TECHNICAL WHITE PAPER

HMP-WP-2601

Development History of SF_6 (Past and Present)

From a Core Insulating Medium to the Most Potent Greenhouse Gas

ABSTRACT

Sulfur hexafluoride (SF_6) has been widely adopted in medium- and high-voltage switchgear for decades owing to its outstanding dielectric and arc-quenching properties. It has shaped the design of gas-insulated switchgear (GIS) and ring main unit (RMU) equipment, and underpins the miniaturisation and high reliability of modern high-voltage networks. This paper traces the development of SF_6 from its first synthesis in 1901, through laboratory research, industrial production and large-scale deployment in the power industry, to the recognition of its potent greenhouse effect, its inclusion in the Kyoto Protocol's list of controlled gases, and European Union legislation mandating its phase-out. Engineering risks arising in field operation and life-cycle management challenges are also examined, so as to provide historical and technical perspectives on the ongoing fluorine-free transition in medium-voltage networks. For an in-depth treatment of greenhouse gases, the GWP metric and the global regulatory framework, see companion White Paper HMP-WP-2602.

1 Invention: The 1901 Synthesis by a Pioneer of Fluorine Chemistry

In 1901 the French chemist Henri Moissan and his assistant Paul Lebeau placed sulfur in an apparatus filled with fluorine gas and synthesised sulfur hexafluoride (SF_6) for the first time [1]. Moissan had earlier isolated elemental fluorine for the first time in 1886 and was awarded the 1906 Nobel Prize in Chemistry. At that period fluorine was one of the most difficult elements to handle: it reacts vigorously with nearly every substance, and many earlier attempts to isolate it had failed or injured their authors. Moissan's command of fluorine chemistry came at considerable personal cost, as prolonged exposure to the gas damaged his health. The synthesis of SF_6 therefore rested on one of the highest achievements of chemistry of its era.

In terms of molecular structure, SF_6 consists of one sulfur atom and six fluorine atoms arranged in a highly symmetric regular octahedron, in which the six fluorine atoms enclose the central sulfur atom. At normal temperature and pressure it is a colourless, odourless, non-toxic gas; it is neither flammable nor combustion-supporting, and its density is about five times that of air. Chemically it is extremely stable, reacting with almost nothing and decomposing only marginally even at elevated temperature. In short, it is among the most inert of industrial gases.

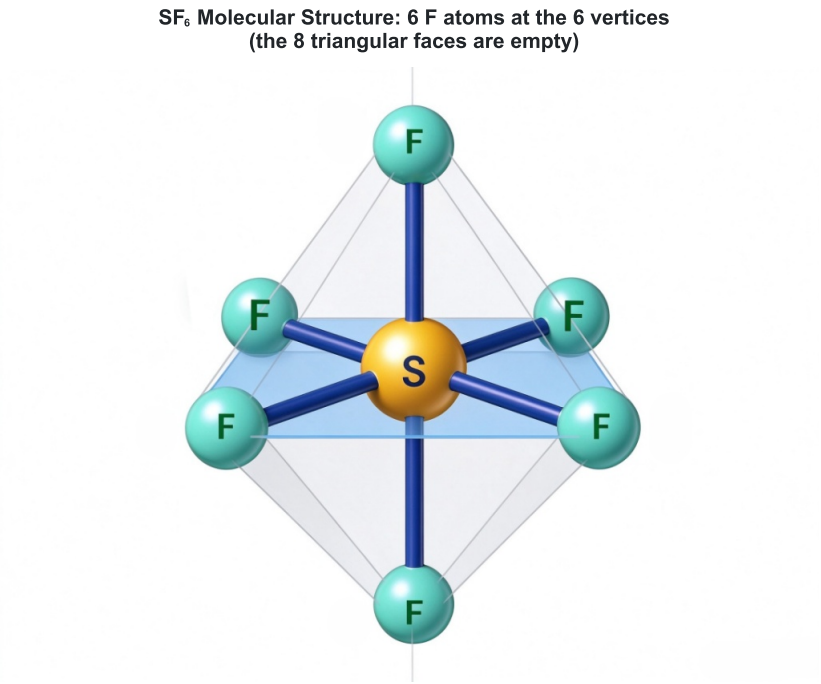


Figure 1 — SF_6 molecular structure (regular octahedron with a central sulfur atom).

Of greater interest to engineers is that this apparently unremarkable molecule combines high electrical performance: its dielectric strength is several times that of air, and its arc-quenching capability far exceeds that of both air and insulating oil. It is precisely this combination of chemical inertness and electrical effectiveness that established SF_6 as a gas of decisive importance to the power industry. Initially it was studied and used only on a small scale; it came into its own only when the power industry entered its period of rapid growth.

Industrial production of SF_6 still follows essentially the route developed by Moissan and Lebeau: sulfur is burned in fluorine gas, and toxic by-products are removed through multiple purification steps. As the process matured, SF_6 moved from a laboratory curiosity to an industrial gas that could be supplied to the market in large volumes at ever lower cost, paving the way for its subsequent large-scale adoption in power equipment and its status as a default design choice for the grid.

2 Contribution: The Core Enabling Medium of the Grid

SF_6 offers both excellent insulation performance and strong arc-quenching performance. The latter refers to the rapid extinguishing of the high-temperature arc that forms between contacts — something air and ordinary insulating oil can achieve only with difficulty.

First, insulation

Air is a common insulating medium, but its dielectric strength is limited: the higher the voltage, the larger and heavier the equipment must be. At atmospheric pressure the dielectric strength of SF_6 is about 2.5 times that of air [2], which means that at a given voltage class equipment can be made significantly more compact. Since the 1960s SF_6 has been widely used in core equipment such as gas-insulated switchgear (GIS), high-voltage circuit breakers, transformers and gas-insulated transmission lines (GIL), and has gradually become the default medium for high-voltage networks [3].

Second, arc quenching

When a high-voltage circuit breaker interrupts a current, an arc with a temperature of several thousand degrees Celsius forms instantaneously between the contacts. If it is not extinguished quickly, the equipment may burn out and the wider network may be affected. SF_6 absorbs arc energy in a very short time, completes the quenching process and rapidly restores dielectric strength, giving the switch a breaking capacity far above that achievable with air or conventional insulating oil. This is the fundamental reason why it remains difficult to replace in ultra-high-voltage (UHV) and extra-high-voltage (EHV) applications to this day.

Third, power transmission

Beyond switchgear and transformers, SF_6 is also used in gas-insulated transmission lines (GIL). In sections that cross large rivers, pass through dense urban areas, or where high-voltage corridors are constrained, GIL can transmit power with a smaller footprint and lower losses, providing a third option alongside overhead lines and underground cables. In sum, from generation plant to end user and from substation to transmission corridor, SF_6 is involved in nearly every key stage of the modern power system.

The contribution of these two capabilities has been transformational. Taking GIS as an example, at the same voltage class its footprint can be several times smaller than that of a conventional open-air substation; the equipment is fully enclosed within metal housings, protected from weather and space-efficient, and is especially suitable for underground cable tunnels and densely built, land-scarce urban areas. Because the insulating medium is insensitive to external temperature and humidity, equipment reliability improves markedly, and failure rates and maintenance frequency fall accordingly. This explains why the vast majority of gas-insulated switchgear uses SF_6 as its insulation and arc-quenching medium, and why the power industry consumes roughly 80% of global SF_6 production [4].

It is reasonable to conclude that a substantial part of the miniaturisation, reliability and safe operation of modern high-voltage networks is attributable to SF_6. It should be noted that in UHV and large-capacity high-voltage GIS applications SF_6 remains difficult to replace fully in the short term, whereas at the 12–24 kV medium-voltage class several mature SF_6-free technology routes have already emerged. These two cases should be assessed separately.

3 Hidden Costs in Operation: The Engineering Price of Stability

The practical consequences of SF_6's chemical stability are seen not only in its greenhouse effect but also in the engineering costs incurred during equipment operation and maintenance:

1. Leakage is concealed and hard to detect: SF_6 is colourless and odourless, so leakage cannot be identified by sight or smell; on-site detection requires dedicated leak-detection instruments. Pressurised equipment operating over long periods carries a risk of slow leakage, requiring periodic pressure monitoring and occasional refilling — a continuing operation-and-maintenance burden.
2. Arc decomposition produces harmful by-products: during switching operations part of the SF_6 decomposes into a range of toxic and corrosive products, so maintenance work must follow specific protection and handling procedures.
3. High life-cycle medium-management cost: filling, operation, maintenance and eventual decommissioning all require recovery and purification of the SF_6 medium, placing high demands on the maintenance system, spare-parts management and personnel skills; where the recovery system is inadequate, the medium is released directly into the atmosphere.

4 Awakening: From Enabling Gas to the Most Potent Greenhouse Gas

The chemical stability that makes SF_6 so useful has a corresponding environmental consequence.

Research has shown that SF_6 is a very strong absorber of infrared radiation, efficiently trapping the heat radiated from the Earth's surface and producing an intense greenhouse effect. In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the 100-year Global Warming Potential (GWP-100) of SF_6 is given as approximately 23,500 times that of carbon dioxide — one of the highest values of any greenhouse gas assessed [5]. It persists in the atmosphere for about 3,200 years, is essentially not broken down naturally, and is removed only very slowly by photolysis [6]. Accordingly, every SF_6 molecule released today will influence the climate for thousands of years.

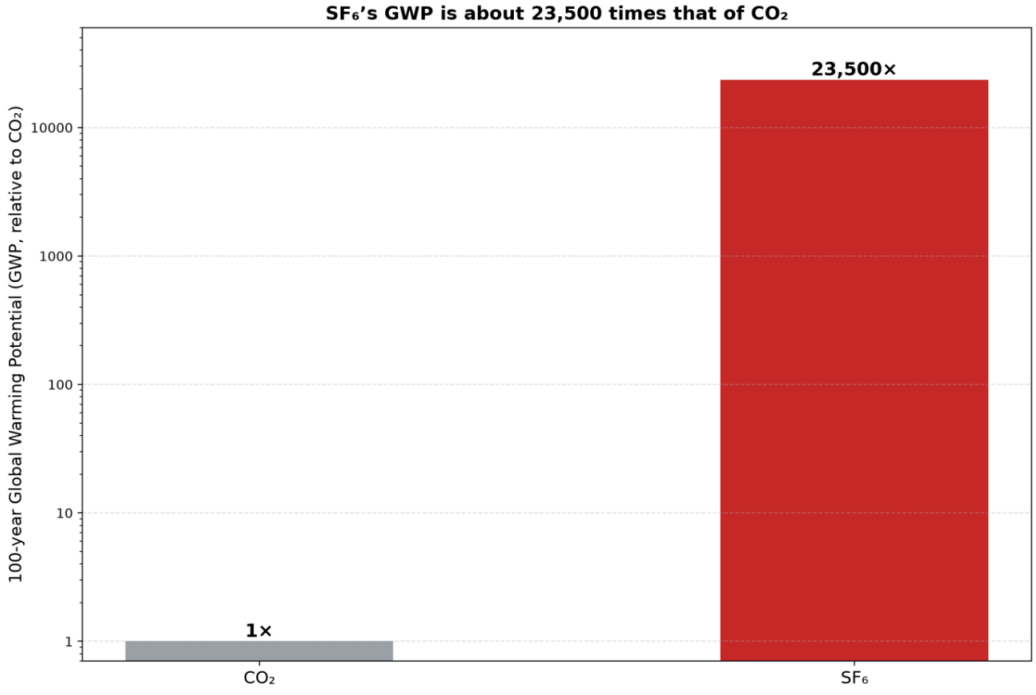


Figure 2 — Comparison of the Global Warming Potential (GWP) of SF_6 and CO_2.

The reason for this high warming potential lies in the molecule's structure and its extremely long lifetime. Carbon dioxide is continually removed from the atmosphere by plants and oceans, so its warming effect decays over time. SF_6, by contrast, is chemically extremely stable, takes part in almost no natural cycle, and once released remains effectively permanent in the atmosphere. For a single molecule, SF_6 can keep absorbing infrared radiation on a timescale of thousands of years, greatly amplifying the cumulative effect. This is why climate scientists regard it as a significant concern even though its absolute emissions are modest.

Global atmospheric monitoring records the steady, compounding accumulation of SF_6. According to observations by the US National Oceanic and Atmospheric Administration (NOAA), the global mean atmospheric mole fraction of SF_6 rose from about 11.39 parts per trillion (ppt) in 2023 to about 12.73 ppt in mid-2026, and continues to increase by roughly 4% per year [7]. This shows that although individual emission sources are small, the cumulative effect of long-term SF_6 emissions keeps driving atmospheric concentration upward, with no sign of peaking. Overall, SF_6 presently accounts for about 0.1% of the anthropogenic greenhouse effect [8] — small in absolute terms, yet a concern because of its extremely high per-molecule warming potential and long atmospheric lifetime.

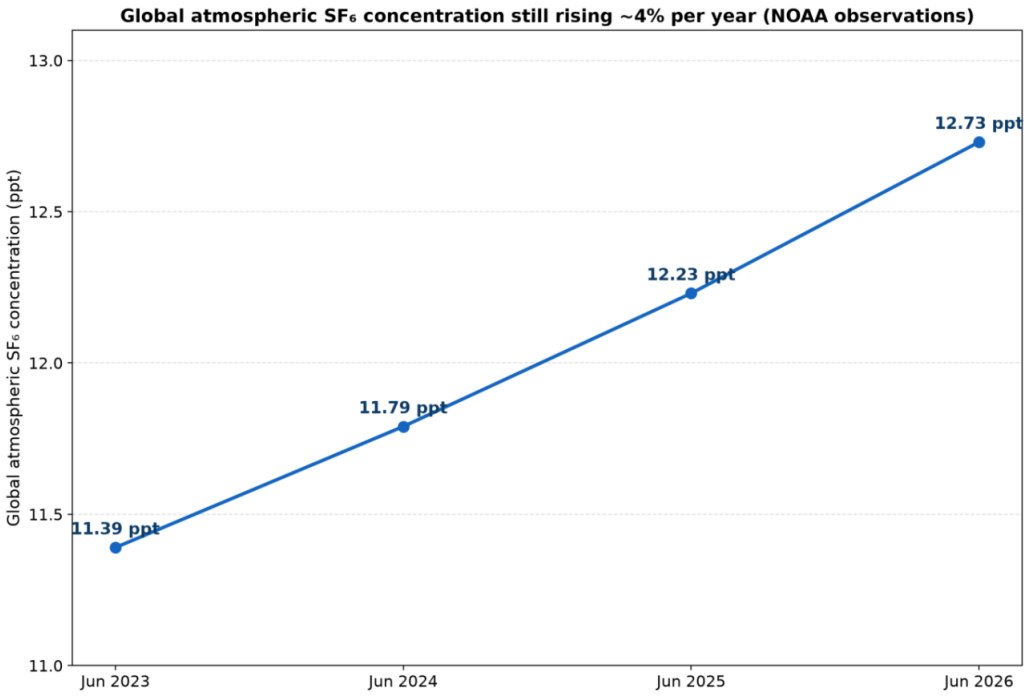


Figure 3 — Global atmospheric SF_6 concentration trend (NOAA observations, 2023–2026).

The distribution of emissions is uneven. Regions with rapidly growing power investment tend to see the fastest emission growth, whereas economies with earlier grid development, such as the EU and Japan, carry a larger share of the historical burden associated with installed equipment. In 1997 the international community adopted the Kyoto Protocol, listing sulfur hexafluoride alongside carbon dioxide, methane, nitrous oxide, hydrofluorocarbons and perfluorocarbons as one of six controlled greenhouse gases, formally bringing SF_6 within the framework of climate governance [9].

From the perspective of the emission profile, the power industry is the principal source of SF_6. Roughly 80% of global SF_6 production is used in electrical equipment, and leakage can occur at every stage — manufacture, filling, operation and decommissioning. For the EU, a European Commission briefing reports that European manufacturers fill about 1,500 tonnes of SF_6 into new equipment each year [10], and studies estimate the stock of SF_6 in the EU's in-service switchgear at roughly 10,800–24,700 tonnes [11]. Converted on a GWP basis, these quantities correspond to emission pressures of tens of millions of tonnes of CO_2-equivalent per year, so that even small leakages are magnified into a large climate impact.

Cross-reference: for a detailed treatment of greenhouse gases, the GWP metric and global regulations, see White Paper HMP-WP-2602.

5 Transition: The Global Shift Away from SF_6

As international attention to climate change has grown and alternative technologies have matured, the position of SF_6 has begun to change.

Governments are tightening the use of SF_6, with Europe leading. In 2024 the EU adopted a new fluorinated-gas regulation — Regulation (EU) 2024/573 — which sets out a clear schedule for removing SF_6 from switchgear: from January 2026, new medium-voltage switchgear rated 24 kV and below may no longer be placed on the EU market; from 2030, medium-voltage equipment rated 24–52 kV will be covered; and from 2032, high-voltage equipment above 52 kV will likewise be subject to the restriction [12].

Important note: this schedule is a market-access restriction on newly placed equipment in the EU market. Existing in-service SF_6 equipment may continue to operate and is not subject to forced removal or replacement, and this is not a globally unified mandatory ban. Projects destined for the EU should prioritise compliant fluorine-free solutions.

The transition is not confined to the EU. Across North America, Asia-Pacific and other regions, grid operators and switchgear manufacturers are accelerating the deployment of SF_6-free products, and bodies such as the International Electrotechnical Commission (IEC) are developing standards for alternative-medium equipment [13]. Driven jointly by regulation, market and technology, the role of SF_6 in the grid will gradually move from a primary medium towards a transitional one, until it is displaced by lower-impact technologies.

In conclusion, SF_6 combines outstanding engineering performance with a heavy environmental cost. Its invention demonstrates humanity's ability to control difficult chemistry, while its environmental impact shows that a convenience made possible by exceptional stability can conceal a long-term cost. From EU regulation to global network upgrading, the task is to maximise its engineering value while containing its environmental cost — a balancing problem both for the electrical industry and, more broadly, for climate policy. How this balance is struck will determine whether the grid can move towards a genuinely low-carbon and sustainable future.

6 Key Takeaways

1. SF_6 was first synthesised by Moissan and Lebeau in 1901. Combining a dielectric strength about 2.5 times that of air with arc-quenching performance far above that of air and oil, it has been deployed on a large scale in GIS, high-voltage circuit breakers, GIL and other equipment since the 1960s, driving the miniaturisation and high-reliability development of high-voltage networks.
2. At the engineering level, SF_6 presents practical issues — concealed leakage, harmful by-products from arc decomposition, and high life-cycle recovery and management costs — that are important drivers for fluorine-free replacement.
3. The GWP-100 of SF_6 is about 23,500 times that of CO_2 (IPCC AR5), and its atmospheric lifetime is about 3,200 years. It was listed as a controlled greenhouse gas by the 1997 Kyoto Protocol. NOAA observations show its atmospheric concentration is still rising by about 4% per year.
4. Regulation (EU) 2024/573 imposes phased market-placement restrictions on newly placed equipment rated 24 kV and below, 24–52 kV, and above 52 kV (2026 / 2030 / 2032). Existing in-service equipment may continue to operate, and the restriction is not a globally unified ban.
5. The industry transition proceeds along two parallel paths: new equipment adopts SF_6-free technology routes, while existing equipment relies on strengthened closed-loop management of medium recovery, purification and reuse.

A Appendix A — Glossary

- SF_6 (sulfur hexafluoride): a gas formerly widely used as an insulating and arc-quenching medium in switchgear; also a potent greenhouse gas.
- GWP (Global Warming Potential): a measure of the warming effect of a greenhouse gas relative to carbon dioxide; this paper uses the 100-year basis (GWP-100) following IPCC AR5.
- GIS (gas-insulated switchgear): metal-enclosed switchgear that uses a pressurised insulating gas as its medium.
- GIL (gas-insulated transmission line): an enclosed transmission channel that uses an insulating gas as its medium.
- F-Gas Regulation (EU) 2024/573: the European Union regulation governing fluorinated greenhouse gases.
- Kyoto Protocol: the international climate agreement adopted in 1997 that lists SF_6 as a controlled greenhouse gas.
- ppt (parts per trillion): a unit for expressing atmospheric concentration.

B Appendix B — References

- [1] SF_6 was first synthesised by the French chemists Henri Moissan and Paul Lebeau; the original report is H. Moissan and P. Lebeau, Comptes Rendus de l'Académie des Sciences, vol. 130 (1900), pp. 865–871. Source: University of Bristol, School of Chemistry, "Molecule of the Month: Sulfur Hexafluoride" (2008). https://www.chm.bris.ac.uk/motm/SF6/SF6%20-%20Molecule%20of%20the%20Month%20-%20April%202008.pdf
- [2] In a uniform electric field, the dielectric strength of SF6 is about 2.5 times that of air. Source: Raytheon, "Properties and Advantages of SF_6 Gas". https://raytheon.com.cn/Uploads/download/6e80f44bd102147b9d356602d874e50c.pdf
- [3] Since the 1960s, SF_6 has been widely used in gas-insulated switchgear (GIS). Source: Electrical Technology (《电工技术》). http://zazhi.chinaet.net/cn/article/pdf/preview/10.19768/j.cnki.dgjs.2026.25.046.pdf
- [4] Globally, about 80% of SF_6 is used in the power industry. Source: US EPA, "Fluorinated Gas Emissions". https://www.epa.gov/ghgemissions/fluorinated-gas-emissions
- [5] The Global Warming Potential (GWP) of SF_6 is about 23,500 times that of CO_2 (100-year horizon, IPCC AR5). Source: IPCC Fifth Assessment Report (AR5), WG1, Chapter 8; see also US EPA, "Fluorinated Gas Emissions". https://www.epa.gov/ghgemissions/fluorinated-gas-emissions
- [6] The atmospheric lifetime of SF_6 is about 3,200 years. Source: UNFCCC (IPCC Second Assessment Report). https://unfccc.int/es/node/10775
- [7] Global atmospheric SF_6 concentration (NOAA observations): about 12.73 ppt in June 2026 and about 12.23 ppt in June 2025. Source: NOAA Global Monitoring Laboratory. https://gml.noaa.gov/ccgg/trends_sf6/
- [8] SF_6 emissions account for about 0.1% of the anthropogenic greenhouse effect. Source: UNFCCC, Life-Cycle Assessment of Electricity Supply Using SF_6 Technology. https://unfccc.int/sites/default/files/wamatt051_1.pdf

- [9] Annex A of the Kyoto Protocol lists SF_6 as one of six controlled greenhouse gases (together with CO_2, CH_4, N_2O, HFCs and PFCs). Source: UNFCCC. https://unfccc.int/process-and-meetings/the-kyoto-protocol/what-is-the-kyoto-protocol/kyoto-protocol-targets-for-the-first-commitment-period
- [10] European manufacturers fill about 1,500 tonnes of SF_6 into new switchgear each year. Source: European Commission — DG Climate Action. https://climate.ec.europa.eu/system/files/2020-04/2020_03_25_sf6_and_alternatives_en.pdf
- [11] The stock of SF_6 in the EU's in-service switchgear is estimated at about 10,800–24,700 tonnes (2017 estimate). Source: MDPI, Energies. https://mdpi-res.com/d_attachment/energies/energies-13-01807/article_deploy/energies-13-01807-v3.pdf
- [12] Schedule of the revised EU fluorinated-gas Regulation (EU) 2024/573 (2026 ≤ 24 kV / 2030 24–52 kV / 2032 > 52 kV). Source: European Parliament; Siemens Energy. https://oeil.europarl.europa.eu/oeil/en/document-summary?id=1776223
- [13] IEC 62271 series of switchgear standards.

C Appendix C — Further Reading

- Detailed treatment of greenhouse gases, the GWP metric and global regulations: HMP-WP-2602.
- Horizontal comparison of SF_6 alternative gas performance: HMP-WP-2603.



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