TECHNICAL WHITE PAPER

HMP-WP-2602

Why Ban SF_6? What Are Greenhouse Gases and What Is GWP?

SF_6 Greenhouse-Effect Principles, GWP Interpretation, and Global Regulatory Policies

ABSTRACT

Starting from the physical mechanism of the greenhouse effect, this paper clarifies the scientific concept of greenhouse gases and their legal status under international climate governance. It systematically explains the definition, determining factors and accounting basis of Global Warming Potential (GWP), and compares the warming impact of CO_2, CH_4, N_2O and SF_6 based on IPCC AR5 data. The deep reasons for restricting SF_6 are then analyzed from three dimensions: the multiplication effect of an extremely high GWP and an extremely long atmospheric lifetime, toxic by-products generated by arc decomposition, and leakage throughout the entire industry chain. The phase-out timetable of the EU F-gas Regulation (EU) 2024/573 and the fluorine-free transition trends in the United States, Japan and China are also reviewed. Under China's carbon-peak and carbon-neutrality goals, State Grid and other utilities have begun shifting procurement of distribution equipment toward SF_6-free products. This document is intended for design institutes, EPC contractors, power utilities and overseas buyers, to build fundamental understanding of the policy and scientific logic behind the fluorine-free transformation.

1 Greenhouse Gases: Concept and "Who Defines Them"

1.1 The Greenhouse Effect: Starting from the Physics

The Sun sends short-wave radiation (mainly visible light) toward the Earth. This energy passes readily through the atmosphere and reaches the surface, heating it. As the surface warms, it emits heat outward in the form of long-wave infrared radiation. Certain gases in the atmosphere absorb this long-wave infrared radiation, trapping heat that would otherwise escape into space and returning part of it to the surface as radiation. It is precisely this mechanism — the high transmission of incoming short-wave radiation combined with the absorption of outgoing long-wave radiation — that keeps the Earth's average temperature far higher than it would be without an atmosphere. This is the greenhouse effect, and the gases that absorb infrared and warm the planet are called greenhouse gases.

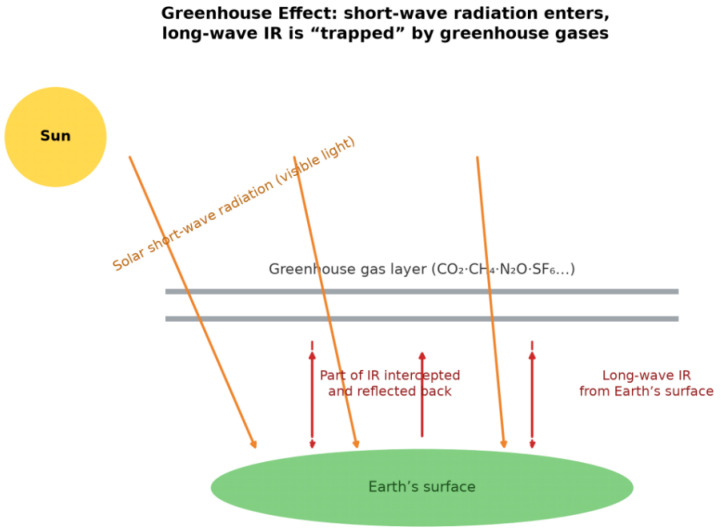


Figure 1 — Greenhouse-effect mechanism: solar short-wave radiation enters; long-wave infrared from the Earth's surface is intercepted by the greenhouse gas layer.

1.2 Scientific Concept and Legal Identity of "Greenhouse Gases"

Here we should clear up a common misunderstanding: the greenhouse gas with the highest natural concentration and the greatest contribution to warming is actually water vapor, but it is mainly governed by meteorological and oceanic processes and is not subject to anthropogenic control. In the context of climate governance, "greenhouse gases" refers to gases emitted by human activities whose atmospheric concentrations are rising and that can persist in the atmosphere for a long time — for example, carbon dioxide, methane and nitrous oxide, as well as industrially synthesized fluorinated compounds (hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and so on). What they have in common is either large emission volumes or extremely strong per-molecule warming capacity.

So who defines "greenhouse gases"? Their "official identity" is conferred by the international climate-governance framework. In 1997, the Kyoto Protocol placed six gases on the controlled list: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride. Thereafter, the Intergovernmental Panel on Climate Change (IPCC) has been responsible for systematically assessing the radiative properties and climate impacts of these gases and providing unified quantitative indicators (including the GWP discussed in the next section), which countries use to account for emissions, set reduction targets and meet their obligations. In short, "greenhouse gas" is both a scientific concept and a legal concept under international climate governance.

2 GWP: The Yardstick for Measuring Greenhouse Gases

2.1 Definition and Two Key Determinants

Different greenhouse gases differ enormously in their capacity to retain heat, so direct comparison is meaningless. Scientists use a unified yardstick — the Global Warming Potential (GWP). It measures, for a given mass of gas and over a given time horizon, the warming effect relative to that of carbon dioxide. The larger the GWP, the greater the unit contribution of the gas to warming. With this metric, various gases can be converted into a unified carbon dioxide equivalent (CO_2e), enabling policy-making, corporate accounting and national compliance to be compared on the same basis.

The numerical value of GWP is determined by two key factors: first, the ability of the gas to absorb infrared radiation (its radiative efficiency), and second, how long it remains in the atmosphere (its atmospheric lifetime). The stronger the absorption and the longer the residence, the higher the GWP. GWP also requires a unified time scale, usually 100 years (denoted GWP-100), to balance the effects of short-lived but potent gases against long-lived stable ones; researchers also use GWP20 and GWP500, and even the temperature-response metric Global Temperature-change Potential (GTP), but GWP-100 is the mainstream accounting basis internationally. An intuitive analogy: GWP represents the warming intensity per unit time, atmospheric lifetime represents how long that warming is sustained, and their product expresses the cumulative climate impact of the gas.

2.2 A Relative Scale Based on Carbon Dioxide

Carbon dioxide is the most dominant and most thoroughly studied anthropogenic greenhouse gas. The IPCC uses it as the reference gas, setting its GWP to 1, with every other gas expressed as a multiple of it. Therefore CO_2 = 1 is the reference point of the scale, not a measure of CO_2's actual warming capacity. It is important to recognize that GWP is a relative value: it indicates how many times more potent a gas is than carbon dioxide, and does not by itself represent absolute warming intensity.

2.3 GWP Comparison of Common Greenhouse Gases

Table 1 lists the GWP-100 values of several common greenhouse gases under the IPCC Fifth Assessment Report (AR5) basis, and Figure 2 shows, on a logarithmic bar chart, differences spanning several orders of magnitude: the GWP of methane is about 28, nitrous oxide about 265, and SF_6 as high as 23,500 — that is, per unit mass, roughly 23,500 times that of carbon dioxide.

Table 1 GWP of common greenhouse gases (100-year, IPCC AR5 basis)

Gas	Chemical formula	GWP (100-yr)	Main sources
Carbon dioxide	Co_2	1	Fossil-fuel combustion, land use
Methane	Ch_4	28	Agriculture, energy, waste
Nitrous oxide	N_2O	265	Fertilizer use, industrial processes
Sulfur hexafluoride	SF_6	23500	Insulation in power switchgear

Note: data follow the IPCC Fifth Assessment Report (AR5) basis; the GWP of fluorinated compounds such as hydrofluorocarbons, perfluorocarbons and nitrogen trifluoride falls between that of nitrous oxide and sulfur hexafluoride.

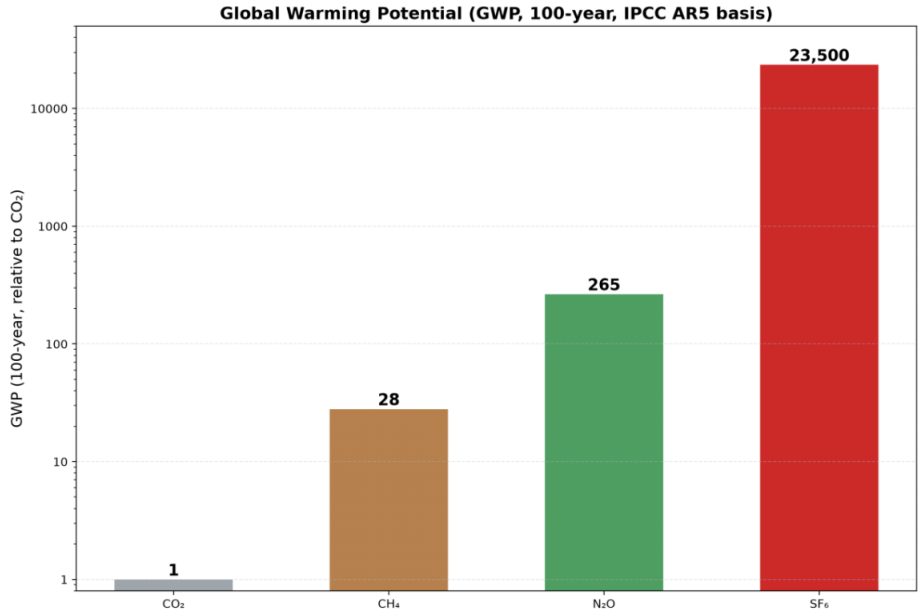


Figure 2 — Global Warming Potential (GWP, 100-year, log scale) of major greenhouse gases.

3 SF_6: Properties, Strengths and Drawbacks

3.1 Molecular Structure and Physicochemical Properties

Sulfur hexafluoride (SF_6) is composed of one sulfur atom and six fluorine atoms, forming a highly symmetric regular octahedral structure; it was first synthesized in 1901 by the French chemists Henri Moissan and Paul Lebeau. Under normal temperature and pressure it is a colorless, odorless, non-toxic gas that is neither flammable nor combustion-supporting, with a density about five times that of air. Chemically it is extremely stable, reacting with almost nothing and barely degraded by biological or chemical processes.

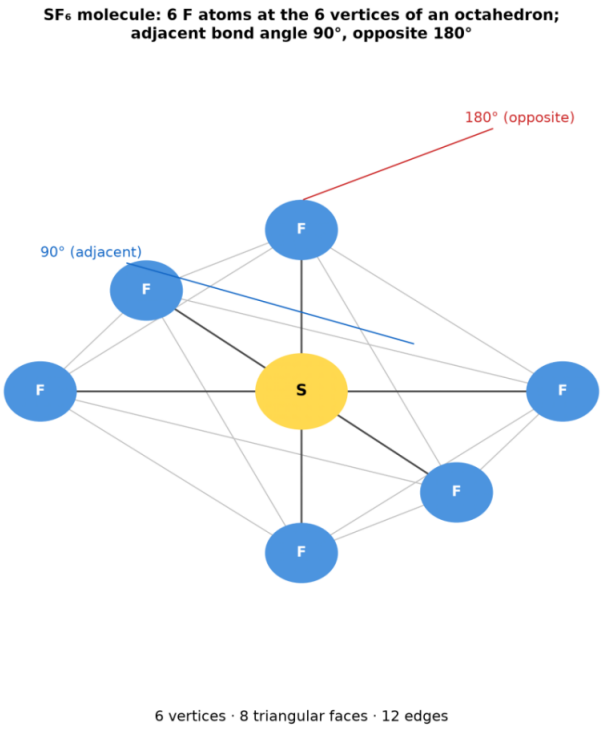


Figure 3 — SF_6 molecular structure: 6 fluorine atoms at the 6 vertices of a regular octahedron; adjacent bond angle 90°, opposite 180°.

3.2 Dielectric Advantages and Applications in the Power Sector

The most outstanding advantage of SF_6 lies in its electrical performance: its dielectric strength is about 2.5 times that of air, and its arc-quenching ability (extinguishing the high-temperature arc between switch contacts) far exceeds that of air and oil. On the strength of these two characteristics it has become the default choice for core equipment such as gas-insulated switchgear (GIS), high-voltage circuit breakers and gas-insulated transmission lines (GIL). At the same voltage class, GIS can occupy several times less footprint than a conventional outdoor substation; the equipment is fully sealed, unaffected by wind, rain or humidity, operates with high reliability and low maintenance needs, and is especially suited to underground cable tunnels and cramped urban spaces. Today, roughly 80% of the world's SF_6 is used in the power sector, and the vast majority of gas-insulated switchgear uses SF_6 as its insulation and arc-quenching medium.

3.3 Strong Greenhouse Properties and Ultra-Long Atmospheric Lifetime

However, SF_6 has a GWP of about 23,500 (IPCC AR5 basis) and an atmospheric lifetime of about 3,200 years. In other words, every kilogram of SF_6 that leaks out has a long-term warming effect equivalent to tens of thousands of kilograms of carbon dioxide, and it is barely decomposed naturally, remaining in the atmosphere for millennia. This means that every gram of SF_6 charged into grid equipment over the past decades, once it escapes, will continue to warm the planet over timescales measured in thousands of years — making SF_6 one of the most prominent members among all anthropogenic greenhouse gases and driving the growing call to replace it.

4 Why Is SF_6 Being Banned?

4.1 The Multiplication Effect: "Extremely High GWP × Extremely Long Lifetime"

Looking only at total emissions, SF_6 currently accounts for only about 0.1% of the anthropogenic greenhouse effect. Why, then, is it so tightly controlled by so many countries? The key lies in the multiplication effect of an extremely high GWP and an extremely long atmospheric lifetime: GWP represents the instantaneous warming intensity per unit mass, while lifetime represents how long that intensity is sustained. SF_6 combines both, so its cumulative warming contribution per unit mass is enormous — SF_6 emitted this year will still be exerting its effect thousands of years from now. On the IPCC AR5 basis, the 100-year warming effect of 1 tonne of SF_6 is equivalent to 23,500 tonnes of carbon dioxide; even if a region leaks only tens of tonnes of SF_6 in a year, the corresponding CO_2e amounts to hundreds of thousands of tonnes — far exceeding many common pollutants.

4.2 Toxic By-Products from Arc Decomposition Threaten Human Safety

SF_6 poses a potential threat to human safety. Pure SF_6 is itself non-toxic, but when switchgear extinguishes arcs, the high-temperature arc decomposes it into a range of toxic by-products — the most dangerous being disulfur decafluoride (S_2F_{10}), whose toxicity is comparable to phosgene and which damages the lungs if inhaled. There are also highly corrosive hydrogen fluoride (HF), sulfur tetrafluoride (SF_4), thionyl fluoride (SOF_2) and others, which either remain as residual gases or deposit as white metal-fluoride powders. During maintenance, decommissioning and dismantling, or even when internal faults depressurize the equipment, operators who inhale or touch these substances may be poisoned or endangered. In summary, the stronger the arc-quenching capability of SF_6, the greater the corresponding hazard it leaves for operation and maintenance.

4.3 Leakage Across the Entire Industry Chain and the Staggering Cumulative Effect

Of greater concern is that leakage occurs at every stage of the industry chain: manufacturing, filling, operation, and decommissioning and dismantling can all cause release. A low leakage rate does not mean no leakage; the hidden release accumulated from in-service equipment is considerable over time. Switchgear requires periodic inspection and refilling, and retired equipment needs recovery and disposal — any lapse at any link releases molecules of an extremely high-GWP gas into the atmosphere. Because the warming potential per unit mass is so large, even a tiny leakage rate converts into very large CO_2e totals — this is precisely the risk most easily underestimated behind the appearance of low emissions. Once the harm of SF_6 is recognised and replacement technologies mature, restricting its use follows naturally — what is restricted is not the technical convenience of the gas but the uncontrolled long-term climate liability it creates.

5 Global SF_6 Phase-Down and Industry Transition

The EU and China are currently the most resolute regions and economies advancing the phase-down of SF_6 in the power industry, albeit by different paths: the EU relies on mandatory legislation to establish market-access thresholds; China, guided by its carbon-peak and carbon-neutrality goals, drives green transformation through industrial policy and optimizes its grid-material procurement catalog to reduce the use of SF_6-containing equipment. Meanwhile, North America, Japan and other countries and regions are also accelerating their technology iteration and control measures.

5.1 EU F-gas Regulation: The Strictest Legislative Framework to Date

The EU has adopted the strictest legislative framework to date for SF_6 control. In February 2024, the EU issued the new fluorinated-gas (F-gas) Regulation (EU) 2024/573, which entered into force in March of the same year and set an explicit phase-out timetable for SF_6-containing switchgear (Table 2, Figure 4). Subsequent EU amendments further tightened some voltage classes — for example, switchgear rated 52–145 kV with a short-circuit current ≤50 kA and GWP ≥1 has been brought forward to a 2028 phase-out. This timetable gives manufacturers and grid operators a clear transition window and makes SF_6-free a mandatory market-access requirement for switchgear placed on the European market.

Table 2 Phase-out timetable for SF_6-containing switchgear under EU Regulation (EU) 2024/573

Milestone	Scope of control
1 January 2026	MV switchgear up to and including 24 kV (secondary distribution such as ring main units)
2028	52–145 kV switchgear with short-circuit current ≤50 kA and GWP ≥1 (brought forward by amendment)
2030	24–52 kV MV switchgear
2032	HV SWITCHGEAR ABOVE 52 KV

Important note: the 2028 milestone is a bring-forward applied only to a specific subclass of high-voltage switchgear (52–145 kV with short-circuit current ≤50 kA and GWP ≥1), whereas the 2032 milestone is the general backstop covering the remaining high-voltage switchgear above 52 kV; the two rows therefore address different scopes rather than the same equipment twice. The phase-out applies to equipment newly placed on the market; existing in-service SF_6 equipment may continue to operate and is not forcibly dismantled or replaced, and this is not a globally unified mandatory ban.

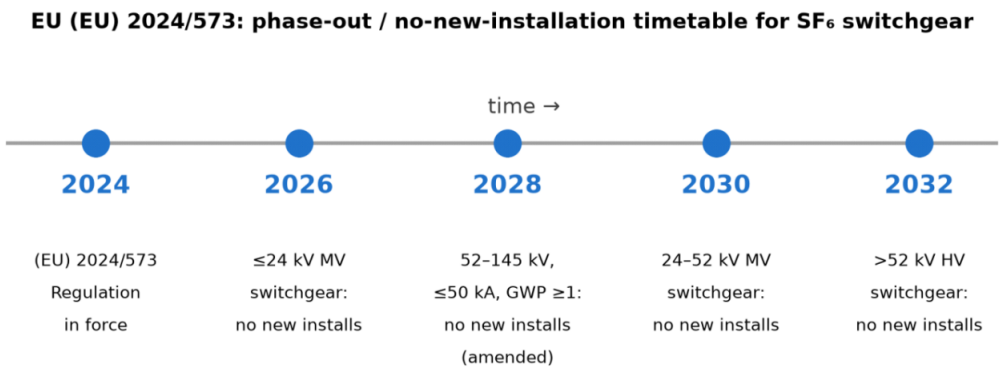


Figure 4 — Phase-out / no-new-installation timetable for SF_6 switchgear under the EU (EU) 2024/573 Regulation.

5.2 China: Driving Emission Cuts through Carbon-Peak Goals and Procurement/Industrial Policy

China has not yet issued dedicated mandatory legislation for SF_6 switchgear, but under the framework of its new power system and dual-carbon strategy, emission-reduction efforts are advancing rapidly.

The National Energy Administration encourages the green, low-carbon upgrading of power equipment. State Grid has proposed overall SF_6 usage-control targets and, at the distribution-network procurement level, no longer purchases SF_6-containing products for MV distribution equipment such as ring main units, pole-mounted switches and pole-mounted circuit breakers, guiding the industry to prefer zero-GWP air/nitrogen insulation solutions.

China is also piloting low-GWP fluorinated-gas high-voltage equipment. It must be recognized objectively that, although gas mixtures based on C_4F_7N (perfluorobutyronitrile, 3M Novec 4710) can substantially reduce GWP, they are still fluorinated media with a GWP far higher than CO_2 and are not truly zero-greenhouse-effect solutions. The domestic engineering community therefore also encourages priority development of the GWP = 0 air/nitrogen insulation technology route.

5.3 Progress in Other Regions

California in the United States restricts the addition of new SF_6-insulated equipment in phases through its CARB policy. Japanese utilities are advancing demonstration projects for SF_6-free HV GIS; in March 2026, Chubu Electric Power Grid (Japan) placed an order for the world's first fully SF_6-free 550 kV GIS, marking the first such milestone at the extra-high-voltage level. Overall, although no unified mandatory international legal framework has yet formed, reducing and replacing SF_6 has already become a clearly defined direction of development for the global power equipment industry.

6 Conclusion: From Core Insulating Medium to Phased Replacement

From core insulating medium to phased replacement, the trajectory of SF_6 reflects a simple truth: the counterpart of any seemingly ideal industrial gas — its exceptional chemical stability — may be an overlooked long-term climate cost. Clarifying the concept of greenhouse gases shows how greatly human activities have changed the atmosphere; GWP, as a yardstick, brings the climate impacts of different gases back onto the same basis; and EU legislation, China's dual-carbon strategy and the global transition turn scientific consensus into enforceable institutions. The restriction of SF_6 is not a rejection of one technology, but a recalibration of the trade-off between technical convenience and climate responsibility — and it is an essential lesson on the path toward a sustainable future.

7 Key Takeaways

1. Greenhouse gases are gases that absorb long-wave infrared radiation from the Earth's surface and warm the planet; in the context of climate governance, the legal list of "greenhouse gases" is established by the Kyoto Protocol, with the IPCC responsible for unified quantitative assessment.
2. GWP is a relative scale based on carbon dioxide (=1), determined by "radiative efficiency × atmospheric lifetime"; the mainstream international accounting basis is 100 years (GWP-100), and CO_2e is the unified conversion unit.
3. GWP-100 of common greenhouse gases: CO_2 = 1, CH_4 ≈ 28, N_2O ≈ 265, SF_6 ≈ 23,500; per unit mass, SF_6's warming potential is about 23,500 times that of carbon dioxide.
4. The fundamental reasons SF_6 is banned are threefold: the multiplication effect of an extremely high GWP and an extremely long lifetime; toxic by-products such as S_2F_{10} produced by arc decomposition that threaten human safety; and leakage across the entire industry chain from manufacturing, filling and operation to decommissioning.
5. The EU F-gas Regulation (EU) 2024/573 sets a phased phase-out timetable; China, guided by its dual-carbon goals and grid procurement policy, is rapidly advancing the reduction and replacement of MV distribution equipment; North America, Japan and other regions are following suit — reducing and replacing SF_6 has become an unmistakable global trend in the power equipment industry.

A Appendix A — Glossary

- 1. Greenhouse gas: an atmospheric gas that absorbs long-wave infrared radiation and warms the planet.
- 2. GWP (Global Warming Potential): a relative indicator, based on CO_2 (=1), measuring the warming effect of a gas; this paper uses the 100-year basis (GWP-100).
- 3. CO_2e (carbon dioxide equivalent): a unified unit that converts different greenhouse gases into equivalent CO_2 by GWP.
- 4. Kyoto Protocol: the international climate agreement adopted in 1997 that placed six gases, including SF_6, on the controlled list.
- 5. IPCC (Intergovernmental Panel on Climate Change): a climate-science assessment body under the United Nations that provides quantitative indicators such as GWP.
- 6. F-gas Regulation (EU) 2024/573: the EU regulation governing fluorinated greenhouse gases.
- 7. S_2F_{10} (disulfur decafluoride): a highly toxic by-product of SF_6 arc decomposition, with toxicity comparable to phosgene.
- 8. Atmospheric lifetime: the average residence time of a gas molecule in the atmosphere; for SF_6 it is about 3,200 years.
- 9. New power system: a modern power system with new energy as the main body that is green, low-carbon, safe and efficient.

B Appendix B — References

- [1] Sulfur hexafluoride is one of the six controlled greenhouse gases listed in the Kyoto Protocol (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride). Source: UNFCCC. https://unfccc.int/process-and-meetings/the-kyoto-protocol/what-is-the-kyoto-protocol/kyoto-protocol-targets-for-the-first-commitment-period
- [2] 100-year GWP values in the IPCC Fifth Assessment Report (AR5): CO_2 = 1, CH_4 = 28, N_2O = 265, SF_6 = 23,500. Source: Ministry of Ecology and Environment (MEE), compilation notes for the "Methodology for Greenhouse Gas Voluntary Emission Reduction Projects". https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202510/W020251013728369855222.pdf
- [3] SF_6 was first synthesized by the French chemists Henri Moissan and Paul Lebeau; the synthesis is generally dated to 1901, while the original communication 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
- [4] In a uniform electric field, the dielectric strength of SF_6 is about 2.5 times that of air. Source: Raytheon. https://raytheon.com.cn/Uploads/download/6e80f44bd102147b9d356602d874e50c.pdf
- [5] Globally, about 80% of SF_6 is used in the power industry; in gas-insulated switchgear (GIS), the vast majority uses SF_6 as its insulation and arc-quenching medium. Source: US EPA, "Fluorinated Gas Emissions". https://www.epa.gov/ghgemissions/fluorinated-gas-emissions
- [6] The GWP of SF_6 is about 23,500 (IPCC AR5 basis) and its atmospheric lifetime is about 3,200 years. Source: Ministry of Ecology and Environment (MEE), compilation notes for the "Methodology for Greenhouse Gas Voluntary Emission Reduction Projects". https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202510/W020251013728369855222.pdf; for the atmospheric lifetime see also IPCC/UNFCCC: https://unfccc.int/es/node/10775
- [7] Global SF_6 emissions account for about 0.1% of the anthropogenic greenhouse effect. Source: UNFCCC. https://unfccc.int/sites/default/files/wamatt051_1.pdf

- [8] Pure SF_6 is itself non-toxic, but a high-temperature arc decomposes it into toxic by-products, of which disulfur decafluoride (S_2F_{10}) is the most toxic and is classified by the EPA as a lethal by-product. Source: US EPA. https://19january2017snapshot.epa.gov/sites/production/files/2016-02/documents/conf04_avery.pdf; for the types of decomposition products and the resulting risk of lung injury see also the German GESTIS occupational safety database: https://gestis.dguv.de/data?name=570131&lang=en
- [9] The EU's new fluorinated-gas Regulation (EU) 2024/573 was published in February 2024 and entered into force in March of the same year. Source: EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32024R0573; for the placing-on-market restriction timetable (2026 ≤24 kV, 2030 24–52 kV, 2032 >52 kV) see also: https://www.naturvardsverket.se/vagledning-och-stod/kemikalier/fluorerade-vaxthusgaser/elektriska-brytare-som-innehaller-sf6/
- [10] A subsequent EU amendment brought forward the placing-on-market restriction for high-voltage switchgear rated 52–145 kV with a short-circuit current ≤50 kA and GWP ≥1 to 2028. Source: EUR-Lex (amending act). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32024R0573R(05)
- [11] The California Air Resources Board (CARB) adopted amendments in 2022 to phase out SF_6 in gas-insulated equipment from 2025; the US EPA tracks state-level regulations. Source: US EPA. https://19january2025snapshot.epa.gov/eps-partnership/state-and-regional-regulations-related-sf6-emissions-electric-transmission-and/index.html
- [12] In March 2026, Chubu Electric Power Grid (Japan) ordered the world's first fully SF_6-free 550 kV GIS. Source: Siemens Energy. https://www.siemens-energy.com/global/en/home/stories/industry-initiative-to-reduce-f-gases.html
- [13] National Energy Administration, "Reply to Proposal No. 6052 at the Fourth Session of the 13th National People's Congress" (supporting the promotion and application of eco-friendly power equipment).
- [14] State Grid, "Standardized Design Scheme for 12 kV Ring Main Units (Cabinets)" and distribution-network eco-friendly equipment procurement guidance.
- [15] IEC 62271 series of switchgear standards.

C Appendix C — Further Reading

- Development history of SF_6: HMP-WP-2601
- SF_6 alternative gases and performance comparison: HMP-WP-2603



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