achieve high reliability and performance while reducing the overall footprint. The ability of GIS to function in constrained spaces, such as underground facilities and high-rise buildings, makes it an ideal choice for modern power distribution networks. GIS technology primarily relies on sulfur hexafluoride (SF_6) gas as an insulating medium due to its excellent dielectric properties and ability to withstand high voltages without significant energy loss. The use of SF_6 ensures operational efficiency and system stability, allowing GIS to support higher power transmission capabilities with minimal risk of electrical failures. Moreover, GIS enclosures provide superior protection against environmental factors such as moisture, dust, and pollution, making them highly reliable in harsh climatic conditions where traditional substations may experience performance degradation.

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The advantages of GIS over AIS extend beyond space efficiency and reliability. GIS requires minimal maintenance due to its enclosed and sealed design, which significantly reduces the need for frequent inspections and component replacements. The absence of exposed conductive parts reduces the risk of electrical faults caused by external factors such as wildlife interference, weather-related damage, and contamination. Additionally, GIS installations have a longer lifespan compared to AIS, making them a cost-effective investment in the long run despite their relatively high initial costs. The applications of GIS are widespread, covering a range of power transmission and distribution needs. Urban substations, industrial facilities, renewable energy integration, and high-voltage direct current (HVDC) transmission projects benefit from GIS technology due to its compactness and reliability. Moreover, GIS is commonly deployed in power plants, offshore wind farms, and substations requiring high safety standards, such as airports and metro stations. The ability to integrate GIS into underground and indoor environments further extends its applicability in locations with stringent land-use regulations.

Despite its numerous benefits, GIS faces environmental challenges, primarily due to its reliance on SF_6 gas, which is a potent greenhouse gas with a high global warming potential. The release of SF_6 during manufacturing, operation, or decommissioning can contribute significantly to environmental degradation. As a result, ongoing research and innovation efforts are focused on developing alternative insulation technologies, such as vacuum and solid-state insulation, to reduce or eliminate dependence on SF_6. Many manufacturers are also exploring SF_6-free switchgear solutions that maintain high insulation performance while mitigating environmental risks. Recent advancements in monitoring and diagnostic systems have further enhanced the efficiency and sustainability of GIS. The integration of IoT-based sensors, predictive maintenance algorithms, and artificial intelligence-driven fault detection systems allows real-time monitoring of GIS components, reducing the risk of unexpected failures and downtime. Smart grid integration and automation technologies have also improved the adaptability of GIS to modern energy networks, enabling better load management and fault response capabilities. These innovations contribute to increased energy efficiency and operational resilience in power distribution.

Hybrid GIS designs, combining elements of AIS and GIS, have emerged as a promising solution to address cost and environmental concerns. These hybrid substations use compact GIS modules for critical high-voltage components while incorporating AIS for lower-voltage sections, striking a balance between space efficiency and reduced reliance on SF_6 gas. Additionally, modular GIS configurations offer greater flexibility in substation expansion and scalability, allowing utilities to optimize infrastructure investments based on evolving energy demands. Looking ahead, the future of GIS will likely be shaped by continued advancements in insulation materials, digital monitoring technologies, and regulatory policies promoting sustainable power distribution. The transition towards eco-friendly insulation alternatives and improved lifecycle management practices will play a crucial role in minimizing the environmental impact of GIS installations. By addressing challenges related to cost, emissions, and technological integration, GIS will remain a key enabler of efficient and resilient power distribution in the face of growing urbanization and energy consumption demands.

2. Related Work

The development of Gas-Insulated Substations (GIS) has been extensively studied in the literature, with a focus on their advantages over Air-Insulated Substations (AIS), advancements in insulation technology, environmental impact, and monitoring systems. This section reviews key studies up to 2020, highlighting trends, challenges, and innovations that have shaped GIS technology.

2.1. Comparison of GIS and AIS

Several studies have provided a comparative analysis of GIS and AIS, emphasizing space efficiency, operational reliability, and maintenance requirements. A study by Mimouni et al. (2016) highlighted that GIS occupies up to 70% less space than AIS, making it ideal for urban applications. Similarly, Jain et al. (2017) discussed the enhanced reliability of GIS due to its encapsulated design, which minimizes exposure to environmental conditions. However, they noted the higher initial cost of GIS as a limiting factor, especially for developing regions.

2.2. Advancements in GIS Insulation Technology

The use of SF_6 gas as an insulating medium has been a major focus in GIS research. Liang et al. (2018) reviewed the dielectric properties of SF_6 and its role in ensuring high voltage insulation with minimal losses. They also examined alternative gases such as fluoronitriles and CO_2-based mixtures, which have been explored to reduce environmental impact. Gheorghe et al. (2019) further analyzed solid-state insulation materials as a potential replacement for SF_6, finding that while promising, these alternatives still faced scalability and performance challenges.

2.3. Environmental Impact and SF_6-Free Alternatives

The environmental concerns associated with SF_6 gas have been widely studied. Papadakis et al. (2015) quantified SF_6 emissions from GIS and estimated their contribution to global warming. Their findings urged stricter regulatory policies and the development of alternative insulation methods. EPRI (2019) documented industry efforts to develop SF_6-free GIS, citing pilot projects that tested vacuum insulation and gas mixtures with lower global warming potential (GWP). However, scalability remained a key challenge due to performance trade-offs.

2.4. Condition Monitoring and Diagnostics in GIS

The implementation of IoT-based condition monitoring and predictive maintenance strategies has gained traction in GIS research. Takeda et al. (2016) proposed a real-time SF_6 leakage detection system integrated with wireless sensors, significantly improving the ability to detect and mitigate leaks before they cause system failures. Similarly, Mahmoud et al. (2018) explored AI-driven fault detection methods, using machine learning algorithms to predict insulation degradation and circuit breaker failures in GIS. These approaches demonstrated enhanced reliability and operational efficiency, reducing maintenance costs.

2.5. Hybrid GIS-AIS Solutions

The concept of hybrid GIS-AIS substations has been investigated as a cost-effective and environmentally friendly alternative. Zhou et al. (2017) analyzed the feasibility of combining GIS modules with AIS components to optimize land use and cost. Their study concluded that hybrid substations provide a viable solution for urban and high-voltage applications while partially mitigating the reliance on SF_6. Kim et al. (2019) extended this research by evaluating the performance of hybrid substations under extreme weather conditions, demonstrating their resilience compared to AIS alone.

2.6. GIS in Renewable Energy Integration

The role of GIS in renewable energy grid integration has been explored in several studies. Huang et al. (2018) discussed GIS applications in offshore wind farms, noting their ability to withstand harsh environmental conditions. Singh and Patel (2019) reviewed GIS implementations in solar power plants, emphasizing their contribution to efficient power transmission in space-constrained renewable energy installations. These studies highlighted GIS as a key enabler of sustainable energy infrastructure.

2.7. Future Challenges and Research Directions

Despite its advantages, GIS technology still faces several challenges. Kumar et al. (2020) outlined key research areas, including the need for improved insulation materials, cost reduction strategies, and enhanced lifecycle management techniques. They emphasized the importance of policy interventions and industry collaboration to accelerate the adoption of SF_6-free GIS.

The literature up to 2020 provides strong evidence of GIS's superiority in terms of space efficiency, reliability, and environmental resilience. However, challenges related to SF_6 emissions, cost, and scalability persist. Advancements in alternative insulation technologies, hybrid GIS designs, and AI-based monitoring systems have paved the way for more sustainable and efficient GIS implementations. Future research must focus on overcoming these limitations to ensure GIS remains a viable solution for next-generation power distribution networks.

Table 1 Comparison of GIS and AIS

Parameter	Gas-Insulated Substations (GIS)	Air-Insulated Substations (AIS)
Space Requirement	Requires 70% less space, making it suitable for urban areas. *(Mimouni et al., 2016)*	Requires large land areas, limiting its use in densely populated regions.
Reliability	High reliability due to encapsulated design, reducing environmental exposure. *(Jain et al., 2017)*	More prone to faults due to exposure to environmental conditions.
Insulation Medium	Uses SF_6 gas, providing excellent insulation properties. *(Liang et al., 2018)*	Uses air as an insulating medium, requiring larger clearances between components.

Environmental Impact	SF_6 has a high global warming potential (GWP); alternative gases under research. *(Papadakis et al., 2015; EPRI, 2019)*	No greenhouse gas emissions, but requires more land and material.
Maintenance	Low maintenance due to enclosed design, reducing contamination and corrosion. *(Mahmoud et al., 2018)*	High maintenance due to exposure to weather and pollution.
Initial Cost	High installation cost due to compact design and SF_6 handling requirements. *(Zhou et al., 2017)*	Lower initial cost, making it more affordable for large-scale projects.
Lifecycle Cost	Lower lifecycle cost due to minimal maintenance and high reliability. *(Takeda et al., 2016)*	Higher lifecycle cost due to frequent maintenance and potential outages.
Operational Safety	Enclosed system enhances personnel safety by minimizing exposure to high voltage components. *(Kim et al., 2019)*	Higher risk of flashovers and electrical faults due to external exposure.
Application Areas	Ideal for urban areas, offshore wind farms, and solar power plants. *(Huang et al., 2018; Singh & Patel, 2019)*	Preferred for rural and industrial applications where space is not a constraint.

3. Design and Components of GIS

Gas-Insulated Substations (GIS) are highly compact, enclosed substations that utilize SF_6 gas as the primary insulating medium. The design of GIS allows for reliable and space-efficient power distribution, making it particularly suitable for urban areas, industrial applications, and renewable energy integrations. Below are the key components of GIS:

- Circuit Breakers:
  - Essential for fault clearance, circuit breakers in GIS are enclosed within SF_6 gas-insulated chambers, ensuring fast and reliable operation.
  - They provide high breaking capacity and arc quenching properties, significantly reducing damage to system components.
- Disconnectors and Earth Switches:
  - Used for safety isolation, these components allow for maintenance operations without interrupting the entire substation.
  - Earth switches provide grounding during maintenance, preventing accidental energization.
- Current and Voltage Transformers:
  - Serve measurement and protection purposes, ensuring proper operation of protection relays and monitoring systems.
  - GIS transformers are enclosed in a gas-insulated environment, enhancing their durability and accuracy.
- Busbars:
  - These conductors distribute electrical power within the substation and interconnect different components.
  - In GIS, busbars are housed in SF_6 gas compartments, reducing phase-to-phase and phase-to-ground clearance.
- Gas-Insulated Lines (GIL):
  - Used for compact and reliable power transmission, GIL provides an alternative to overhead transmission lines, particularly in underground applications.
  - They offer low transmission losses and high efficiency over long distances.

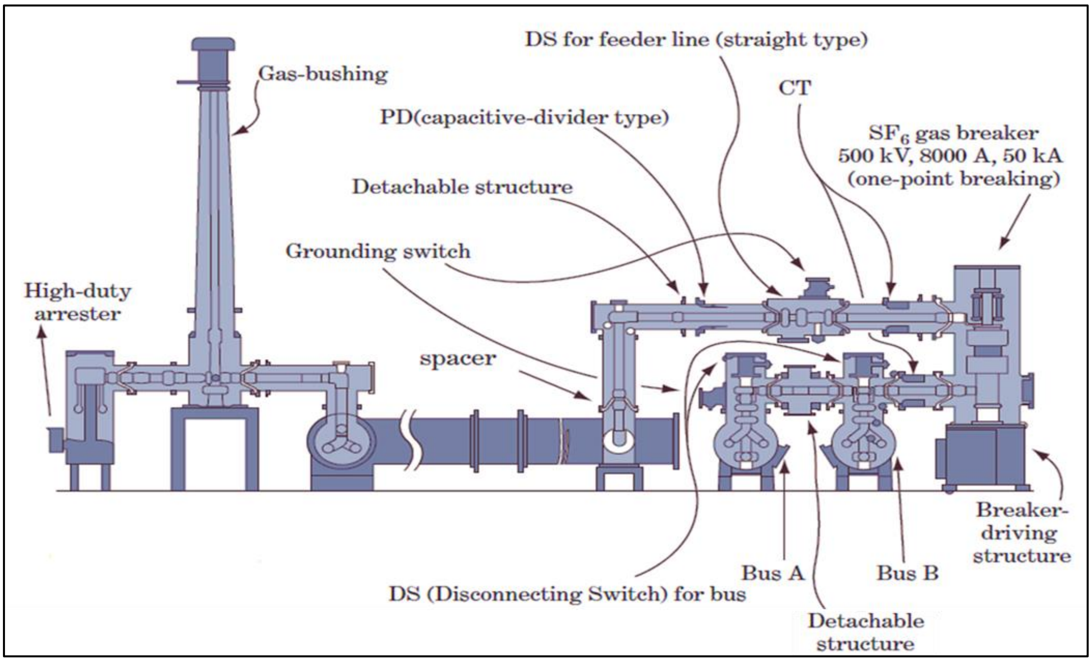

Figure 1 Block diagram of GIS

Table 2 Comparison of GIS and AIS

Feature	GIS (Gas-Insulated Substation)	AIS (Air-Insulated Substation)
Space Requirement	Low – Requires 70% less space due to compact design.	High – Requires large land area for air-clearance insulation.
Maintenance	Minimal – Enclosed components reduce contamination and wear.	Frequent – Exposure to environmental conditions leads to higher maintenance needs.
Installation Cost	High – Requires specialized equipment and SF_6 gas handling.	Moderate – Lower equipment cost but higher land and material costs.
Reliability	High – Enclosed design protects from external weather and contaminants.	Moderate – Prone to environmental influences such as dust, moisture, and corrosion.
Operational Safety	High – Gas-insulated chambers reduce electrical hazards.	Moderate – Higher risk of flashovers and external faults.
Environmental Impact	SF_6 gas has a high global warming potential (GWP), but alternative gases are being researched.	Requires more land, and air pollution can affect insulator performance.
Application Areas	Ideal for urban, industrial, offshore wind farms, and high-voltage applications.	Suitable for rural and remote areas with abundant land availability.

GIS technology offers significant advantages in reliability, space efficiency, and safety but faces challenges related to SF_6 gas emissions and cost. Ongoing research focuses on SF_6-free alternatives and hybrid solutions to enhance environmental sustainability.

4. Advantages of GIS in Urban Areas

The increasing demand for reliable power distribution in urban environments has led to the widespread adoption of Gas-Insulated Substations (GIS). Due to their compact design, high reliability, and low maintenance requirements, GIS is a preferred solution for cities facing space constraints and environmental challenges. Below are some key advantages of GIS in urban areas:

4.1. Space Efficiency

One of the most significant advantages of GIS is its compact design, which requires up to 70% less space than traditional Air-Insulated Substations (AIS).

In dense urban environments where land is expensive and scarce, GIS enables substations to be built underground or inside buildings, maximizing land use for other infrastructure.

Example: Many major cities, including Tokyo, New York, and London, have adopted GIS to integrate substations into high-rise buildings and underground facilities.

4.2. High Reliability

GIS technology provides superior reliability by encapsulating electrical components within SF_6 gas-insulated chambers.

Unlike AIS, which is exposed to environmental factors like rain, dust, humidity, and pollution, GIS remains unaffected by harsh weather conditions.

This feature ensures continuous operation with minimal risk of outages, making GIS an ideal choice for critical urban infrastructure, such as hospitals, metro systems, and financial hubs.

4.3. Low Maintenance

GIS systems have fewer moving parts and are enclosed in a sealed, dust-free environment, reducing the need for frequent inspections and repairs.

The absence of air-exposed conductors means there is no need for periodic cleaning, a requirement in AIS to prevent flashovers caused by dirt and moisture.

Example: Studies have shown that GIS maintenance costs can be 40-60% lower than AIS over a 30-year operational period.

4.4. Enhanced Safety

- GIS significantly reduces the risk of electrical hazards, as all high-voltage components are enclosed within grounded metallic chambers.
- Risk of accidental contact with live parts is minimized, protecting both personnel and nearby public spaces.
- Lower risk of arc faults makes GIS suitable for high-density areas where safety is a primary concern.

4.5. Environmental Considerations

While SF_6 gas is a potent greenhouse gas, modern GIS designs focus on leak detection systems and SF_6 alternatives to mitigate environmental impact.

New developments in vacuum and solid-state insulation aim to replace SF_6, improving the sustainability of GIS technology.

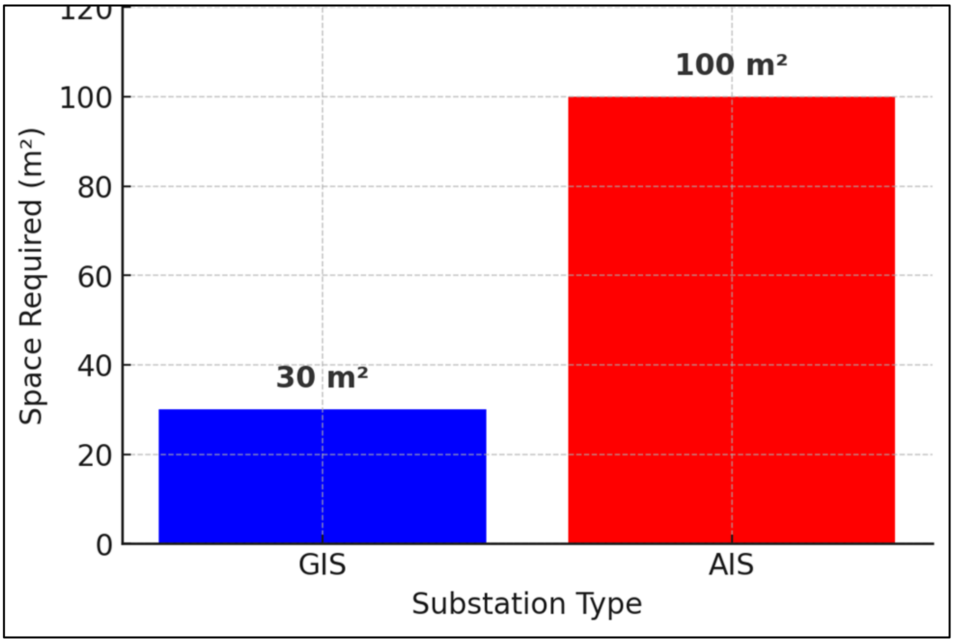

Figure 2 Space Savings of GIS vs. AIS

5. Challenges and Environmental Considerations

While Gas-Insulated Substations (GIS) offer numerous advantages, they also pose certain challenges and environmental concerns that must be addressed to ensure sustainability and cost-effectiveness. The primary concerns include SF_6 gas emissions, high initial investment, and complex maintenance procedures. Below is a detailed discussion of these challenges:

5.1. SF_6 Gas Emissions

Sulfur Hexafluoride (SF_6) is widely used in GIS due to its excellent insulation and arc-quenching properties.

However, SF_6 is a potent greenhouse gas with a Global Warming Potential (GWP) of approximately 23,500 times that of CO_2 over a 100-year period.

Regulatory agencies, such as the European Union (EU) and the Environmental Protection Agency (EPA), are pushing for SF_6 emission reductions through stricter policies and alternative gas solutions.

5.2. High Initial Investment

The capital cost of GIS is significantly higher than that of Air-Insulated Substations (AIS) due to:

- Advanced gas-insulated components
- Specialized SF_6 handling and monitoring systems
- Compact design requirements, which involve high-precision engineering
- Despite the higher upfront costs, GIS often proves to be cost-effective in the long run due to lower maintenance and longer service life.

5.3. Complex Repairs and Maintenance

Unlike AIS, where faults can be easily detected and repaired in an open environment, GIS is a fully enclosed system, making fault detection and component replacement more challenging.

Specialized equipment and trained personnel are required to handle SF_6 gas and enclosed components, leading to longer repair times and higher operational costs.

Some advancements in real-time monitoring systems and predictive maintenance techniques aim to reduce downtime and improve reliability.

5.4. Environmental and Sustainability Challenges

Apart from SF_6 concerns, GIS manufacturing and disposal involve high energy consumption and resource-intensive processes.

Efforts are being made to develop recyclable GIS components and introduce alternative insulation technologies to minimize environmental impact.

Hybrid GIS solutions, integrating vacuum switching technology and solid insulation, are emerging as potential low-emission alternatives.

Table 3 SF_6 Emission Control Technologies

Technology	Description
SF_6 Recycling	Reuse and purification of SF_6 gas to minimize emissions.
Alternative Gases	Development of eco-friendly insulating gases such as C4-FN, C5-FK, and dry air.
Monitoring Systems	Continuous leakage detection and mitigation systems to ensure minimal gas loss.

6. Recent Innovations in GIS

Gas-Insulated Substations (GIS) continue to evolve, driven by the need for enhanced efficiency, reliability, and environmental sustainability. Recent innovations focus on eco-friendly insulation, smart monitoring technologies, and hybrid GIS solutions that optimize both cost and performance. Below is a detailed discussion of these advancements:

6.1. Eco-Friendly Insulation Technologies

- Traditional GIS relies on Sulfur Hexafluoride (SF_6), a highly effective insulating gas but also a potent greenhouse gas.
- Research is actively exploring alternative gases that provide comparable insulation and arc-quenching properties while reducing environmental impact.
- Promising alternatives include:
  - Fluoronitriles (C4-FN): Demonstrated as a viable low-GWP replacement for SF_6 in medium-voltage GIS.
  - Fluoroketones (C5-FK): Shows potential as an insulation medium with improved sustainability.
  - Dry Air and Nitrogen-Based Mixtures: Being tested for applications in low- and medium-voltage systems.
- Leading electrical companies such as Siemens, ABB, and GE have already introduced SF_6-free GIS prototypes to align with global carbon reduction targets.

6.2. Smart Monitoring and Predictive Maintenance

- The integration of IoT (Internet of Things) and AI-powered sensors has revolutionized the way GIS performance is monitored and maintained.
- These advancements enable:
  - Real-time condition monitoring of GIS components, including circuit breakers, transformers, and insulation systems.
  - Early fault detection to minimize the risk of catastrophic failures.
  - Predictive maintenance algorithms that analyze historical data and prevent unplanned downtime.
- Examples of smart monitoring systems:
  - Partial Discharge (PD) Sensors: Detect insulation degradation before failure occurs.
  - Gas Leak Detectors: Continuously monitor SF_6 levels to prevent leakage and environmental impact.
  - Temperature and Humidity Sensors: Ensure optimal operating conditions for critical GIS components.
- Utilities adopting digital GIS solutions benefit from reduced operational costs, improved reliability, and extended equipment lifespan.

6.3. Hybrid GIS Solutions

- A hybrid GIS combines the best features of Gas-Insulated and Air-Insulated Substations (GIS + AIS) to achieve an optimal balance between cost, space utilization, and performance.
- Key benefits of hybrid GIS:
  - Cost-effectiveness: Reduces dependency on SF_6 while maintaining high insulation performance.
  - Space optimization: Uses compact GIS where space is constrained and AIS where space is available.
  - Improved reliability: Maintains the protective enclosure benefits of GIS while allowing easier access for aintenance.
- Hybrid GIS is particularly useful in:
  - Suburban and semi-urban areas, where AIS may still be feasible.
  - Expansion projects, where existing AIS infrastructure can be upgraded with GIS modules.
  - Renewable energy integration, such as offshore wind farms, where hybrid designs optimize transmission efficiency.

Recent innovations in GIS technology are shaping the future of power distribution by enhancing sustainability, reliability, and cost efficiency. The transition to eco-friendly insulation, smart monitoring, and hybrid solutions reflects the industry's commitment to addressing environmental concerns while improving grid performance. As global energy demands continue to grow, these advancements will play a crucial role in ensuring a sustainable and resilient power infrastructure.

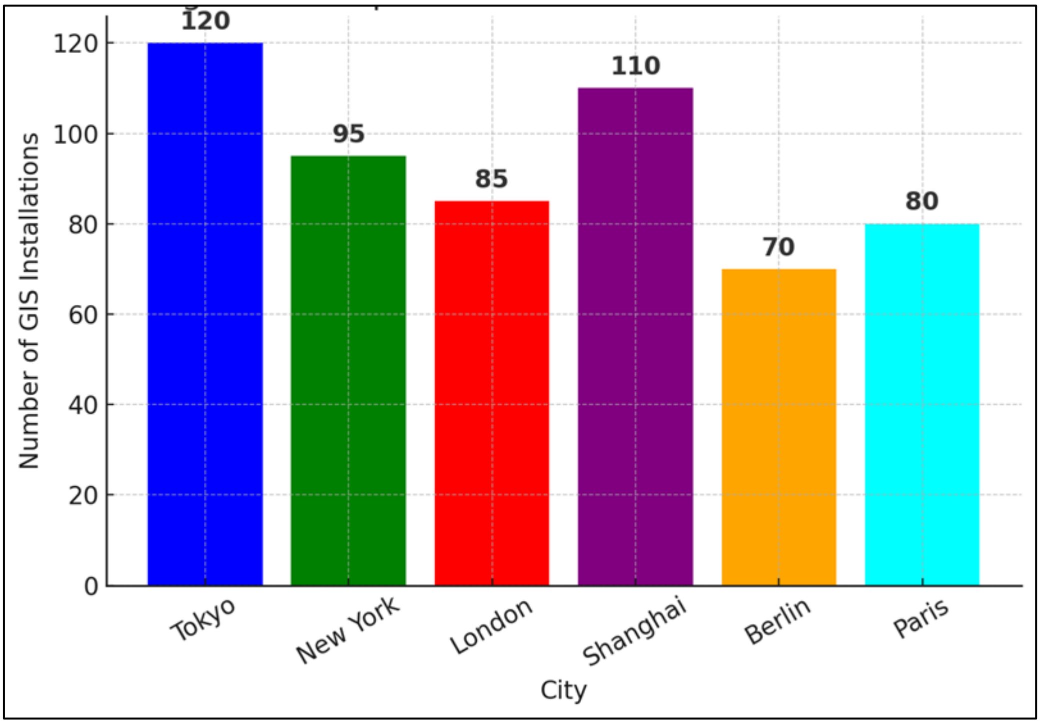

Figure 3 Adoption of GIS in Different Urban Areas

7. Future Trends and Recommendations

As the demand for efficient and sustainable power distribution grows, Gas-Insulated Substations (GIS) are expected to undergo significant advancements. Future trends focus on enhancing environmental sustainability, improving space efficiency, and leveraging digitalization for predictive maintenance and operational optimization.

7.1. Green GIS Solutions

- The transition to SF_6-free GIS remains a top priority due to SF_6's high global warming potential.
- Researchers and manufacturers are developing alternative insulation gases, such as:
  - Fluoronitriles (C4-FN) and Fluoroketones (C5-FK): Low-GWP replacements with promising insulation properties.

- CO_2-based and Nitrogen-based gas mixtures: Providing sustainable solutions while maintaining high dielectric strength.
- Vacuum Interruption Technology: Reducing the need for gaseous insulation in medium-voltage applications.

- Future GIS designs will emphasize closed-loop SF_6 recycling systems, ensuring that emissions are minimized through advanced recovery and reuse techniques.

7.2. Compact and Modular Designs

- Urbanization demands space-efficient substations, making compact GIS solutions essential for infrastructure expansion.
- Innovations include:
  - High-voltage, compact GIS modules that reduce the footprint while maintaining performance.
  - Prefabricated modular GIS designs that enable faster deployment and scalability.
  - Lightweight materials and optimized component layouts to further enhance space efficiency.
- Future GIS will integrate plug-and-play designs, allowing for seamless expansion and easy integration with existing grid systems.

7.3. Digital Twin Technology for Smart Grid Integration

- The adoption of AI, machine learning, and digital twin technology is transforming GIS operation and maintenance.
- Digital twin models—virtual representations of GIS substations—enable:
  - Predictive maintenance by analyzing sensor data and historical performance trends.
  - Fault detection and diagnosis before failures occur, reducing downtime and repair costs.
  - Real-time grid monitoring for optimized load management and energy distribution.
- Cloud-based analytics platforms will play a crucial role in automating GIS monitoring and optimizing power flow in smart grids.

7.4. Enhanced Cybersecurity and Grid Resilience

- With increased digitalization, GIS systems are becoming more vulnerable to cyber threats.
- Future GIS deployments will integrate advanced cybersecurity frameworks, including:
  - Encryption and secure communication protocols for data transmission.
  - AI-driven intrusion detection systems to mitigate cyberattacks.
  - Redundant and fail-safe mechanisms to enhance resilience against system failures.
- Secure and resilient GIS will be crucial for the integration of renewable energy sources and the evolution of smart grids.

8. Conclusion

With rapid urbanization and increasing energy demands, the need for efficient, reliable, and space-saving power distribution solutions has never been greater. Gas-Insulated Substations (GIS) have emerged as a crucial innovation, offering a compact, high-performance alternative to conventional Air-Insulated Substations (AIS). By utilizing SF_6 gas for insulation, GIS provides enhanced reliability, safety, and operational efficiency, making it ideal for densely populated urban environments where land availability is limited. One of the most significant benefits of GIS is its space efficiency. Unlike AIS, which requires large open areas for insulation clearance, GIS reduces footprint requirements by up to 90%, allowing for installation in underground facilities, high-rise buildings, or densely packed urban zones. This makes GIS an attractive solution for cities struggling with land scarcity. In addition to space savings, GIS offers high reliability due to its enclosed design. The encapsulation of critical electrical components within SF_6-insulated chambers minimizes exposure to environmental pollutants, extreme weather conditions, and external mechanical impacts. This results in lower failure rates and increased operational longevity. Another key advantage is the low maintenance requirement of GIS. Since all components are housed within a sealed gas-insulated system, the risk of contamination from dust, moisture, and external elements is significantly reduced. As a result, GIS requires less frequent inspections and maintenance compared to AIS, leading to lower operational costs over time. Furthermore, safety enhancements are a crucial factor driving GIS adoption. The enclosed structure reduces the risk of electrical arcs, short circuits, and direct human contact with live components, making GIS a safer option for workers and the surrounding environment.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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