Overview of SF_6 Emissions Sources and Reduction Options in Electric Power Systems

August 2018

The SF_6 Emission Reduction Partnership for Electric Power Systems *is an innovative voluntary program developed jointly by the United States Environmental Protection Agency (EPA) and the electric power industry to improve equipment reliability while reducing emissions of sulfur hexafluoride (SF_6), a potent greenhouse gas that remains in the atmosphere for thousands of years.*

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- *Southern California Edison*
- *3M*
- *Franklin Electric*
- *Doble Engineering Company*
- *ITC Holdings Group*

Additional Resources

The EPA's SF_6 Emission Reduction Partnership for Electric Power Systems website contains links to workshops and partner meetings as well as case studies and research studies, including several references in this paper. Please visit: https://www.epa.gov/f-gas-partnership-programs/electric-power-systems-partnership.

Introduction

Understanding potential emissions sources is the first step to effectively managing them. In electric power systems, as the industry's understanding of sulfur hexafluoride (SF_6) emissions has evolved, so have practices for handling and managing those emissions. The industry in the United States is much more efficient in managing SF_6 emissions today than it was in the 1990s.[1] This report provides an overview of SF_6 emissions sources and reduction opportunities throughout the gas's lifecycle in the power sector.

EPA's SF_6 Emission Reduction Partnership for Electric Power Systems

Established in 1999, the SF_6 Emission Reduction Partnership for Electric Power Systems is a collaborative, voluntary effort between EPA and the electric power industry to identify, recommend, and implement cost-effective solutions to reduce or eliminate SF_6 emissions. The SF_6 emissions of Partners have reduced by 74% since 1999.

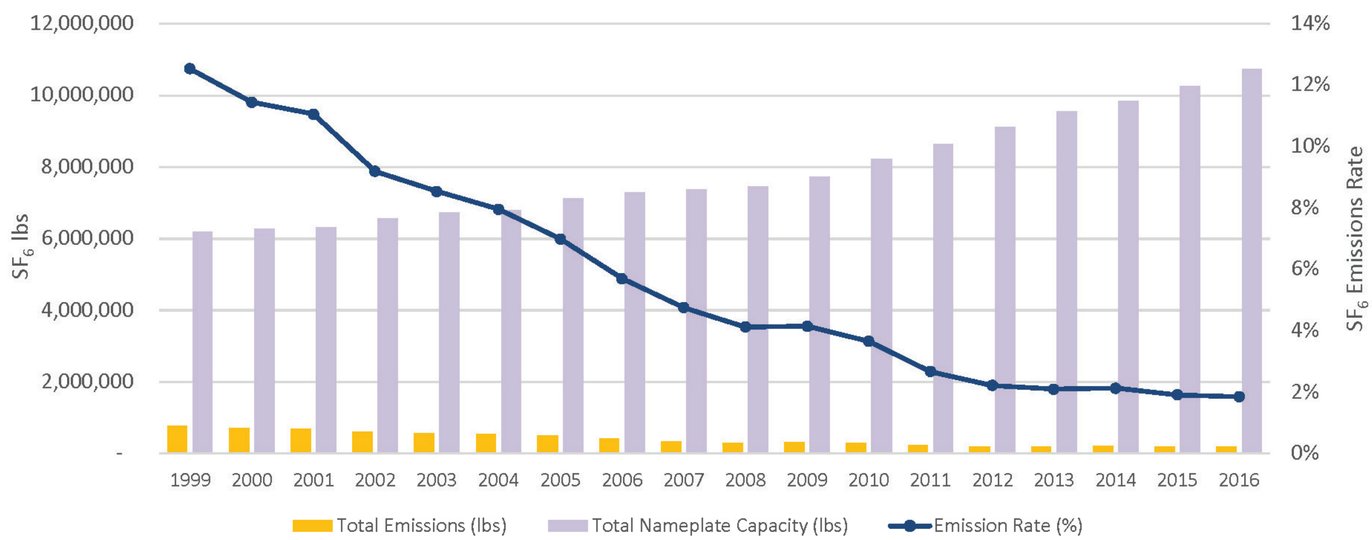

Figure 1. SF_6 Partnership accomplishments, 1999 to 2016.

In addition to voluntary action, some electric power systems are subject to EPA's Greenhouse Gas Reporting Program. In December 2009, EPA published the Mandatory Greenhouse Gas Reporting Rule, codified at 40 CFR Part 98, that requires large U.S. greenhouse gas emitters and suppliers to monitor and report annual greenhouse gas emissions.

[1]U.S. Environmental Protection Agency (EPA). (2017). "Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2015." EPA 430-P-17-001. Available at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2015. Accessed April 2018.

Overview of the Electric Power Sector and SF_6 Use

Society's demand for electricity has been growing over time as people increasingly rely on electricity for operating appliances, electronics, and vehicles. Utilities deliver electricity to customers through transmission and distribution networks, which vary in voltage levels[2] to minimize transmission losses and ensure service reliability and safety. Within networks, voltage levels are changed with transformers, used to increase the voltage to improve efficiency of transmission or to decrease the voltage to improve safety and direct supply. In addition to transformers, networks rely on switchgear to protect electrical equipment against overload and short circuit currents ("circuit breaking") as well as to interrupt the load current ("load breaking"). These types of electrical equipment are needed to ensure safety and service reliability at optimal operating and capital costs. In the first half of the 20th century, different media including air, nitrogen, oil, and vacuum were used for insulation and load breaking in transformers and circuit breakers. Since the 1950s, SF_6 has replaced those media in some applications, particularly for insulating high-voltage circuit breakers. Because of its high electronegativity and density, SF_6 has excellent dielectric (insulating electricity) and arc-quenching (extinguishing an electric arc) properties.[3] The high density of SF_6 has also enabled the redesign of electrical equipment, making it smaller, easier to maintain, and safer for higher-voltage loads.

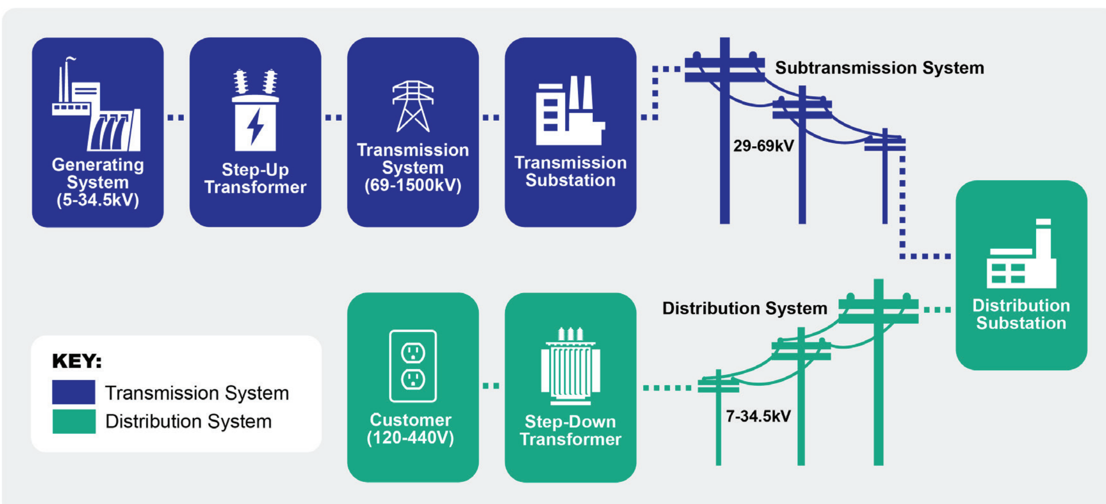

Figure 2. Basic structure of electric power system. Adapted from DOE (2014)[4] and (2015).[5]

[2]In the United States, electric power systems are nationally classified according to the following voltage classes, per ANSI C84.1-2016:

- Low Voltage: 1,000 volts or less
- Medium Voltage: greater than 1,000 volts and less than 100 kV
- High Voltage: greater than 100 kV and equal to or less than 230 kV
- Extra-High Voltage: greater than 230 kV but less than 1,000 kV
- Ultra-High Voltage: equal to or greater than 1,000 kV.

(Some states have different approaches to classifying electric power systems).

[3]In the United States, SF_6 is contained primarily in transmission and distribution equipment rated above 34.5 kV.

[4]U.S. Department of Energy (DOE). (2014). "Infographic: Understanding the Grid." Available at: https://energy.gov/articles/infographic-understanding-grid. Accessed April 2018.

[5]U.S. Department of Energy (DOE). (2015). "United States Electricity Industry Primer." Available at: https://www.energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf. Accessed April 2018.

Despite its efficiency and effectiveness, use of SF_6 has some drawbacks and operational constraints. First, to maintain the required dielectric properties for the circuit breaker to operate, SF_6 must be kept at minimum functional pressure (density). If the pressure of SF_6 decreases in a piece of switchgear equipment due to leaking or loss, operators must purchase additional gas to replace the emitted SF_6. This is an added cost to facilities that can be avoided through better handling practices. Next, the gas' exposure to moisture must be minimized, since moisture not only affects the dielectric properties of SF_6, but can also react with decomposed SF_6, creating dangerous by-products such as hydrofluoric acid (HF). Finally, SF_6 is a highly potent greenhouse gas (22,800 times more potent than CO_2 in trapping heat over 100 years), which can enter into the atmosphere and remain there for 3,200 years.[6] To minimize emissions of SF_6 to the atmosphere, the industry continues to focus on improving its SF_6 handling practices.

SF_6 in Switchgear

In electric power systems, SF_6 gas is used in medium voltage and high voltage switchgear for insulation (such as in gas-insulated switchgear and ring main units) and breaking (in circuit breakers and load break switches). Additionally, less common uses of SF_6 in electric power systems include high voltage gas-insulated lines, outdoor gas-insulated instrument transformers, and other equipment.

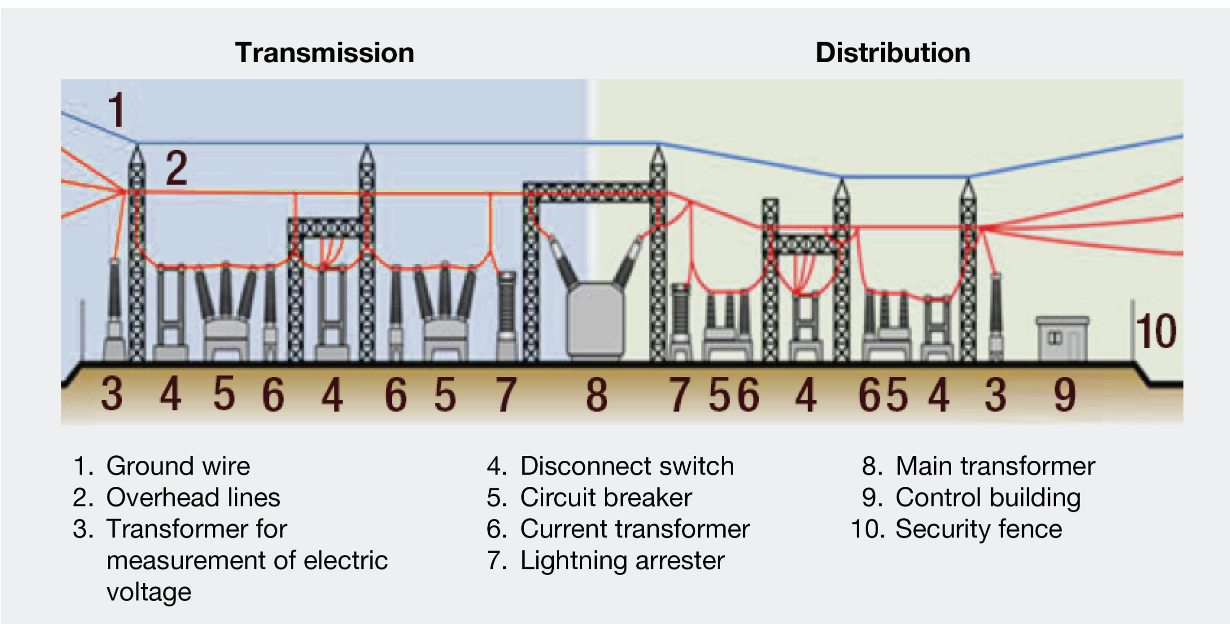

Figure 3. Gas-insulated switchgear in a typical electric power transmission and distribution system.
Adapted from IESL (2013)[7] to display an assembly of gas-insulated switchgear (GIS) and air-insulated transmission lines installed to control the transmission and distribution of electric power.

[6]Intergovernmental Panel on Climate Change (IPCC). (2007). [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. "Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change." Cambridge University Press. Cambridge, United Kingdom. pp 996.

[7]The Institution of Engineers Sri Lanka (IESL). (2013). "Gas-Insulating Substation (GIS) at the Norochcholai Coal Power Plant in Sri Lanka." Available at: http://www.iesl.lk/page-1668324. Accessed April 2018.

Gas insulated equipment (GIE) can be divided into two major categories[8,9] (although in reality equipment in the field can vary and be of hybrid types):

- *Sealed-pressure systems* (also known as 'hermetically sealed-pressure systems' or 'sealed-for-life' equipment) include gas-insulated circuit breakers and gas-insulated switchgear from 1 to 52 kV, and are most commonly used in distribution. These are smaller pieces of equipment that are meant to be operated without maintenance for the operating life of the GIE. Equipment typically arrives at operating pressure and requires no refilling, or topping off, of gas. Gas handling only takes place during manufacture and decommissioning. Hermetically sealed-pressure equipment typically contains several pounds (lbs.) of SF_6.
- *Closed-pressure systems* include switchgear above 52 kV and may have the capacity to contain hundreds of pounds of SF_6. During its lifetime, such switchgear might require replenishing with SF_6 by manual connection to an external gas source to ensure that the gas is at the minimally functional pressure.

Both categories of equipment have typical lifetimes of more than 30 to 40 years.

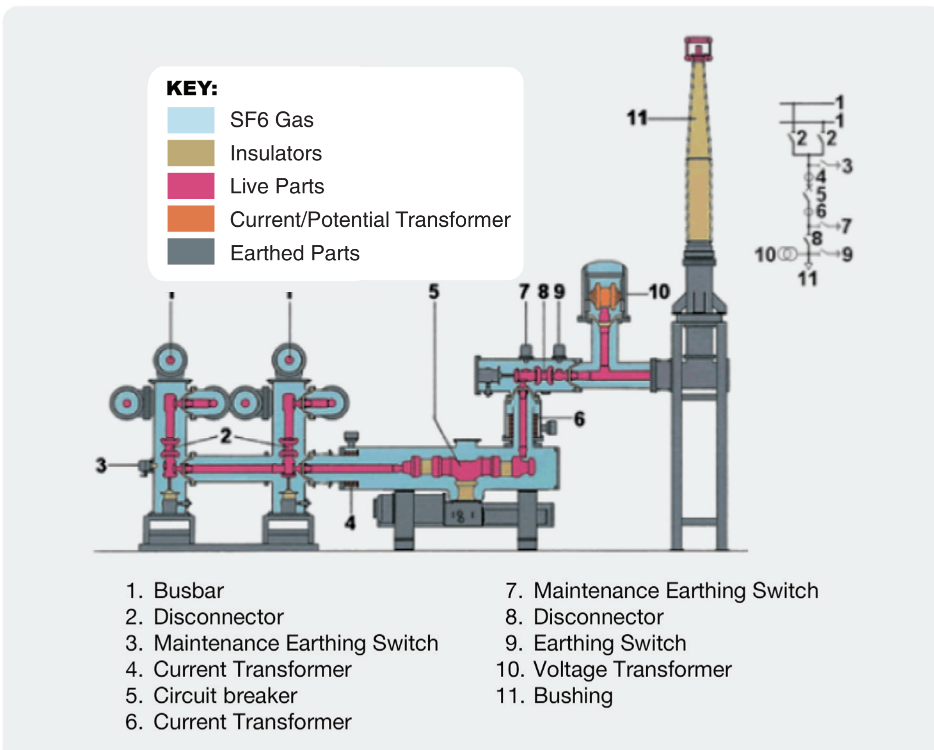

Figure 4. Example of gas-insulated switchgear. *Reproduced with permission from Toshiba (2017).*[10]

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[8]Intergovernmental Panel on Climate Change (IPCC). (2006). [Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds)]. "2006 IPCC Guidelines for National Greenhouse Gas Inventories – Chapter 8: Other Product Manufacture and Use." Vol.3. Prepared by the National Greenhouse Gas Inventories Programme. Published by the Institute for Global Environmental Strategies (IGES), Japan. Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_8_Ch8_Other_Product.pdf. Accessed April 2018.

[9]International Electrotechnical Commission (IEC). (2017). "IEC 62271-1: 2007: High-voltage Switchgear and Controlgear – Part 1: Common Specifications." Switzerland, October 2007.

[10]Toshiba. (2017). "GIS/GCB Gas Insulated Switchgear: GIS (550kV and Over)." Available at: http://www.toshiba-tds.com/tandd/products/giswitchgear/en/gis550.htm. Accessed April 2018.

SF_6 Emissions in Electric Power Systems

Potential sources of SF_6 emissions occur from 1) losses through poor gas handling practices during equipment installation, maintenance, and decommissioning and 2) leakage from SF_6-containing GIE.[11]

Closed-pressure equipment is the category of GIE that is the most susceptible to SF_6 emissions. Emissions associated with sealed-pressure equipment mostly occur during the manufacturing process and at disposal. Below is an overview of potential sources of SF_6 in transmission and distribution equipment, focusing on closed-pressure equipment. At the disposal stage, all equipment can release SF_6. Therefore, proper disposal procedures are critical to reduce emissions of SF_6 into the atmosphere.

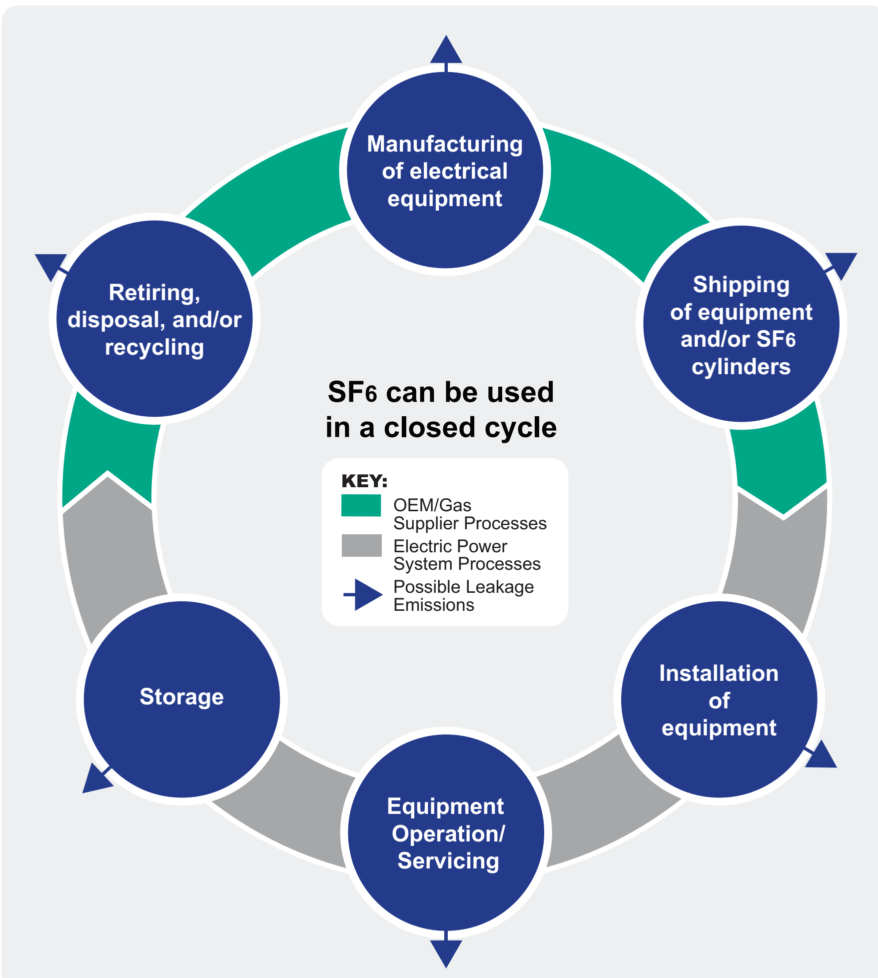

Figure 5. SF_6 emissions in the lifecycle process of switchgear.

[11]Estimating emissions using the 2006 IPCC Guidelines Tier 3 mass-balance method consists of four sub-calculations (A,B,C,D) and a final total emissions estimate (E), which is calculated by taking the decrease in inventory (A) + purchases/acquisitions (B) - Disbursements (C) - Net increase in total nameplate capacity (D). While this method will not reveal the exact process or piece of equipment that is the source of emissions, it will provide an estimate of total emissions. Having accurate inputs on the quantities associated with all gas flows and inputs to the mass balance equation will prevent over- or under-estimating emissions.

Potential sources of SF_6 emissions at various stages in the lifecycle of transmission and distribution equipment are as follows:

- ***Manufacturing of electrical equipment:*** Before switchgear is acquired by utilities, manufacturers produce, assemble, and test components, fill equipment, and, in some cases, test assembled equipment. Release of SF_6 by manufacturers may occur at this stage. SF_6 volumetric tightness testing is one method used by manufacturers to test a circuit breaker's ability to retain pressurized SF_6 gas.[12]
- ***Shipping of equipment and/or SF_6 cylinders:*** Properly sealed equipment or equipment shipped with dry gas should not leak during shipping when transported in a secure position. Cylinders, when containing SF_6 above certain pressure (29 pounds per square inch gauge (PSIG) at 68°F), must meet packaging, shipping, documentation, and driver-licensing requirements established by the U.S. Department of Transportation. Accidental release of SF_6 can occur at this stage; however, requesting the manufacturer to ship closed-pressure GIE using dry gas instead of SF_6 can minimize emissions during shipping.
- ***Installation of equipment:*** While hermetically sealed-pressure switchgear is completely filled with SF_6 at the factory prior to shipping, closed-pressure switchgear is partially filled with SF_6 or N_2 at a pressure slightly above atmospheric for shipping. It is completely filled to the required pressure when installing equipment. During the installation process of closed-pressure systems, emissions of SF_6 can occur, especially if staff are not properly trained or are operating faulty refilling equipment.
- ***Equipment operation:*** As closed-pressure GIE seals wear out as a result of normal operation, gas leaks can occur in several locations, such as at the flanges, fittings, seals, or bushings, as well as from the casting.[13,14] GIE can deteriorate and result in emissions of SF_6 if subject to:
    - high ambient temperatures and heat produced by the current passing through the circuit breaker;
    - chemical changes resulting from arcing due to current interruptions (e.g., SF_6 by-products reacting with the gasket material), if water is present to mix with by-products;
    - corrosion due to the external environment, such as salt spray from the ocean and pollution;[15] or
    - lightning, fires, storms, or other catastrophic events that can also cause sudden and severe damage to equipment.

  Additionally, poor maintenance, poor construction, and component failure can also cause leaks in operating GIE.
- ***Equipment servicing:*** Servicing the equipment to repair leaks and refilling to operating pressure creates opportunity for potential emissions. For example, hoses on gas filling carts can wear out and create leaks during top offs, so all equipment and equipment parts should be checked prior to use. Similarly, faulty

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[12] Hermosillo, V., Broglio, M., and Keller, J. (2017). "Recent Advancements in Productions Testing of AC High-Voltage Outdoor Circuit Breakers." Excerpt from a paper presented at the 21st Annual Circuit Breaker Test & Maintenance Training Conference, October 2015. Pittsburgh, Pennsylvania, USA.

[13] Campbell, E. (2006). "SF_6 Accounting Practices." DILO summary paper.

[14] Blackman, J., Averyt, M., and Taylor, Z. (2006). "SF_6 Leak Rates from High Voltage Circuit Breakers – U.S. EPA Investigates Potential Greenhouse Gas Emissions Source." Proceedings of the 2006 IEEE Power Engineering Society General Meeting, June 2006. Montreal, Quebec, Canada. Available at: https://www.epa.gov/sites/production/files/2016-02/documents/leakrates_circuitbreakers.pdf. Accessed April 2018.

[15] Bessede, J., Buescher, A., Marshall, R., Montillet, G., Stelter, A. (2006). "Limiting SF_6 Gas Emission by Optimization of Design and Handling over the Life Cycle of HV Switchgear." EPA Conference on SF_6 and the Environment. San Antonio, USA.

recovery equipment can result in gas losses. Some companies routinely analyze the SF_6 in serviced equipment to detect any harmful by-products, but even though safety control protocols, such as safety integrity level (SIL) or performance level d (PLd), can help to reduce the risk, this kind of analysis also releases SF_6. Even when leaking equipment is prioritized for repair or replacement, delays due to extreme weather or inability to take equipment off-line may impede timely repair and replacement.

- ***Storage:*** It is common for companies to keep a stock of SF_6 cylinders; additionally, partially-filled GIE that are recently purchased and not yet installed may be stored temporarily on-site. Storage cylinders or de-energized GIE present another potential SF_6 emissions source.
- ***Decommissioning, disposal, or recycling:*** All equipment, including hermetically sealed-pressure, has to be decommissioned properly to reduce emissions of SF_6. The gas must be either recycled or destroyed, either by the gas producer or a specialized service. When closed-pressure equipment is opened, SF_6 can be released to the atmosphere, especially if decommissioning staff are not properly trained to handle SF_6 and prevent its release. Emissions from sealed-pressure equipment can occur when staff decommissioning such equipment are not aware that it contains SF_6 or that the SF_6 should be recovered. This risk is greater when different service teams manage closed-pressure and sealed-pressure equipment, and only the former are trained to handle SF_6.[16]

Owners and operators of electric power systems and manufacturers and refurbishers of electric power systems equipment report their emissions of SF_6 to EPA's Greenhouse Gas Reporting Program (GHGRP)[17] if they exceed certain thresholds. This reported data can be helpful in estimating the relative percent of emissions from most stages of the SF_6 lifecycle. While emissions from ***shipping*** and ***storage*** of SF_6 cylinders and equipment could not be estimated at this time, emissions from these stages are understood to be minimal. Review of 2016 GHGRP reported data shows that SF_6 emissions from ***manufacturing of electrical equipment*** are estimated to be 12 percent of the total SF_6 emissions, while ***installation of equipment*** combined with ***equipment operation*** and ***servicing*** represent 76 percent of total reported emissions. Emissions from ***retiring, disposing,*** and ***recycling*** of equipment are estimated to constitute 12 percent. These data show that equipment installation, operation, and servicing account for the largest portion of emissions of the SF_6 lifecycle. However, it is important to remember that this breakdown of total emissions by lifecycle is only an estimation based on one year of reported data. In addition, emissions at different lifecycle stages can vary year to year, and utilities may experience different percent losses at each lifecycle stage due to different equipment types, operating conditions, practices, and other circumstances.

Reducing Emissions of SF_6 in Electric Power Systems

Over the last two decades, the industry has made significant progress in reducing SF_6 leakage rates and handling losses, based on improved understanding of practices and technologies for managing SF_6. This overview of approaches for reducing SF_6 losses is based on experiences shared by participants in EPA's SF_6

[16]Globally, about 50% of sealed medium voltage equipment is not sold to utilities but, rather, to a diverse set of other industries for which the fate of equipment at end-of-life is less understood and emissions are presumed to be substantially higher because of the lack of awareness and training. These other industries include: commercial buildings such as supermarkets; industry and infrastructure such as hospitals; and high power industries such as mining.

[17]EPA (2017) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart DD -Use of Electric Transmission and Distribution Equipment for Calendar Year 2016. U.S. Environmental Protection Agency, Washington, D.C. Available at: https://www3.epa.gov/enviro/facts/ghg/search.html.

Emission Reduction Partnership for Electric Power Systems. For a number of these approaches, several utilities are also able to work with their service providers to improve practices for handling gas and reducing emissions related to gas handling.

1. ***Companies' policies, protocols, and standard operating procedures:*** Understanding emissions sources is the first step to better managing SF_6 gas in electric power systems. However, improving that understanding and being able to act on it depends on companies' policies, protocols, and standard operating procedures. Such company documents can establish a lifecycle approach to SF_6 management, which can help ensure that employees track inventories of SF_6, detect and repair leaks, properly recover SF_6 from circuit breakers, recycle SF_6, and dispose of equipment and gas, as well as take advantage of other options for reducing SF_6 emissions. Ideally, company policies establish a process for continuous improvement and training on SF_6 management and emphasize that senior management supports the goal of reducing emissions. As a general example, some companies make their standard operating procedures available online to all employees, who, in the process of applying them, can recommend changes and improvements, which are then taken to leadership for buy-in and implementation. Some utilities incentivize the goal of reducing SF_6 emissions (e.g., by tying it to performance metrics) and incorporate these targets as part of their larger environmental management plans.[18] Developing company policies and programs that are comprehensive, allow for innovation, clearly designate responsible parties, and train and empower employees is a powerful approach that can create a solid foundation for successful SF_6 management. For example, Consolidated Edison has established "Fix-It-Now" (FIN) teams that consist of dedicated management and union personnel that work to improve the timeliness and effectiveness of maintenance repairs to address SF_6 related equipment deficiencies. The program takes a centralized view of all equipment conditions and a structured approach to the current repair program.[19]

2. ***Gas inventory, accounting, and tracking procedures and systems:*** Procedures and systems for gas accounting, tracking, and management can monitor all SF_6 activities, such as purchases, cylinder rentals, recycling, and disbursals. It is imperative that any residual SF_6 gas from cylinders be accounted for either by physical removal of SF_6 from a facility or by removal from inventory when the cylinders are returned to the suppliers. Protocols work best if they designate and instruct employees to measure SF_6 at every installation and handling and to document activities undertaken during the year. Tracking procedures can include labelling and inventorying of gas cylinders, use of warehouse cylinder log sheets, and inventorying of all GIE, including sealed-pressure equipment.[20] Tracking leak history of GIE also creates awareness and allows for the preparation of prioritization plans for equipment repair and/or replacement.[21] Utilities hiring contractors to manage their SF_6 could include such SF_6 handling procedures as part of their scopes of work

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[18] Slezak, M. (2014). "SF_6 – A Utility Perspective on Sustaining Low SF_6 Gas Emission Rate." ComEd presentation at the 2014 Workshop on SF_6 Emission Reduction Strategies. Long Beach, California, USA. Available at: https://www.epa.gov/sites/production/files/2016-02/documents/slezak-comed-presentation-2014-wkshp.pdf. Accessed April 2018.

[19] Blute, M., Szabo, J., and Dilillo, P. "Con Edison Emissions Reduction Program." Presented at EPA's 2012 Workshop on SF_6 Emission Reduction Strategies, April 2012. Available at: https://www.epa.gov/sites/production/files/2017-02/documents/blute_presentation_2017_workshop.pdf. Accessed April 2018.

[20] U.S. Environmental Protection Agency (EPA). (2006). "Reducing SF_6 Emissions Means Better Business for Utilities." Partner Pacific Gas and Electric case study, April 2006. Available at: https://www.epa.gov/sites/production/files/2016-02/documents/pge_casestudy.pdf. Accessed April 2018.

[21] McNulty, M. and Jasinski, J. (2012). "SF_6 Equipment Maintenance, Repair, and Replacement and Emission Programs." ITC Holdings Group. Presented at EPA's 2012 Workshop on SF_6 Emission Reduction Strategies, April 2012. Available at: https://www.epa.gov/sites/production/files/2016-02/documents/conf12_mcnulty.pdf. Accessed April 2018.

and specifications. Multiple robust SF_6 data tracking systems, such as TrackRef, TrackAbout, and DirectTrack, offer a number of features:

- automated cylinder barcode scanning and other direct upload features to reduce manual keying errors;
- customizable report capabilities that include real-time tracking of leak rates to make GIE owners instantaneously aware of effective leak rates;
- predictive functionality to forecast and project trends and identify chronic leakers; and
- validation features to track inconsistent data or outliers.[22]

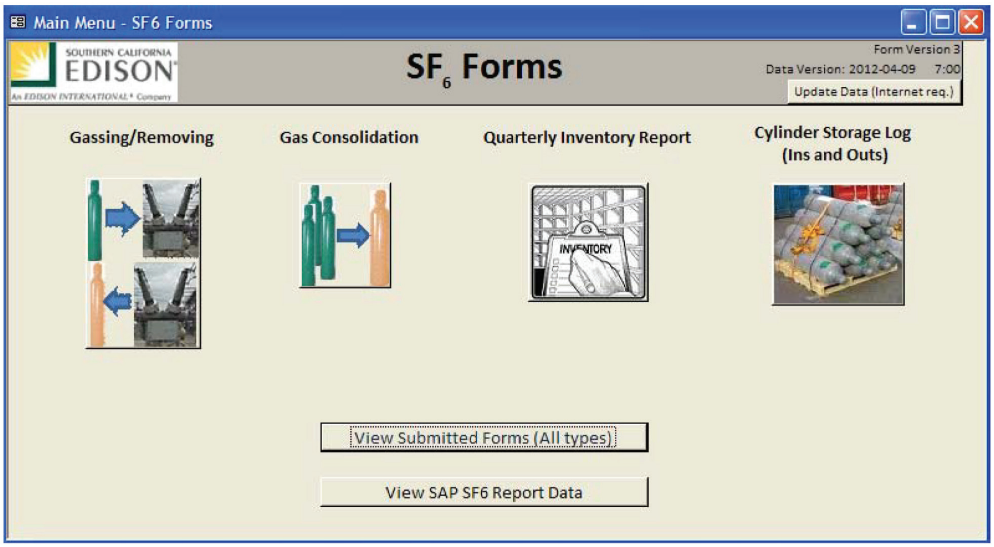

Figure 6. Example of a field tool for tracking SF_6 gas handling, Southern California Edison's SF_6 smart form tracking tool.[23]

3. ***Management of SF_6 acquisitions and gas inventory:*** Several utilities have found that improving management of their SF_6 acquisitions and gas inventory can offer several benefits. Utilities that consolidate their storage inventory and/or select a single vendor have found that it simplifies the tracking of their gas flows, increases transparency of costs, and offers other benefits such as cylinder inventory support from the vendor. Vendors can also support practices such as using the correct cylinder size and customizing the cylinder delivery system to minimize handling, limit cylinder inventories, and maximize gas utilization from each cylinder.[24] This can also make supplying gas easier, safer, and more cost-effective. Timely calibration of scales and other measurement devices can also help to ensure any issues are detected correctly when gas measurements are taken.

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[22]Helak, M. (2018). Feedback on draft paper titled Overview Opportunities for Electric Power Systems. Representative from Sacramento Municipal Utility District (SMUD). April 13, 2018.

[23]Preston, R. (2012). "An Asset Management Approach for EPA/CARB SF_6 Regulations. Southern California Edison. Available at: https://www.epa.gov/sites/production/files/2016-02/documents/conf12_lloyd2.pdf. Accessed April 2018. Note: This tool is used by Southern California Edison's crews to enter gas handling data and ensure accuracy of tracking SF_6-containing GIE and cylinders.

[24]Mueller, R. (2005). "10 Steps to Help Reduce SF_6 Emissions in T&D." Airgas Inc. Available at: http://www.airgas.com/medias/Utility-Automation-Ten-Steps-to-Reduce-SF6-Emissionspdf?context=bWFzdGVyfHJvb3R8MjAzNTI1fGFwcGxpY2F0aW9uL3BkZnxoMzQvaDBiLzExNDg2MzgyNjg2MjM4LnBkZnw4ZDdhODQ3MjQ1NTk3NTEzOTZkYzk1NzFhYWFiYTlkMGY0NDBlOWYwYzUxNDFlY2UzZjlmNTU0Y2NkZmQ1ZmI4. Accessed April 2018.

4. ***Training:*** Training is a vital ingredient for successfully managing SF_6 emissions at all phases of the life-cycle. Training raises awareness of emissions, environmental and health impacts of SF_6 and by-products, and potential reduction options, but training also enables employees to follow procedures and protocols properly. Employees involved in handling gas should be specifically trained in SF_6 handling and using equipment for performing this task on a routine basis (e.g., annual refresher trainings). For example, Consolidated Edison requires all field employees whose responsibilities involve handling SF_6 to complete an on-the-job training course for handling SF_6. It is common for companies to maintain in-house certification requirements and develop specialized training courses as part of a broader program. SMUD, for example, promotes rigorous cylinder management practices, which include not allowing SF_6 cylinders to be dropped or rolled, not applying direct heat, and prohibiting cylinder temperature to exceed 122 degrees Fahrenheit.

Figure 7. A gas cart can enable employees to more efficiently handle SF_6.

5. ***Recycling of SF_6 gas:*** Commonly practiced in the United States, recycling of SF_6 gas allows utilities to capture used gas that otherwise would be vented to the atmosphere. For example, Consolidated Edison utilizes three zero-waste DILO SF_6 pass-through gas analyzers for sampling, which exhaust into Tedlar bags that reclaim all of the sampled SF_6 gas. Consolidated Edison has had significant success in reducing emissions with this process as compared to traditional units. Utilities can reduce emissions further by ensuring that they use and maintain recovery equipment, or gas service carts, properly. ***Gas cart operation and maintenance*** is key to SF_6 emission reduction programs. Companies have found that gas carts can enable employees to efficiently handle SF_6, such as when off-loading and transferring SF_6 for maintenance and recycling.[25] In order to minimize emissions during the service or disposal of equipment, SF_6 must be

[25]Rothlisberger, L. (2009). "SF_6 Emission Reductions through Recovery/Recycling/Reuse." Presented at EPA's 2009 Workshop on SF_6 Emission Reduction Strategies, February 2009. Available at: https://www.epa.gov/sites/production/files/2016-02/documents/conf09_rothlisberger.pdf. Accessed April 2018.

recovered to the correct "blank-off pressure," ensuring that very little SF_6 remains in the equipment when it is opened to the atmosphere. When the equipment is evacuated only to atmospheric pressure, 20% or more of the SF_6 may remain; a vacuum must be generated to remove the remaining gas to appropriate blank-off pressures.[26] It is critical to follow correct procedures, including verifying that residual SF_6 is removed using mass flow scales or weight scales; referring to temperature/pressure curves; and using properly functioning recovery equipment, gauges, and scales. Because purchase of gas carts could be a large capital expense, another option is to rent equipment. Renting gas carts has advantages, as rental costs can be recorded as operating expenses rather than as capital expenditures, the renting service takes responsibility for maintenance, and carts can be onsite only when needed, saving space.[27] Used gas can be recycled either through processing using gas carts or by partnering with a supplier that takes it to offsite processing facilities. In some cases, suppliers or specialized services offer technical assistance and mobile equipment for onsite purification.

Figure 8. Thermal imaging cameras help visualize the leak of SF_6.
An example camera and an example image captured by the camera are shown above.

6. ***Leak detection and repair (LDAR):*** LDAR is a vital strategy to managing SF_6 emissions. Components of LDAR are included below.
   - ***Leak detection*** techniques identify gas leaks from SF_6-insulated equipment. Leak detection methods vary from simple techniques such as soap and water solutions to more sophisticated techniques such as thermal imaging cameras that visualize the source of SF_6 leaks. Such cameras exploit the strong infrared absorption of SF_6 to detect it. Thermal imaging cameras can detect minor, chronic leaks that are not detectable with conventional methods (i.e. soapy water or halogen leak detectors) without the need

[26]Rothlisberger, L. (2012). "SF_6 Management Challenges Version 2016 & Beyond." Presented at Dilo's 2016 SF_6 Gas Management Seminar, November 2016. Available at: http://www.dilo.com/2016-seminar-agenda-and-slides/. Accessed April 2018.

[27]Mueller, R. (2005). "10 Steps to Help Reduce SF_6 Emissions in T&D." Airgas Inc. Available at: http://www.airgas.com/medias/Utility-Automation-Ten-Steps-to-Reduce-SF6-Emissions.pdf?context=bWFzdGVyfHJvb3R8MjAzNTI1fGFwcGxpY2F0aW9uL3BkZnxoMzQvaDBiLzExNDg2MzgyNjg2MjM4LnBkZnw4ZDdhODQ3MjQ1NTk3NTEzOTZkYzk1NzFhYWFiYTlkMGY0NDBlOWYwYzUxNDFlY2UzZjlmNTU0Y2NkZmQ1ZmI4. Accessed April 2018.

to take equipment out of service. A limitation to thermal imaging is having the correct background to insure image visibility. A more cost-effective method for chronic leaks is bagging. This method takes plastic lining taped to various sections of the switchgear to trap any escaped gas. Upon waiting several hours, a user can slide the wand of a standard halogen leak detector under the plastic. All detection methods have relative advantages and disadvantages in terms of cost, outage times, and efficacy (e.g., false positives).[28] A number of Partners utilize an optical gas imaging camera to immediately detect small SF_6 leaks.

- ***Monitoring programs*** also identify leaks and help understand the specific characteristics of company's equipment at various locations. Leak detection frequency and strategies can vary. Some companies have established leak detection teams that are equipped with such technologies as thermal imaging cameras and sniffers to identify leaks. Such teams regularly inspect switchgear with available tools. Technologies are available to provide real-time monitoring of SF_6 leaks and to identify and prioritize leaking components that require the most immediate repair.[29] For example, SMUD institutes an inspection and maintenance program that includes monthly visual inspections to check for gas pressure.
- ***Leak repair*** on identified leaks is typically handled by applying a sealing material to the component that is leaking. Leak repair should be done using new gaskets and desiccant, as well as lubricant for flanges and o-rings. Kits are usually available from the manufacturer. Equipment should always be tested before and after repairs, using proper SF_6 recovery procedures and equipment. Some leak repair technology is available that uses clamps and sealant injection. This method reduces down time of the equipment, which reduces costs by avoiding loss of transmission. Leak repair requires planning ahead. Several utilities have leak prioritization plans that address worst performers first. GIE replacement can be the more effective mitigation strategy for the worst performers.[30]

7. ***Equipment upgrade and replacement:*** Upgrading and replacing equipment is a successful strategy that can significantly reduce emissions. Over time, engineering design changes have reduced the amount of SF_6 necessary for the operation of switchgear and increased the tightness of equipment, resulting in smaller leakage amounts and less frequent leakage over time. Low and medium voltage systems can use CO_2, a vacuum, and "Clean Air" (i.e., N_2 and O_2) as base gases. For medium and high voltage systems, more non-gas filled and vacuum equipment is now on the market. Specifically, vacuum technology for 72.5 kV has been available in the United States since 2007. For high-voltage systems, equipment with alternative insulating gases (including clean air as well as fluoronitrile and fluoroketone which typically use CO_2 as the base gas in switchgear) is scheduled to become available in 2018 for vacuums between 72.5 kV and

[28]Wolf, M. "SF_6 Leak Management, Repairs, and Considerations." Presented at DILO 2nd Annual SF_6 Gas Management Seminar, November 2017. Tampa, Florida, USA. Available at: http://www.dilo.com/wp-content/uploads/2017/11/DILO-Version-SF6-Leak-Management-and-Repair-Techniques-Wolf.pdf. Accessed April 2018.

[29]Examples include: 1) Hoffman, R. (2009). "SF_6 Emission Monitoring: State-of-the-Art SF_6 Tracking." EPA Workshop, February 2009. Phoenix, Arizona, USA. Available at: https://www.epa.gov/sites/production/files/2016-02/documents/conf09_hoffman.pdf. Accessed April 2018; and 2) Wacker, J. (2014). "Continuous Emissions Monitoring of Substation Assets: Spotlight on Sulfur Hexafluoride (SF_6)." Energy Utility & Environment Conference (EUEC), February 2014. Phoenix, Arizona, USA. Available at: https://www.epa.gov/sites/production/files/2016-02/documents/wacker-incon-presentation-2014-wkshp.pdf. Accessed April 2018.

[30]McNulty, M. and Jasinski, J. (2012). "SF_6 Equipment Maintenance, Repair, and Replacement and Emission Programs." ITC Holdings Group. Presented at EPA's 2012 Workshop on SF_6 Emission Reduction Strategies, April 2012. Available at: https://www.epa.gov/sites/production/files/2016-02/documents/conf12_mcnulty.pdf. Accessed April 2018.

145 kV.[31, 32] These alternatives have lower GWPs ranging from less than one to 2,100.[33] SF_6 alternatives are promising but might require some industry adaption, including new equipment and maintenance procedures that will necessitate training and adjustments to manage systems with different insulating mediums. A systematic approach to identifying and anticipating equipment replacement and repair needs can significantly reduce overall emissions.

Figure 9. Example of CO_2-based switchgear. *Image from Toshiba (2018).*

8. ***Proper decommissioning:*** At the end of life, all SF_6 equipment, including hermetically sealed-pressure switchgear, should be properly decommissioned to avoid emissions. Any remaining gas should be fully extracted using recovery systems that achieve acceptable blank-off pressure (i.e., vacuum generated during the recovery process to levels of 35 Torr and lower depending on the size of the GIE). Used SF_6 should be purified either on-site or off-site. Heavily arced, contaminated gas that is non-reusable can be sent to specialized incineration plants for destruction.[34] Proper handling and disposing of non-reusable SF_6 gas is important for safety reasons and can help to avoid emissions of contaminated gas. Although it might not be obvious, proper decommissioning also applies to hermetically sealed-pressure switchgear, which will eventually breakdown and release SF_6 if not properly disposed.

[31]Helak, M. and Rak, T. Feedback on draft paper titled Overview Opportunities for Electric Power Systems. Representatives from Pacific Gas and Electric (PG&E) and Sacramento Municipal Utility District (SMUD). April 2018.

[32]Rak, T. "SF_6 Free HV GIS and Breakers." Pacific Gas and Electric (PG&E). Presented at EPA's 2017 Workshop on SF_6 Emission Reduction Strategies, January 2017. Available at: https://www.epa.gov/sites/production/files/2017-02/documents/rak_presentation_2017_workshop.pdf. Accessed April 2018.

[33]Nyberg, D. "3M™ Novec™ Dielectric Fluids SF_6 Alternatives for Power Utilities: Workshop for SF_6 Emission Reduction Strategies." 3M. Presented at EPA's 2017 Workshop on SF_6 Emission Reduction Strategies, January 2017. Available at: https://www.epa.gov/sites/production/files/2017-02/documents/nyberg_presentation_2017_workshop.pdf. Accessed April 2018.

[34]The maximum tolerable impurity level of SF_6 contaminants for reuse is 50 parts per million by volume (ppmv), which translates into a reading of 12 ppmv if the sum concentration of SO_2 and SOF_2 is measured (IEC 60480 and CIGRE TFB3.01.01/2004).

Figure 10. Reclaimed cylinders can be rented or a specialized service can ensure that your equipment is properly decomissioned.

Conclusion

As the world moves towards electrification, electric power systems have become major users of SF_6 and sources of SF_6 emissions. Tracking SF_6 from leaking equipment and better gas handling techniques are crucial for reducing the impact of the industry on the environment, since there are many sources of fugitive emissions in the life cycle of electrical transmission and distribution equipment. By relying on best practices and technologies in managing SF_6, electric power industries will be able to lower their SF_6 emissions, while also reducing costs from purchases of replacement SF_6.

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