THE PHASE-OUT OF SF_6 IN MEDIUM VOLTAGE SWITCHGEAR BY 2026: TECHNICAL CHALLENGES, ENVIRONMENTAL IMPLICATIONS, AND ENGINEERING PERSPECTIVES

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Abstract - The decarbonization of the energy sector is reshaping not only generation technologies but also the material and design paradigms of electrical infrastructure. Within the European Union, the revision of the F-Gas Regulation introduces stringent restrictions on sulfur hexafluoride (SF_6) in medium voltage (MV) switchgear due to its extremely high Global Warming Potential (GWP). From 2026 onward, new regulatory provisions will significantly limit and in specific applications prohibit the placing on the market of SF_6-based MV equipment. This regulatory milestone compels manufacturers to qualify alternative insulation and arc-interruption technologies and to reconsider consolidated design philosophies. This paper critically examines the regulatory framework, evaluates the principal technological alternatives, analyzes engineering and manufacturing implications, and identifies unresolved technical challenges associated with the transition toward SF_6-free MV switchgear.

I. INTRODUCTION

The progressive decarbonization of electrical power systems is driving structural modifications in medium voltage distribution networks. The large-scale integration of renewable energy sources, increased penetration of distributed generation, bidirectional power flows, and higher operational variability impose new technical constraints on switchgear performance and reliability. In this evolving context, environmental sustainability and material selection have become primary design parameters alongside electrical and mechanical performance.

Medium voltage switchgear assemblies, comprising disconnectors, load break switches, circuit breakers, and associated protective devices, constitute critical nodes within distribution systems. For more than five decades, sulfur hexafluoride (SF_6) has been the reference insulation and arc-quenching medium in gas-insulated switchgear (GIS) and ring main units (RMUs). Its widespread adoption is attributable to its superior dielectric strength, high thermal conductivity, chemical inertness, and exceptional arc-interruption capability, enabling compact and highly reliable equipment configurations.

However, SF_6 is characterized by an exceptionally high GWP, approximately 23,500 times that of CO_2 over a 100-year time horizon, making it one of the most environmentally impactful greenhouse gases currently in industrial use. Although modern sealed-for-life switchgear exhibits relatively low annual leakage rates, cumulative emissions over the full life cycle, including manufacturing, commissioning, maintenance, and end-of-life treatment remain environmentally significant.

In response to climate policy objectives, particularly within the European Union, regulatory measures have progressively restricted fluorinated greenhouse gases. The 2026 restrictions represent a decisive turning point for medium voltage switchgear technology. As the European Union moves toward climate neutrality by 2050, the phase-out of SF_6 in secondary and primary distribution networks has become an urgent regulatory and environmental priority.

Voltage (kV)	Date of ban	Typical voltage level (kV)
Ur ≤ 24	1st January 2026	3.6, 7.2, 12, 17.5, 24
24 < Ur ≤ 52	1st January 2030	27, 36, 40.5, 52

Fig. 1 The ban dates for MV switchgear

II. REGULATORY FRAMEWORK AND THE 2026 TRANSITION

The revised European F-Gas Regulation establishes a structured phase-down mechanism for fluorinated greenhouse gases, combining quota reductions, usage prohibitions, and sector-specific restrictions. Within the electrical sector, the regulation introduces explicit constraints on the placing on the market of medium voltage switchgear containing SF_6, subject to voltage level and application thresholds.

The 2026 milestone constitutes a critical inflection point characterized by:

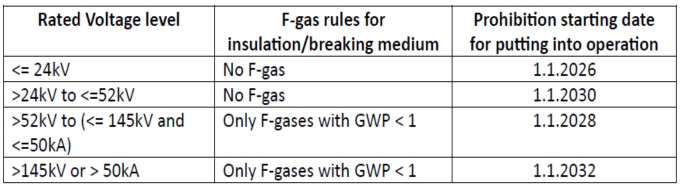
- Prohibition or severe limitation of SF_6-containing MV switchgear in newly installed systems;
- Mandatory adoption and qualification of alternative low-GWP or gas-free insulation technologies;
- Revision of technical procurement specifications by utilities, industrial operators, and network planners.

The regulatory framework generates not only environmental obligations but also strategic and economic implications. The progressive reduction in SF_6 production quotas is expected to affect market availability and cost stability, thereby increasing supply chain risks and reinforcing the incentive for technological substitution.

Key Insights of Gas Insulated Switchgear SF6-Free Market 2026-2033

- Market size (2024): USD 2.5 billion
- Forecast (2033): USD 5.1 billion

- CAGR 2026-2033: 8.5%
- Leading Segments: Voltage Class: High Voltage (HV) Product Type: Compact GIS End-User: Utilities & Power Transmission
- Key Application: Power Transmission & Distribution
- Key Regions/Countries with market share: North America, Europe, Asia-Pacific, China, Germany, India



Rated Voltage level	F-gas rules for insulation/breaking medium	Prohibition starting date for putting into operation
<= 24kV	No F-gas	1.1.2026
>24kV to <=52kV	No F-gas	1.1.2030
>52kV to (<= 145kV and <=50kA)	Only F-gases with GWP < 1	1.1.2028
>145kV or > 50kA	Only F-gases with GWP < 1	1.1.2032

Fig. 2 General restrictions (subject to derogations)

III. TECHNOLOGICAL ALTERNATIVES TO SF_6

The replacement of SF_6 does not rely on a single universally applicable technology. Instead, multiple engineering solutions are being developed and industrialized, each involving distinct trade-offs in dielectric performance, compactness, manufacturability, and long-term reliability.

a) Vacuum Interruption Combined with Solid or Air Insulation

Vacuum interrupter technology is well established for medium voltage arc interruption. In vacuum, arc extinction is achieved through rapid dielectric recovery following current zero, enabled by the absence of ionizable gas and the metal vapor condensation mechanism.

When vacuum interruption is combined with alternative insulating systems, such as epoxy-based solid insulation, air insulation, or fully encapsulated resin structure, it enables entirely SF_6-free switchgear configurations.

Technical advantages include:

- Elimination of greenhouse gas emissions from the insulation medium;
- Mature and extensively validated vacuum arc-interruption technology;
- Simplified maintenance due to the absence of gas handling requirements.

Engineering challenges include:

- Increased equipment volume compared to compact SF_6-based GIS;
- More complex thermal management due to altered internal convection conditions;
- Long-term ageing and partial discharge behavior of solid insulation systems.

The shift from gas-insulated to solid- or air-insulated architectures requires comprehensive re-optimization of electric field control, creepage distances, and surface insulation geometry.

b) Clean Air and Low-GWP Gas Mixtures

An alternative strategy involves substituting SF_6 with gases characterized by significantly lower GWP, including clean dry air, nitrogen-based mixtures, and novel fluoronitrile or fluoroketone blends.

These solutions attempt to preserve the operational and architectural philosophy of traditional GIS systems while mitigating environmental impact.

Potential advantages:

- Substantial reduction in greenhouse gas emissions;
- Retention of sealed pressure systems;
- Compatibility with existing GIS design concepts.

Technical limitations:

- Lower intrinsic dielectric strength compared to SF_6, requiring either higher operating pressure or increased electrode spacing;
- Mechanical implications associated with pressure vessel design;
- Limited long-term empirical data under diverse environmental and operational stress conditions.

Material compatibility, chemical decomposition by-products under arcing, and long-term gas stability remain active research areas.

c) Hybrid Architectures

Hybrid switchgear configurations combine vacuum interrupters for current interruption with clean air or solid insulation for dielectric isolation. These architectures aim to achieve a compromise between compactness, environmental compliance, and mechanical simplicity.

However, such systems require comprehensive validation through type testing, accelerated ageing protocols, and extended field operation to ensure equivalence with the established reliability benchmarks of SF_6-based equipment.

IV. ENGINEERING IMPLICATIONS

The phase-out of SF_6 introduces substantial modifications to established electrical and mechanical design methodologies.

a) Dielectric Design Optimization

The exceptional dielectric strength of SF_6 enables reduced clearances and highly compact assemblies. Alternative media necessitate:

- Increased phase-to-phase and phase-to-ground distances;
- Advanced electric field grading techniques (e.g., optimized electrode profiling and stress control);
- Enhanced surface insulation strategies to mitigate partial discharge inception.

These modifications directly influence panel footprint, structural mass, and installation constraints within substations.

b) Electrical and Mechanical Endurance

SF_6-based switchgear has historically demonstrated high electrical endurance, stable interruption capability, and extended service life. Alternative systems must demonstrate equivalent reliability through:

- High-duty short-circuit interruption testing;
- Mechanical endurance cycles;
- Accelerated thermal and humidity ageing tests;
- Long-term partial discharge monitoring.

The challenge is amplified by the evolving operational conditions of renewable-dominated networks, characterized by higher switching frequencies, distributed generation, and increased transient stresses.

c) Environmental Sensitivity of Alternative Insulating Media

Compared with hermetically sealed SF_6 systems, alternative insulation solutions, particularly air and solid dielectric configurations, may exhibit greater sensitivity to environmental parameters such as:

- Relative humidity and condensation;
- Surface contamination and pollution;
- Temperature cycling and thermal gradients;
- High-altitude dielectric derating.

Ensuring stable long-term performance under outdoor or industrial conditions remains a critical qualification requirement.

c) Manufacturing Processes and Supply Chain Adaptation

The elimination of SF_6 requires substantial modifications in manufacturing and quality control processes, including:

- Removal of gas filling, recovery, and leak detection infrastructure;
- Implementation of advanced resin casting and encapsulation techniques;
- Increased procurement of vacuum interrupters;
- Qualification and traceability of alternative insulating materials and gas mixtures.

V. ENVIRONMENTAL ASSESSMENT AND LIFE CYCLE CONSIDERATIONS

The substitution of SF_6 in medium voltage switchgear must be evaluated within a comprehensive environmental assessment framework extending beyond the operational phase. Although the elimination of a high-GWP insulating medium substantially reduces direct greenhouse gas emissions associated with leakage and end-of-life release, a holistic evaluation requires the application of standardized Life Cycle Assessment (LCA) methodologies in accordance with ISO 14040 and ISO 14044 principles.

A rigorous LCA should consider the following life cycle stages:

- **Raw material extraction and processing**, including increased utilization of epoxy resins, thermosetting polymers, copper conductors, ferromagnetic materials, and structural steel;
- **Manufacturing and assembly processes**, encompassing energy consumption for resin casting, machining, encapsulation, and quality control testing;
- **Transportation and installation**, potentially affected by increased equipment mass and volume;
- **Operational phase**, including maintenance frequency, failure rates, and energy losses;
- **End-of-life treatment**, including disassembly, recyclability of metallic components, and management of composite insulating materials.

In SF_6-free architectures, the reduction in direct greenhouse gas emissions may be partially offset by increased material intensity due to larger clearances and reinforced enclosures. In particular, solid-insulated and air-insulated configurations may require greater quantities of copper and steel to ensure equivalent thermal and mechanical performance. The environmental burden associated with polymer-based insulation systems, characterized by limited recyclability, must also be quantitatively assessed.

Therefore, the net environmental benefit of SF_6 substitution cannot be inferred solely from GWP reduction of the insulating medium. Instead, it must be derived from comparative, scenario-based LCA studies incorporating:

- Functional unit normalization (e.g., per kA of breaking capacity or per MVA of installed capacity);
- Sensitivity analysis on service life assumptions;
- Consideration of failure rates and replacement cycles;
- End-of-life recovery efficiencies.

Only through such system-level analysis can the environmental superiority of alternative technologies be robustly demonstrated.

VI. ECONOMIC IMPLICATIONS

The transition toward SF_6-free medium voltage switchgear entails both direct and indirect economic impacts across the value chain. From a capital expenditure (CAPEX) perspective, alternative technologies are frequently associated with higher initial acquisition costs due to:

- Increased material requirements;
- Redesign of dielectric structures;
- Investment in new tooling and manufacturing infrastructure;
- Extended type-testing and certification campaigns.

Furthermore, substations originally designed for compact GIS installations may require spatial reconfiguration to accommodate larger air-insulated or solid-insulated panels. This may generate additional civil engineering and installation costs, particularly in retrofit scenarios where footprint constraints are critical.

However, a comprehensive economic assessment must incorporate life-cycle cost (LCC) analysis, including operational expenditure (OPEX) components such as:

- Elimination of gas handling, monitoring, and recovery procedures;
- Reduced regulatory compliance costs associated with fluorinated gas reporting;
- Mitigation of future carbon pricing or environmental taxation risks;
- Potential reduction in insurance and environmental liability exposure.

In addition, supply chain resilience considerations are increasingly relevant. The progressive restriction of SF_6 production quotas may introduce price volatility and procurement uncertainty. From a strategic standpoint, early adoption of alternative technologies may reduce exposure to regulatory discontinuities and stranded asset risks.

A rigorous techno-economic evaluation should therefore integrate CAPEX, OPEX, regulatory risk, and projected service life within discounted cash flow models to determine the total cost of ownership (TCO) under multiple regulatory and market scenarios.

VII. OPEN TECHNICAL QUESTIONS AND RESEARCH DIRECTIONS

Despite rapid technological development, several technical uncertainties persist and require systematic investigation through experimental validation and long-term field monitoring.

a) Ageing and Reliability of Alternative Insulation Systems

Solid insulation materials, including epoxy-based encapsulation systems, are subject to thermo-mechanical stresses, partial discharge activity, and environmental ageing phenomena. Long-term degradation mechanisms, such as electrical treeing, surface tracking, and interfacial delamination, must be quantitatively characterized under representative load and environmental conditions.

Similarly, low-GWP gas mixtures require extended evaluation of:

- Chemical stability under repetitive arcing events;
- Decomposition by-products and their interaction with internal materials;
- Long-term sealing integrity and leakage rates.

b) High-Altitude and Environmental Derating

The dielectric strength of gaseous insulation decreases with reduced atmospheric pressure. In high-altitude installations, this phenomenon may require additional insulation distances or pressure compensation mechanisms. The impact of altitude on clean air and alternative gas mixtures requires further empirical validation to establish reliable derating coefficients.

Moreover, air-insulated configurations may exhibit increased sensitivity to environmental contamination and humidity. The long-term evolution of partial discharge inception voltage (PDIV) under polluted conditions remains a critical research topic.

c) Partial Discharge Behaviour and Diagnostic Methodologies

In SF_6-based sealed systems, partial discharge levels are typically minimal due to the high dielectric strength and homogeneous field distribution. Alternative architectures may exhibit different PD patterns over time, necessitating the refinement of diagnostic thresholds and condition-monitoring strategies.

The development of standardized testing protocols for PD behavior in solid- and air-insulated MV systems represents an essential step toward harmonized qualification criteria.

d) Standardization and International Harmonization

The rapid evolution of alternative technologies introduces potential fragmentation across international markets. Divergent technical specifications, testing procedures, and environmental metrics may hinder interoperability and scalability.

Harmonized standards, covering dielectric performance, environmental classification, ageing protocols, and LCA methodology, are therefore essential to ensure technological comparability and market transparency.

Notably, the regulatory transition has stimulated renewed interest in air-insulated switchgear architectures previously considered less advanced than compact GIS solutions. Contemporary computational modeling techniques (e.g., finite element electric field simulations), improved insulating materials, and optimized electrode geometries are enabling the re-engineering of these configurations to achieve performance levels compatible with modern grid requirements.

e) Brownfield Installation Vacuum interrupters introduce high frequency transient voltage due to current chopping phenomena. Surge protection for equipment (e.g.transformers) should be considered at the design stage when vacuum interrupter technology is selected.

f) Italian Regulation

The DM (Ministerial Decree) 12.01.1980 was published with the limits originally imposed by Royal Decree (RD) no. 824 of 1927 (subject to inspection were all containers with a volume greater than 25 liters containing gas at a pressure exceeding 0.049 bar) but shortly thereafter its scope of application/exclusion was modified to align with that defined by Presidential Decree (DPR) no. 341 of February 13, 1981. Consequently, DM 12.01.1980, as amended by DPR 341 of 1981, does not apply to gas pressure vessels [...] containing active parts of electrical equipment if:

1. they have a capacity of less than 25 liters (for any design pressure, provided they are installed in places not frequented by the public)
2. they have a capacity of less than 2000 liters and a design pressure (i.e., maximum operating pressure) of less than 0.49 bar
3. they have a capacity even greater than 2000 liters but a design pressure of less than 0.49 bar, provided they are adequately protected against the risk of 'overpressure'

More simply: DM 12.01.1980 (as amended by DPR 341 of 1981) applies to gas pressure vessels [...] containing active parts of electrical equipment if: they have a capacity greater than 25 liters and a design pressure greater than 0.49 bar.

Currently in Italy, Ministerial Decree (DM) 1.12.1980 (as amended by Presidential Decree (DPR) 341 of 1981) applies to gas pressure vessels [...] containing active parts of electrical equipment if they have a capacity greater than 25 liters and a design pressure greater than 0.49 bar.

Currently in Europe, for circuit breakers with a voltage up to 52 kV, a design pressure up to 3 bar, and a pressure x volume product up to 2000 bar x liter, the CEI EN 50187 standard is followed. If the circuit breakers are for voltages over 52 kV, or have design pressures over 3 bar, or the pressure x volume product exceeds 2000 bar x liter, then CEI EN 50052, CEI EN 50064, CEI EN 50068, and CEI EN 50069 must be used.

The value of 2000 bar x liter set by CEI EN 50187 as one of the 3 current limits for its field of application does not originate from Italian regulations.

VIII. CONCLUSIONS

The phase-out of SF_6 in medium voltage switchgear by 2026 represents a structural transformation in electrical equipment engineering rather than a mere material substitution. The transition affects dielectric design principles, manufacturing processes, supply chain organization, environmental assessment methodologies, and economic evaluation frameworks.

While technically viable alternatives are currently available, their equivalence to established SF_6-based systems must be demonstrated through long-term reliability data, comprehensive life cycle assessments, and rigorous standardization efforts. The environmental advantage of SF_6 elimination, although significant in terms of direct GWP reduction, must be validated through system-level analyses incorporating material intensity, manufacturing energy consumption, and end-of-life management.

The successful implementation of SF_6-free technologies will depend on coordinated collaboration among manufacturers, utilities, research institutions, and regulatory bodies. The establishment of transparent environmental metrics, harmonized testing standards, and robust engineering validation procedures will be essential to ensure that environmental objectives are achieved without compromising grid reliability, operational safety, or economic sustainability.

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X. VITA

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