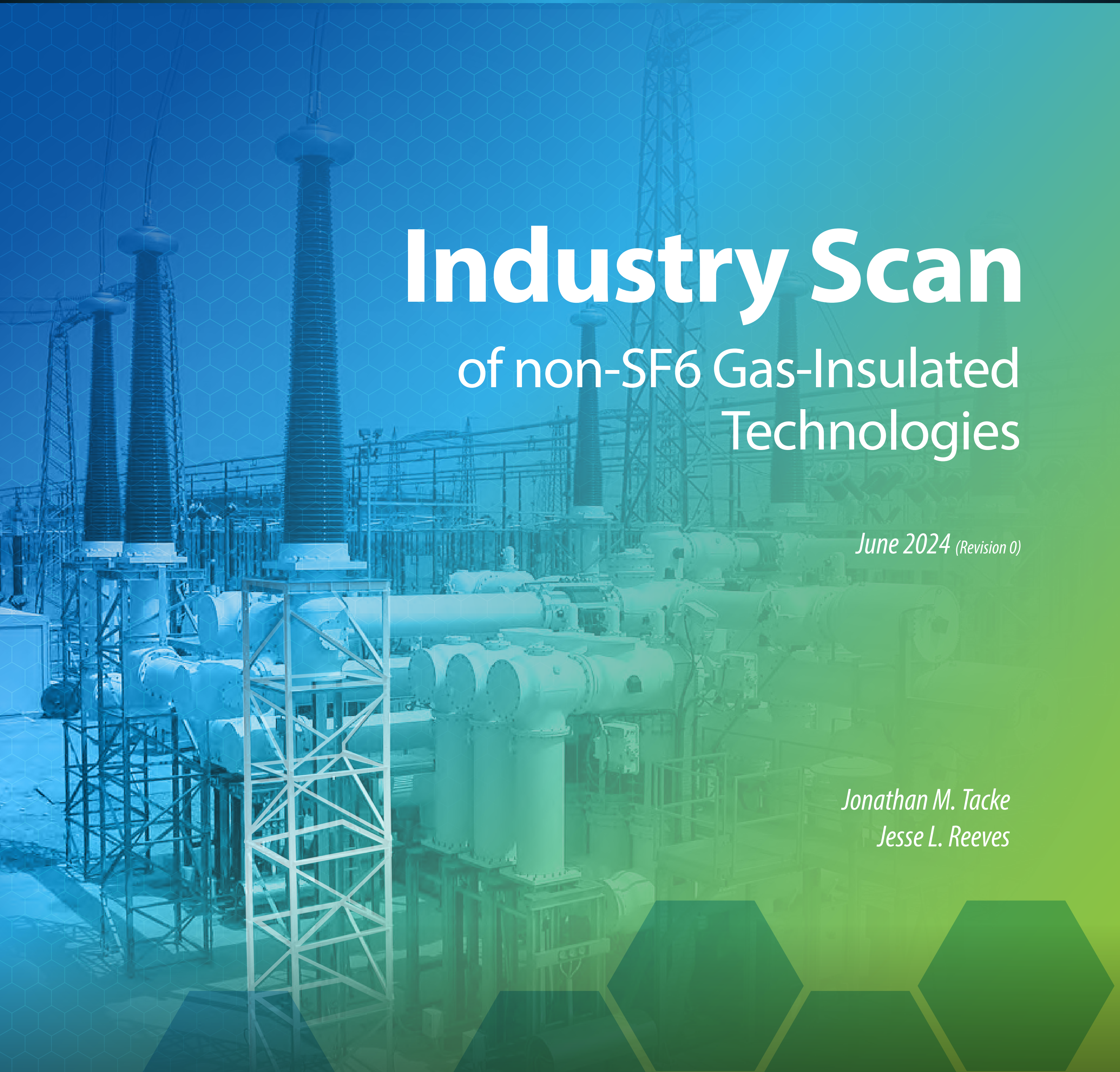

Industry Scan

of non-SF6 Gas-Insulated Technologies

June 2024 (Revision 0)

Jonathan M. Tacke
Jesse L. Reeves

INL/RPT-24-78805

INL is a U.S. Department of Energy National Laboratory operated by Batelle Energy Alliance, LLC

Idaho National Laboratory INL

24-50516_R2

DISCLAIMER

INL/RPT-24-78805
Revision 0

Industry Scan of Non-SF6 Gas-Insulated Technologies

Idaho National Laboratory

June 2024

Idaho National Laboratory

Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the U.S. Department of Energy
Office of Electricity Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

Executive Summary

Sulfur Hexafluoride (SF_6) is a specialty gas with excellent electrical insulation properties which has been used extensively in the power industry. This gas is unfortunately also one of the most potent greenhouse gases known to humanity. A 2014 report by the Intergovernmental Panel on Climate Change found that SF_6 has a global warming potential (GWP) 23,000 times higher than Carbon Dioxide, and has the highest GWP of all gases assessed (Myhre 2013). SF_6 is almost exclusively man-made and is produced for use as an insulator in high voltage electrical equipment. This makes the production and use of SF_6 one of the leading sources of anthropogenic climate change.

Since SF_6 recognition as a significant contributor to climate change, most governments and organizations have sought ways to reduce or eliminate their use of this gas. Many utilities have initiated leak monitoring and repair programs which have significantly reduced emissions of this gas into the atmosphere. While leak reduction programs have been effective at reducing emission rates in the developed world, leak rates remain frozen at ~1% annually. However, one of the largest and fastest growing markets for this gas is in the developing world where emissions standards are often lacking (P&S Intelligence. 2023).

To fully eliminate the environmental impacts of SF_6, alternative technology is needed. The ideal replacement would be a technology that can fulfil the same role as SF_6, at the same cost or cheaper, but without adverse environmental effects. Currently, no technology fits this description, however several promising technologies have begun to enter the market. This report was commissioned by the United States Department of Energy's Office of Electricity under the Transformer Resilience and Advanced Components (TRAC) program to assess the state of industry adoption and manufacturing capability for SF_6-free alternative technologies for use at the high-voltage level, and the primary barriers to broader adoption. While this report is tailored to the United States, the findings should be relevant to all stakeholders seeking to reduce SF_6 emissions.

As detailed in this report, that there are two dominant technologies poised to displace the use of SF_6 in the marketplace. While these technologies show tremendous potential, and demand for them is growing rapidly, there remain technical and economic challenges which prevent them from fully replacing the use of SF_6 gas. This report explores these technologies in detail including some of the utilities which have begun adopting them, their manufacturers, and the remaining challenges in the industry. This assessment is tied to the broader effort to eliminate the use of SF_6 gas, and recommendations are provided to industry stakeholders.

This report is organized as follows: Chapter 1 provides a detailed description of SF_6 gas, its origins, and its use within the power system. This Chapter also introduces the leading SF_6 alternative technologies for high voltage applications. Chapter 2 attempts to quantify the state of utility adoption of non-SF_6 equipment by assessing the market for these technologies to infer the trends among utility customers. This assessment is supported by case studies which profile the major and minor adopters of these technologies and is concluded by an enumeration of the primary barriers to further adoption. Chapter 3 discusses the state of manufacturing for non-SF_6 equipment, including the major market participants and their capacity to meet demand in the domestic market. This report concludes with a summary of the major findings and recommendations for regulators, utilities, and manufacturers seeking to eliminate SF_6 from the power system.

Page intentionally left blank

Contents

Figures

Tables

Acronyms

CARB .... California Air Resources Board
CT .... Current transformers
DOE .... Department of Energy
DTB .... Dead-tank breakers
GCB .... Gas circuit breakers
GIE .... Gas-insulated equipment
GIL .... Gas-insulated lines
GIS .... Gas-insulated switchgears
GVEA .... Golden Valley Electric Association
GWP .... Global warming potential
GWV .... Global-warming value
LTB .... Live-tank breaker
OCB .... Oil circuit breakers
PG&E .... Pacific Gas and Electric
PT .... Potential transformers
T&D .... Transmission and Distribution
TCL&P .... Traverse City Light and Power

1. Gas-Insulated Equipment, SF_6, and Alternatives

1.1 Motivation: SF_6 and the Environment

Climate change represents a serious threat to the health, safety, and prosperity of every nation on earth. Overwhelming evidence shows that climate change is affected by the concentration of various greenhouse gases in the atmosphere, many of which have anthropogenic origins. While carbon dioxide is possibly the most familiar of these greenhouse gases, many other greenhouse gases exist, some with significantly more global warming potential (GWP) than CO_2. One such gas is sulfur hexafluoride.

While some natural sources of SF_6 exist, SF_6 is primarily an engineered gas, produced deliberately for industrial purposes (Dilo , 2023). Eighty percent of the SF_6 gas produced in the world is used in the power industry as an insulator in high voltage gas-insulated switchgears (GISs) and other gas-insulated equipment (GIE) (History and Evolution of SF_6 Gas 2023) . Sulfur hexafluoride is a very potent greenhouse gas, with an estimated GWP between 22,000 and 25,000 times that of CO_2. Furthermore, SF_6 is highly stable and has an atmospheric lifespan of several thousand years (Electrical4U 2020).

In 2018, 9,040 tons of SF_6 were emitted globally, accounting for ~1% of the global-warming value (GWV) in that year (Simmonds & al., 2020). At present, the volume of CO_2 emissions has a much greater total impact on atmospheric greenhouse effect. However, if current decarbonization goals are achieved and terrestrial and oceanic CO_2 absorption is accounted for while SF_6 deployments continue unabated, SF_6 will overtake CO_2 as the primary contributor to global climate change by 2035. This is because the GWV of SF_6, fully accounted for is high, based on its incredible durability combined with the assumption that all SF_6 will ultimately find its way into the atmosphere. The 2035 projection is the most extreme case; however, the accumulated impacts of unmitigated atmospheric SF_6 loading over time will certainly dominate in the future.

Reducing or eliminating SF_6 emissions from the electric power industry may be achieved by improved monitoring and maintenance, regulations, international agreements, and non-SF_6 replacement technologies. However, this goal becomes more difficult to achieve given the current state of the markets and market-trend projections. Both non-SF_6 equipment installations and SF_6 installations are increasing. An economic analysis by Prescient

Strategic Intelligence determined in 2023 the global insulated switchgear market was valued at ~$23.7 billion, only ~$7.5 billion of which involved SF_6-free equipment (P&S Intelligence 2023). By 2030, the market is projected to be worth ~$37.4 billion, with ~$12 billion of that value being SF_6-free equipment (P&S Intelligence 2023). Non-SF_6 equipment projected to represent ~32% of equipment installations by 2030 (P&S Intelligence 2023). While the global non-SF_6 market is projected to grow at a rate of 7.2%, the global SF_6-equipment market is projected to grow at a pace only 0.5% less: 6.7%, (P&S Intelligence 2023). The electrification of the developing world and decarbonization efforts in the developed world generate market demands, and these are being filled by both SF_6 and non-SF_6 equipment. Without conscious mitigation, this trend will significantly alter the future dynamics of the climate-change crisis.

To reduce human impacts on global climate change, alternatives to SF_6 are desperately needed. Unfortunately, SF_6 is an essential part of most GIEs. SF_6 emissions are primarily the result of gas leakage: either accidental releases during manufacturing, installation, and maintenance, or bleed-off from imperfect seals during normal operation. Recent technological efforts to reduce SF_6 emissions have focused on improving the quality of seals. Behavioral efforts have focused on implementing policies and procedures to reduce accidental releases and track leak rates. However, such efforts represent a significant burden on utilities, and their effectiveness is limited. Utilities that have implemented leak reduction programs still have annual leak rates of ~1%. Furthermore, the majority of current GIE is procured by developing nations that do not require such emissions tracking and mitigation procedures. A better solution is needed.

This report assesses the emerging industry of SF_6-alternative equipment. This group of technologies are like SF_6 GIE; however, they use alternatives to SF_6 that have much lower GWP. Examples include GISs, gas circuit breakers (GCBs), live- and dead-tank breakers (DTBs), and gas-insulated lines (GILs). The report begins with an introduction to SF_6 and GIE, including the origins of this equipment and their current applications in the power industry. The report then includes a description of modern commercially available SF_6 alternatives. Next, the report discusses some American utilities that have begun deploying these non-SF_6 products, including case-studies. The focus of the report then shifts to discuss the manufacturers of non-SF_6 GIEs and their ability to supply this equipment in the American power system with domestic labor and materials. This report concludes with a presentation of the broader lessons learned and recommendations for promoting the phase-out of SF_6 gas.

1.2 Introduction to GIE

Switching devices have been an essential component of the power system since its origin. Originally, switches were operated manually; however, as power-system voltages increased, this became increasingly dangerous, and automated systems were developed. At higher voltages, the air between two contacts can break down, creating an arc, a conductive path of ions that allows current to continue to flow even though the switch has been moved to the open position. To address this phenomenon, circuit breakers were designed to interrupt this arc and stop the flow of electrical current. To interrupt the current at higher voltages, a larger distance is needed between the electrical contacts. This results in high voltage switching equipment being quite large and causing substations to have particularly large footprints.

Figure 1. Gas-insulated switchgear, source: Fuji Electric Global.

One way to mitigate the need for larger equipment is to encase the switching mechanisms in a medium with better dielectric properties than air. Some of the earliest such devices were oil circuit breakers (OCBs), many of which are still used today. By increasing the dielectric strength between the contacts, the device can be made smaller, making them less expensive and requiring a smaller footprint in the substation. While OCBs are an improvement over open-air systems, they still have some disadvantages. During a fault, the oil is vaporized. This assists in quenching the arc because oil vaporization increases the pressure in the sealed vessel, which increases the dielectric strength of the medium. However, as the oil vaporizes, it also decomposes into free atoms of carbon, hydrogen, and oxygen. Consequently, repeated operation results in the buildup of carbon in the vessel, which can interfere with device operation. Water formation in the vessel will degrade its circuit-interrupting capability and cause corrosion of the components. The buildup of free hydrogen can also result in a potentially explosive mixture of gases inside the vessel, causing an increased risk of fire when using these devices. The devices require constant maintenance and replacement of the insulating oil, making them expensive to maintain as well.

Another alternative is to use a gas to insulate the mechanism (Figure 1). Starting in the 1960s, this became a popular solution due to the desirable electrical properties of SF_6 gas. Compared to OCBs, GIEs require significantly less maintenance and are much safer to operate. However, the primary advantage of GIEs is their reduced footprint, roughly 1/10 of air-insulated equivalents. This makes these systems particularly popular in interconnections with high population densities. They are also popular in regions with harsh climates because they allow an entire substation to be contained in a climate-controlled structure. In the U.S., between 2 and 5% of all new substations are gas insulated (Parnell 2024).

While they all share similar characteristics, there are many types of GIEs currently in use in the power system. The most common devices are GISs, GCBs, LTBs and DTBs, and GILs. Brief descriptions of each of these devices and their uses are presented below:

- High-voltage GISs. A device that contains all the equipment necessary to isolate a circuit from the power grid. The use of an insulating gas makes GISs much smaller and less expensive than other designs.
- GCBs. A device that interrupts the flow of electrical current and is often contained within a switchgear. Again, the use of insulating gas allows the device to be smaller and less expensive in high-voltage applications.
- LTBs and DTBs. Types of circuit breakers where the mechanisms are fully enclosed in a tank to isolate them from the environment. DTBs are grounded, allowing for circuit transformers to be used on the connections, while LTBs are not, making them generally less expensive. Both use insulating gas to reduce size.
- GILs. Typically short segments of transmission line used to connect components within a substation or in otherwise densely populated areas. The use of the insulating gas reduces stray electromagnetic fields that can adversely impact equipment and personnel.
- Current transformers (CTs) and potential transformers (PTs). Measurement devices used for power system monitoring, protection, and control. They are typically installed alongside the transformers and circuit breakers in the substation.

1.3 Introduction to SF_6 Gas

Sulfur hexafluoride is an engineered gas, developed for its insulating and non-reactive properties. It was first discovered in 1901 by French chemist Henry Moissan (Cui et al. 2024). The potential to use the gas as an insulating medium was first realized by General Electric in 1937, and the use of SF_6 for high-voltage switchgears became prevalent in the 1960s (Yedinak, Lentijo and Kizilyalli 2023). Initially, the gas was only used for its insulating properties, but it was discovered that SF_6 worked as an arc suppressant, and its use in high- and medium-voltage circuit breakers increased rapidly (Electrical4U 2020). Sulfur hexafluoride was, however identified as one of six significant greenhouse gases identified by the 1997 Kyoto Protocol, and there has been a concerted effort to reduce its usage since (United Nations 1998).

The SF_6 molecule is comprised of one sulfur and six fluorine atoms, arranged in an octahedral configuration (Figure 2). This molecule is colorless, odorless, nontoxic, and highly stable. SF_6 does not suffer molecular breakdown at temperatures below 500°C. It is non-flammable and does not react with either water or chlorine. It is strongly electro-negative, having a dielectric strength 2.5 times that of air. Sulfur hexafluoride is less thermally conductive than air; however, its other properties make it useful for heat transfer in breakers. During arc quenching, SF_6 decomposes into unstable compounds. These compounds are highly toxic; however, they rapidly recombine exothermically back into SF_6 at the edge of the arc. This process assists in transferring energy away from the arc, allowing the arc's energy to dissipate into the environment.

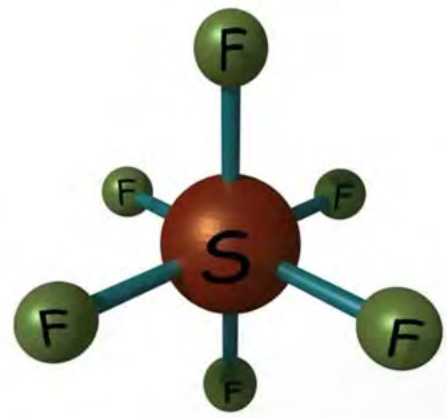

Figure 2. The structure of an SF_6 molecule.

These properties make SF_6 ideal for use in high-voltage circuit brakers and switchgears, as well as in other industrial processes where an inert gas is required. Unfortunately, these same properties are what make SF_6 such a potent greenhouse gas. The insulating properties of SF_6 mean that it traps infrared radiation, and the chemical stability of SF_6 ensures it will remain in the atmosphere for thousands of years.

Alternatives to SF_6 gas have been sought since as early as the 1970s (Devins 1980). While it has desirable electrical properties, its impact on climate change means emissions must be prevented or reduced. An analysis of SF_6 inventories in Great Britain suggests that many utilities may have an annual leak rate of between 0.4 and 1.3% (Widger and Haddad 2018). If climate change is to be addressed, non SF_6 alternatives must be deployed, and SF_6 inventories must be kept out of the atmosphere. Effectively managing SF_6 emissions will require a significant effort due to the extent of legacy SF_6 equipment already deployed and their ongoing deployment.

1.3.1 SF_6-free Technologies

Currently, alternative technologies to SF_6 exist for low- and medium-voltage equipment; however, the viable non-SF_6 products for use in high-voltage systems are limited to two main product types, despite years of research. In addition, the alternative products have disadvantages that must be balanced against their GWV advantages (Parnell 2024). Manufacturers are engaged in active research, development, and deployment to capture market share for non-SF_6 alternatives in high-voltage systems. To date, the highest voltage non-SF_6 GIE is limited to 450 kV (Heimbach 2023). Planned technologies envision these technologies' reaching as high as 550 kV in the next few years (Hitachi 2024). This level of technological achievement will facilitate phasing out many SF_6 systems, but it is not capable of eliminating SF_6 entirely because 765 kV systems still have no viable alternatives available or planned. Additionally, while new technologies show promise, most utilities have large inventories of SF_6 GIE which are expected to operate for decades to come. Thus, SF_6 will continue to be used, at least for the foreseeable future (Parnell 2024).

Japanese power-system operators have identified seven criteria which are essential performance metrics for GIEs (Uchii et al. 2022). An ideal SF_6 replacement technology is expected to be equivalent or superior in all seven metrics (Toshiba 2024). These criteria include health and safety, operating conditions, supply chain, simplicity of handling, life-cycle cost, footprint, and voltage range (Uchii 2022). Once installed, comparable electric-power equipment is expected to last for more than 30 years. Currently, no technology can beat SF_6 equipment in all seven criteria; however, some are close, performing better in several areas while presenting comparative deficiencies in other areas. Cost benefit analysis, regulation, and decisions by specific utilities needs have resulted in much greater acceptance and deployment of the non-SF_6 equipment. Industry is factoring in the environmental impacts of SF_6 as a significant criterion in procurement decisions. The remainder of this section details the most promising technologies in the market today.

1.3.2 Clean Air/Dry Air/Synthetic Air + Vacuum:

Clean-air products are commercialized by a wide range of manufacturers under different trade names including Dry Air or Synthetic Air. The term natural-origin gas is also commonly used to describe these gases. Different manufacturers list different compositions and market under different brands; however, all these gases are produced in the same way—namely, by dehydrating ambient air or mixing pure gases in the same proportions found in nature. A quick list of the clean-air providers includes:

- Commercialized by Siemens under the Blue line of products.
- Commercialized by Toshiba Electric under the Aeroxia brand.
- Manufactured by Mitsubishi Electric, Meidensha, and Schneider Electric.

Clean-air products are characterized by:

- Mixture of N_2 and O_2, vacuum in circuit breakers.
- Other variants can include mixtures of CO_2 or other atmospheric gases.
- GWP of the gas is zero.
- Comparable footprint to SF_6 products
- Available for:
    - » 72.5 and 145 kV GISs
    - » 72.5 and 145 kV LTBs
    - » 145 kV DTBs
    - » 420 kV GCBs
    - » <420 kV CTs and PTs
- Roughly 700 units in operation, with 2500 sold globally.

Benefits of air-insulated vacuum breakers include (GVEA 2022):

- Reduced greenhouse-gas equivalent to about 1000 tons of CO_2, the amount of CO_2 emitted annually by about 200 passenger vehicles.
- Reduced power consumption, leading to further cost and greenhouse-gas reductions.
- Cost savings due to reduced maintenance and operations requirements.
- Ability to refill insulating air without de-energizing the breaker, eliminating costly switching operations, and reducing interruptions in electric service to members.
- Increased up-time for power plants and substations.

Benefits of air insulated vacuum breakers include (GVEA 2022):

- Reduced greenhouse gas equivalent to about 1000 tons of carbon dioxide – This is the amount of carbon dioxide emitted annually by about 200 passenger vehicles.
- Reduced power consumption, leading to further cost and greenhouse gas reductions.
- Cost savings due to reduced maintenance and operations requirements
- Ability to refill insulating air without de-energizing the breaker, eliminating costly switching operations, reduces interruptions to electric service to members, and reduces the number of unexpected power plant shutdowns.
- Increased up-time for power plants and substations.

Clean or Dry Air are manufactured gases that have the same composition as the air in the atmosphere—i.e., approximately 80% N_2 and 20% O_2—but without moisture or contamination. Clean air is approximately 45% dielectrically inferior to SF_6 at the same pressure. Therefore, clean air requires higher operating pressures than SF_6 to function inside a switchgear. Clean air is a poor arc-interruption medium, so it is necessary to supplement a vacuum interrupter (VI)for arc suppression when clean air at high pressure is used as insulation (Manna, Bess and Ghosh n.d.).

Air and vacuum systems are a promising technology for the medium- to high-medium-voltage range, and different versions of this technology have been used at this range for years. Unfortunately, natural origin gases are much weaker dielectrics than SF_6. This means that, for their use in higher-voltage applications, they must operate at much higher pressures than their SF_6 counterparts. This makes devices larger, heavier, and more expensive. This has also limited the use of this technology at voltage levels higher than 145 kV.

1.3.3 Flouronitrile Gas

Flouronitrile gas is an alternative to SF_6 used for insulation and arc quenching in electrical equipment. The gas was originally developed and marketed by 3M under the trade name Novec 4710; however, it is now produced by many different suppliers and is commonly referred to as C_4-FN. This alternate gas has facilitated the development of GIEs above 145 kV and is critical in the efforts to eliminate SF_6. It offers excellent dielectric properties, a wide range of operating temperatures, and significant reductions in environmental impact compared to SF_6. Novec gas is non-flammable and has a wide safety margin for workers when used as designed in intended applications. The intended applications are as a dielectric medium for medium- and high-voltage power-generation and distribution equipment, which includes GISs, GILs, and circuit breakers. Novec gas is mixed with inert gases for use in the intended applications (3M 2022). By adopting a 20% C_4-FN and 80% CO_2 mixture, a carbon-footprint reduction of up to 98% of SF_6 is achieved with a comparable dielectric strength (Loizou et al 2023).

Relevant C_4-FN properties include (3M 2022.):

- GWP of 2100 (pure) and 292 (3.5 mole% in CO_2)
- Potential to reduce greenhouse-gas (GHG) emissions by more than 99% in gas mixtures
- Dielectric breakdown voltage approximately twice that of SF_6 at a given pressure (in pure form)
- Wide margin of safety for workers
- Non-flammability
- Compatibility with a wide range of equipment components
- Dielectric breakdown voltage of 27.5 kV at 1 bar over a 2.5 mm gap.

Novec gas was commercialized through a cross-licensing agreement with both GE and Hitachi. GE products are commercialized under the g^3 brand while Hitachi products are sold under the EconiQ brand (GE Vernova 2021).

1.3.4 Gas-Retrofit Technology

One advantage of the flouronitrile gas is that it is similar enough to SF_6 that in some very specific cases, the SF_6 in a piece of equipment can be directly replaced with a mixture of C_4-FN and other gases, leaving the other physical equipment unchanged. However, many considerations need to be accounted for when determining the viability of this option. In practice, materials compatibility of C_4-FN differs somewhat from that of SF_6. While the product is compatible with most common metals, it can be affected by some of the components found in lubricating greases and the elastomers used in gaskets and O rings (3M 2022). This interaction can cause component seals to degrade, leading to a leaking of the gas and, ultimately, total equipment failure.

Despite material limits, there has been development toward retrofitting of existing gas equipment. In the United Kingdom, 3M and National Grid have collaborated to develop this solution. Some of the results of that testing have found (Loizou et al. 2023):

- A 20% C4-FN/80% CO_2 gas mixture possesses comparable dielectric performance to SF_6 necessary for a retro-fill solution.
- Type tests with a gas-insulated breaker demonstrator showed that the chosen gas mixture successfully passed all the required International Electrotechnical Commission tests specified for 420/550 kV basic insulation level (BIL).
- Additional non-standard tests in 420 kV BIL also had no breakdown occurrence even when the operating pressure was reduced to 4 bar.

While research on this technology continues, Hitachi has begun to offer it as a commercial service. This is described in more detail in Chapter 3, under the manufacturer profile for Hitachi Energy. Hitachi's applications for flouronitrile gas are limited to installed ELK-3, 420 kV GULs.

1.4 Summary

This chapter has explained the origin and characteristics of SF_6, its use in the power system, the need for its reduction or elimination, and some potential technologies to replace it. Decades of research have enabled industry to begin offering viable commercial alternatives to SF_6 gas at new voltage levels. Development of these technologies has yielded a range of relatively new commercial products now available, with other higher-voltage products on the cusp of commercialization. This means it will be many years before these systems become more commonplace in the power industry than traditional SF_6 systems, and even longer until SF_6 can be phased out entirely. Even so, there is a strong demand for these systems. The following section explores this demand by showcasing some of the early adopters of non-SF_6 technology.

2. Utility Adoption Assessment

Developing alternative technologies to SF_6 has been a slow process. Despite the pressing need for these systems, finding viable gas chemistries has proven challenging. Viable high-voltage products have only begun to enter the market within the last 5 years. Despite their limited commercial availability, these products have seen rapid adoption within the U.S. power system, with multiple utilities adopting them in dozens of projects in the last few years. This indicates a strong and growing demand for non-SF_6 GIEs within the power industry. Recent sales numbers support this conclusion, with manufacturers reporting hundreds of orders for their newest products in 2024 alone.

This section highlights the state of non-SF_6 switchgear from the utilities' perspective. This is done by presenting a market assessment for non-SF_6 GIE in the domestic and global sectors, one that emphasizes the procurement rates for these technologies. This is followed by discussion of notable cases where these products have been deployed within the North American power system. Despite the sharp uptick in sales for these products, there is a surprising lack of publicity surrounding these projects. This can likely be attributed to the relative novelty of these systems leaving utilities unwilling to publicize their purchases until the efficacy of the systems can be validated. This hypothesis is discussed in more detail in the conclusion of this section.

2.1 Domestic Market for non-SF_6 GIE

In 2023, the size of the global market for GIEs was $23.76 billion, and the annual growth rate was 2.3% between the years 2017 and 2023. This is anticipated to increase considerably to a global growth rate of 6.8% annually between 2024 and 2030, with a final market size of $37.44 billion in 2030. This growth is driven by a combination of factors, including the electrification of the developing world, the need for more infrastructure to support decarbonization in the developed world, and the need to replace aging equipment (P&S Intelligence 2023).

The U.S. is not excepted from this trend, with energy infrastructure investment rising from $25.1 billion in 2021 to $26.7 billion in 2022 and $29.1 billion in 2023, an almost 20% increase in only 2 years. This investment is desperately needed because much of the American power system was built during the 1960s and 70s. The average age of electrical infrastructure in the U.S. is more than 40 years old, and most electrical equipment has a service life of roughly 30 years (Gräf 2019). This expansion is being supported by such federal programs as the Grid Resilience Innovative Partnership, which provides $10.5 billion to support electricity-infrastructure projects (P&S Intelligence 2023).

In the U.S., this expansion is being driven in many areas by the construction of large data centers and renewable-energy sources, as well as considerable population growth. The size of the GIS market in the U.S. was $6.7 billion in 2023. This represents 23% of all domestic electrical-infrastructure spending and 28% of the entire global GIS market. High-voltage equipment represents most of this spending, with voltage ratings above 75 kV representing a total value of $4.8 billion. Of this spending, $2.1 billion was for non-$SF_6$ equipment, primarily at the lower-voltage level (P&S Intelligence 2023). In a recent interview, one GIS supplier stated that, at the high-voltage level, the portion of orders for non-SF_6 GIE rose from 1 to 10% of total orders in 2023 alone.

In the North American GIS market, SF_6 insulation holds a larger share than the SF_6-free alternatives primarily because of its superior insulating properties, which are critical for high-voltage applications. However, the environmental impact of SF_6 is driving the shift toward SF_6-free solutions. North America is witnessing a gradual increase in the adoption of SF_6-free GISs, spurred by stringent environmental regulations and increasing awareness of climate-change impacts. The market for SF_6-free GIS is expected to grow at a rate of 7% annually between 2024 and 2030, compared to 6.5% for SF_6 GIEs (P&S Intelligence 2023).

Power utilities hold the largest share in the North American GIS market. Growth is also being fueled by the ongoing integration of renewable-energy sources. The aging power infrastructure in North America also necessitates significant upgrades, for which GIS is ideally suited due to its enhanced reliability and reduced footprint. Additionally, regulatory pressures to decrease environmental impact and improve energy efficiency will further drive the adoption of GIS technologies by power utilities, ensuring their role as a cornerstone of North America's evolving energy landscape (P&S Intelligence 2023).

2.2 Domestic Utility case-studies

Despite the results of the economic analysis presented above indicating a growing demand for non SF_6 equipment, the publicly available information on high-voltage SF_6-free GIE projects is relatively sparse. This survey found only six American utilities that had publicized their acquisition of non-SF_6 equipment. Of these utilities, only one, Pacific Gas & Electric, is considered a major adopter, having deployed these technologies widely throughout their system. The other utilities are all considered minority-level adopters, having only deployed these technologies in a single project.

The discrepancy between the estimated market size for non-SF_6 equipment and the scarcity of public documentation on these projects is quite striking. However, possible explanations for the discrepancy include, first, that the market analysis performed by PSI and presented above does not distinguish between non-SF_6 at the low-voltage level versus at the high-voltage level. Because high-voltage variants of non-SF_6 equipment are recent additions to the market, it is likely that the non-SF_6 GIE market is dominated by low-voltage sales. This is supported by the case studies below: five out of the six utilities procured their first piece of high-voltage non-SF_6 GIE after 2020, and three installed their equipment within the last 12 months. This implies a second explanation for why very little public information is available on these projects: the utilities are waiting to publicize their projects until they are confident in their performance. Investing in novel technologies is high risk for public utilities because they must justify capital expenditures to rate payers. This can make it challenging for them to procure technologies without proven records of performance, and utilities are unwilling to disclose such procurements when they do. This hypothesis is supported by the lack of utility respondents to inquiries on this subject.

2.2.1 Major Adopters:

In this report, only one American utility was found to have deployed non-SF_6 equipment at a rate that can mark it as an innovator in the market. This utility is Pacific Gas and Electric (PG&E), which has been using high-voltage non-SF_6 technologies since 2008. In this section, public documents are used to identify PG&E's driving motivations, observations, and concerns around their use of non-SF_6 GIE. Notable projects are described, with any barriers encountered and how those barriers were overcome, as well as any recommendations for regulators and utilities.

2.2.1.1 PG&E – California 2010

PG&E's widespread adoption of SF_6 alternatives can be attributed to two main factors: the California Air Resources Board (CARB) initiative and simple economics. CARB requires PG&E to maintain a corporate-wide SF_6 leak rate below 1% of inventory. Consequently, adding SF_6 gas and repairing SF_6 leaking equipment drives the utility's equipment cost. PG&E has four guidelines to address the management of SF_6:

- Fix all SF_6 leaks
- Only purchase equipment with the lowest SF_6 leak rate
- When possible, purchase equipment that does not contain SF_6
- Manage SF_6 inventory with accountability.

PG&E has already phased out the use of SF_6 at the medium-voltage levels and currently is using this knowledge and experience to support its new goal to phase out the use of SF_6 in all high-voltage GIEs.

Eliminating SF_6 will reduce overall equipment-maintenance costs because of the substantial effort required to maintain SF_6 leak rates at the regulated limit of 1% or lower. Fixing a single SF_6 leak costs $25,000 on average (Rak 2020). These costs have three components: the cost of replacing gas lost from chronic leaks, the cost of replacing flange O-rings at 10-year intervals, and the cost of managing toxic by products resulting from electrical discharges that occur within SF_6-insulated equipment (Rak 2020).

Motivated to reduce costs, PG&E evaluated alternative technologies that could replace SF_6 and concluded dry-air/vacuum was the most cost-effective alternative. The utility purchased three 72 kV dry air/vacuum DTBs in 2008, which were installed and evaluated for the next 8 years (Rak 2020). In 2017, PG&E's asset-strategy department evaluated the historical maintenance cost of its fleet of oil, sulfur hexafluoride, and dry-air/vacuum DTBs. That evaluation overwhelmingly concluded SF_6 DTBs were significantly more expensive to maintain than oil and dry-air/vacuum DTBs. This cost study resulted in PG&E's phasing out the use of SF_6 DTBs at the 72-kV level where technically feasible (Rak 2020). PG&E no longer purchases new 72-kV DTBs that use SF_6, and more than 30 72-kV dry-air/vacuum DTBs were installed as of 2020 (Rak 2020). PG&E installed its first 115-kV dry-air/vacuum DTBs in early 2021 (Rak 2020). The 3AV1 DT DTBs offer a rated voltage of 115 kV, a rated short-circuit breaking current of up to 40 kA, and a rated current of up to 3,000 A (T&D World 2018).

Because PG&E realized a reduction in maintenance cost when it switched from SF_6 to dry-air/vacuum DTBs, the utility's goal was to reproduce those savings with GIS equipment (Rak 2020). PG&E's sourcing department completed a strategic supplier evaluation to identify dry-air/vacuum GIS suppliers. Based on PG&Es evaluation, it was concluded the most cost-effective option was to procure technology to replace SF_6 in GIS with the same dry-air/vacuum technology that replaced SF_6 in the DTBs. PG&E identified the following advantages to this technology (Rak 2020). Dry-air vacuum technology:

- Is the most extensively available commercial product, with thousands of DTBs and hundreds of GIS installed around the world
- Has 0 GWP and no toxic by-products
- Will meet the proposed CARB phase-out schedule
    - The leak rate from dry-air/vacuum technology is exempt from California's state mandatory annual reporting (a significant cost savings for California utilities)
- Is available from multiple suppliers
- Is the lowest-cost life-cycle option at present
- Has been tested up to 65-kA interrupting current and 230-kV rated voltage.

The utility's first purchase of a dry-air/vacuum GIS was for its Evolution substation at the Livermore training center (Rak 2020). The 8VN1 GIS features a rated voltage of 115 kV, a rated short-circuit breaking current of 50 kA, and a rated current of 3,000 A (T&D World 2018). Most recently, the utility purchased a second dry-air/vacuum GIS for a 115-kV, 50-kA, 3000-A multi-bay GIS at its new Hunters Point substation. It is also currently evaluating the component for its Rio Oso substation rebuild (Rak 2020).

The case of PG&E shows that despite slightly higher upfront costs, the savings realized in lifetime costs by adopting non-SF_6 equipment represent a significant advantage for the technology and potential benefit for utilities. This is particularly true in California where SF_6 monitoring, and leak-reduction standards make SF_6 equipment expensive to maintain. For regulators seeking to reduce SF_6 usage, such regulations create a clear incentive for utilities to phase out the gas. For utilities, as SF_6 gas usage is reduced globally, the widespread availability of natural-origin gases may make these technologies cheaper to procure and maintain than SF_6 GIEs, even in areas without monitoring requirements.

2.2.2 Minority Adopters:

Several other utilities were found which have installed at least one piece of non-SF_6 equipment at the voltage level of 75kV or more. These minority adopters are described below:

2.2.2.1 Traverse City Light and Power, Traverse City 2020

Traverse City Light and Power (TCL&P) located in Traverse City, Michigan, installed circuit switchers that use clean, dry air instead of traditional SF_6 insulating gas, making it the first utility in the U.S. to use the new technology. TCL&P is a community-owned municipal utility serving over 12,700 customers in Traverse City, as well as parts of East Bay, Elmwood, Garfield, and Peninsula townships. Known for its focus on environmental stewardship, TCL&P implemented many programs and standards to reduce its carbon footprint (Siemens Energy 2020).

In 2020 Tony Chartrand, system engineer at TCL&P, was interviewed by Peter Maloney for American Public Power Association on why the utility chose to deploy this technology. He said the utility chose to upgrade to the Blue Clean Air technology to "[p]rovide more reliability to our customers and save maintenance costs along with being more environmentally friendly" (Maloney 2020). In addition, SF_6 will likely be outlawed at some point in the future—as many refrigerants were—and it is getting harder and harder to refill a bottle of SF_6, he said (Maloney 2020). TCL&P has adopted renewable generation sourcing goals of 40% by 2020 and 100% by 2040. The new switchers "match up with that goal by getting rid of devices that could leak greenhouse gases into the atmosphere," Chartrand said (Maloney 2020). TCL&P has several other SF_6 switchers, most of which are not even 20 years old and still have life in them, Chartrand said, adding that the utility is taking a phased approach to replacing them (Maloney 2020). "We have no plan to buy any more SF_6 devices; we plan to move exclusively to vacuum technology for all of our breakers and circuit switchers," Chartrand said.

Built at the Siemens Energy plant in Richland, Mississippi, and commissioned by TCL&P in October 2020 (Maloney 2020), the Blue Clean Air 72.5 kV CPV2V circuit switcher is the first in the U.S. to provide reliable short-circuit interruption without emitting harmful gases into the atmosphere Siemens 2020). The two new switchers were installed to replace fuses that were protecting the transformers. It was the utility's last substation that was still using transformer fuse protection (Maloney 2020). Eventually TCL&P plans to replace all its traditional SF_6 switchers with clean-air switchers, but they are more expensive, currently costing about 68% more than traditional technology, Chartrand said. On the other hand, the new switchers offer estimated life-cycle cost savings of up to 40% over SF_6 circuit switchers, and the new switchers have a longer expected operating life and longer maintenance intervals (Maloney 2020).

2.2.2.2 Golden Valley Electric Association, Fairbanks 2022

Golden Valley Electric Association (GVEA), located in Fairbanks, Alaska, serves over 100,000 residents in the interior of the state. The cooperative's mission is to "safely provide members with reliable electric service, quality customer service, and innovative energy solutions at fair and reasonable prices" (GVEA, 2022).

Meiden America Switchgear, Inc. (MAS), a subsidiary of Meidensha Corporation of Japan, delivered the world's first environmentally friendly 145 kV dead-tank, dry-air, insulated, vacuum circuit breaker (VCB) (145kV VCB) to GVEA. The 145 kV VCBs are GHG free and have been advertised as a safe, reliable addition to the GVEA's electric system. A total of three 145kV VCBs were delivered to the project for installation by summer 2022 (Meiden America 2019). These circuit breakers are unique because of their environmentally friendly classification and minimal maintenance requirements, resulting in reduced operational costs. The air-insulated vacuum breakers are free of GHGs and require less electric heat during the winter and less maintenance than traditional gas- or oil-insulated breakers.

The three 145 kV VCBs are the first dry-air vacuum circuit breakers of this size to be purchased in the world. Vacuum circuit-breaker technology is not new to GVEA. In 2012, GVEA installed a 69 kV air-insulated vacuum breaker and has since installed 24 more; all of which have performed exceptionally well in Alaska's extreme conditions. "GVEA has been sourcing environmentally sustainable circuit breakers for many years," said John Burns, GVEA President/CEO. "GVEA is committed to consistently pursuing technologies that will enable us to achieve efficiencies and reduce greenhouse gas emissions" (GVEA 2022).

2.2.2.3 Eversource, Mount Pleasant 2023:

Eversource is the largest electrical utility in New England, with over 4.4 million customers (Eversource 2024). On June 20, 2023, Hitachi Energy delivered the world's first eco-efficient EconiQ 420- kV DTB to Eversource. The breaker was installed at a 345 kV substation in mid-2023 (T&D World 2022). This is the first SF_6-free 420 kV circuit breaker installation in the world (Heimback 2023). This project supports the company's sustainability goals, including meeting targets to achieve carbon-neutrality in their operations by 2030. Replacing or reducing SF_6 in their 345 kV transmission system is a key part of that effort (T&D World 2022).

In 2023, Eversource also completed the $190 million Eastern Connecticut Reliability Program, which is composed of several upgrades to the electric grid, including infrastructure improvements to local substations and transmission lines, enhancements to system reliability, and communication between substations to assist customers. The upgrades included the installation of a clean air circuit breaker at Eversource's substation in Preston (T&D World 2024). This was the first eco-efficiency Clean Air Blue 115 kV circuit breaker installation in the U.S. (Eversource 2023).

2.2.2.4 Entergy, Vicksburg 2023:

Entergy Mississippi, LLC, provides electricity to approximately 461,000 customers in 45 counties. Entergy Mississippi is a subsidiary of Entergy Corporation, an integrated-energy company engaged in electric-power production, transmission, and retail-distribution operations. Entergy delivers electricity to three million utility customers in Arkansas, Louisiana, Mississippi, and Texas. Entergy owns and operates one of the cleanest large-scale U.S. power-generating fleets, with approximately 30,000 MW of electric generating capacity, including 7,000 MW of nuclear power. Headquartered in New Orleans, Louisiana, Entergy has annual revenues of $10 billion and approximately 12,500 employees (Entergy 2023).

Entergy recently installed a 123-kV Siemens Energy Blue circuit breaker at one of its substations in Vicksburg as part of its effort to achieve net-zero carbon emissions by 2050. The Blue circuit breaker is a replacement for a high-voltage OCB. The Blue circuit breaker uses clean air in combination with a vacuum interrupter to provide an SF_6-free switchgear (Wolf 2023). When crews installed the breaker, two Mississippi-based companies reached milestones. The installation was the first in Entergy's four-state service area and only the second U.S. dead-tank Blue circuit breaker in the country for the manufacturer (Entergy 2023). Manufactured in Richland, Mississippi, the Blue circuit breaker is a 123 kV high-voltage clean-air vacuum breaker. The gas-free breaker is a pilot project that will help Entergy understand how this kind of technology can help reduce its GHG footprint and emissions (Entergy 2023).

2.3 Conclusions from Utility Assessment:

The American power system is in the process of a massive expansion and renovation. This is being driven by the integration of renewable-energy sources, population changes, and new technologies like data centers and electric vehicles. Of the six utility case studies found in this scan, three of them installed their first piece of SF_6-free GIE in 2023, and one of them installed their first piece in 2022. Only one of the six utilities had used high-voltage SF_6-free equipment prior to the year 2020. It is clear to see that SF_6 alternatives have only begun to enter the market at scale. Despite this, rapid adoption of these products by multiple utilities suggests a clear demand for this technology in the market. Given the continued advancements in these technologies and their advantages over SF_6 equipment, it is likely that their adoption will increase in the near and long term.

Despite the growth in adoption of this technology, several barriers remain to adoption. Ranked in order of importance, these barriers are:

1. **Procurement lead times**

   While the demand for these products has been explosive since their introduction, the high-voltage varieties of non-SF_6 GIE are very recent entrants into the market, and most are still only at the level of low-rate initial production. The aggressive rate of infrastructure expansion motivates utilities to procure equipment as quickly as possible. Until production rates of the novel non-SF_6 products increase, conventional SF_6 GIEs will remain the primary option for equipment replacements and new construction.

2. **Functional performance**

   Sulfur hexafluoride is an exceptionally effective insulating material for GISs, which makes it difficult to replace from a technical standpoint. However, recent technological advances have brought products into the market which can compete with SF_6 in most performance areas, although none are able to outcompete SF_6 in all of them. This is particularly true in the extremely high-voltage arena, where SF_6 remains the only option for GIEs at voltages above 420 kV as of 2024.

3. **Equipment longevity**

   One of the advantages to the chemical stability of the SF_6 molecule is that it does not corrode equipment over time. While this is true for technical air solutions as well, the flouronitrile alternatives are not as stable. This raises concerns about the ultimate longevity of the devices which cannot be answered without years of proven performance in the field. This factor is particularly important because the technical air products are not available for voltages above 145 kV.

4. **Viability of SF_6 monitoring programs**

   While it is generally understood that SF_6 is a potent GHG, emission rates for SF_6 have plummeted in the U.S., despite the growth in its use. This is due to the advent of gas-leak monitoring programs, and renewed efforts to repair leaking equipment. For most utilities, such efforts are less cost-intensive than replacing the equipment outright and alleviate some of the pressure to phase-out the use of SF_6.

3. Manufacturer Scan

If the goal of phasing out SF_6 is to be achieved, several major factors must align. First, viable technologies must exist that can replace SF_6 systems. Second, there must be a market demand for the new non-SF_6 systems. Finally, the manufacturers must be able to effectively transition their plants or develop new production to build the new technologies to meet emerging market demands. During any technology transition, many risk factors across an industry affect both producers and consumers. Supply-chain imbalances will be created as the markets and supply-chain relationships reset to a new normal. This section will report information collected about and from manufacturers of non-SF_6 high-voltage equipment. The information presented is an accumulation of publicly available literature, marketing material, and some conversations with sales representatives and engineers.

A cursory examination of the industry quickly leads to a short list of primary manufacturers that compete to replace SF_6 in the high-voltage (above 72 kV) equipment market. Other companies' market non-SF_6 equipment; however, they (like Schneider Electric) are focused on medium-voltage switchgears or are smaller manufacturers. These other companies should not be dismissed as unimportant elements of the supply base for transitioning away from SF_6, but they are not the focus of this scan. This report focuses on the large manufacturers with the technology, resources, and large manufacturing facilities necessary to supply non-SF_6 GIE in bulk at the high-voltage level.

3.1 Survey of Manufacturers and their non-SF_6 Products

3.1.1 Siemens

Siemens has a commercial line of products known as Energy Blue high-voltage products. These products are a combination of vacuum and clean-air insulation technologies for a variety of breakers and insulated lines. Siemens is advertising that they will soon have additional 420 kV breaker options. Siemens produces its Blue line in Germany, but also has a large manufacturing capability in the U.S. Siemens has over 20 million hours of commercial operation on their Blue line with 1500 units currently in operation. They have sold more than 4200 units globally. Blue clean-air circuit switchers are reportedly capable of reliable short-circuit interruption at voltage levels above 69 kV in temperatures as low as 50°C. This capability eliminates the need for external heaters (Maloney 2020).

Siemens is marketing a range of new products from 72.5 to 420 kV. They are working to develop additional products for the 420 kV market, but currently do not have any options for voltage levels above 420 kV.

Non-SF_6 Equipment	Voltage Class
Wind Tower GIS	72 kV
GIS	145, 420* kV
GIB	420 kV
LTB	145, 420* kV
DTB	145 kV

Table 1. Siemens Blue Line.

3.1.2 General Electric

General Electric has developed its g^3 product line, which includes breakers up to 145 kV and insulated lines and a breaker up to 420 kV. GE's g^3 line features a gas mixture made up of CO_2, O_2, and C4-FN (Ficheux, Laruelle and Walter 2021). GE has established partnerships with leading industrial gas suppliers, including Air Liquide, Dilo, and Inventec. These gas-handling experts have developed specialized equipment and processes for g^3 mixing. They are currently developing additional 245- and 420 kV breakers. GE manufactures in the U.S. and globally and has installed g^3 non-SF_6 equipment at over 75 sites. GE's g^3 products have been adopted by 16 different utilities around the world (Ficheux, Laruelle and Walter 2021). While g^3 uses a GHG, it is far less impactful to the environment than SF_6, the C4-FN gas technology is essential to the elimination of SF_6 at voltages above 145 kV, based on current technologies and constraints.

The g^3 development road map is available on GEs website (GE Vernova 2023). A listing of g^3 products currently available along with products planned up to 2026 are listed as Table 2 (GE Vernova 2024).

Non-SF_6 Equipment	Voltage Class
GIS	72, 145, 175*, 245, 420, 550* kV
GIL	362, 420 kV
LTB	72.5, 100, 123, 145, 420*, 550 kV
DTB	72*, 145, 170*, 245*, 362*, 550* kV

Table 2. General Electric g^3.

* planned products

3.1.3 Hitachi

Hitachi has a product line known as the EconiQ high-voltage portfolio. They have mapped their development efforts from now until 2027 including a range of breaker types, voltages, and insulated lines. This roadmap can be found on Hitachi's website (Hitachi 2024a). They currently have a 420- kV GIS breaker and are planning to make 550 kV GIS breakers available in late 2024. Hitachi Energy has booked orders for over 65 units of its groundbreaking EconiQ 420-kV DTBs (Hitachi 2024). Their gas-insulated technologies also depend on NOVEC gas. Hitachi manufactures in the US and the EconiQ products they currently offer are presented as Table 3.

Non-SF_6 Equipment	Voltage Class
GIS	72.5, 145, 170*, 245*, 420, 550 kV
GIL	245*, 420, 550 kV
LTB	72.5, 145, 170, 245, 420 kV
DTB	72.5*, 145*, 245*, 420, 550 kV
Insulated Line Gas Retrofit	420, 550 kV

Table 3. Hitachi EconiQ portfolio.

A notable service provided by Hitachi is the EconiQ retrofill for GILs ELK-3, 420 kV. The EconiQ retrofill service uses a C4-FN-based gas mixture to replace SF_6 in existing GILs. In this process, SF_6 from the installed lines is evacuated, and each GIL is then flushed to remove any humidity. The new gas mixture is then filled into the GIL, and the switchgear is reenergized to connect back to the grid. The process is relatively quick and enables the reuse of passive gas components designed for SF_6 to be converted into non-SF_6 equipment (Hitachi 2024b). Hitachi advertises minimum changes are required for the existing equipment. This service has the potential to replace SF_6 in some applications without needing to replace all installed equipment.

3.1.4 Mitsubishi

Mitsubishi currently manufactures five 72 kV vacuum circuit breakers, and they have facilities in the U.S. to produce their systems. The only offering at the transmission-voltage level is the 72 kV vacuum breaker. While this breaker will undoubtedly aid in the transition away from SF_6, Mitsubishi's non-SF_6 product line is largely focused on distribution systems. To compete in the high-voltage, non-SF_6 space, their product offerings will need to catch up to Hitachi, GE, and Siemens.

3.1.5 Schneider

Schneider Electric advertises their non-SF_6 product line AirSeT technology, which focuses on medium-voltage switchgears. Currently, no high-voltage options are offered in the AirSeT product line, and it is not clear whether Schneider intends to develop any. Because Schnider focuses on medium voltage equipment, and this scan was focused on high-voltage non-SF_6 technology, responses from Schnieder representatives were weighted less than responses from GE, Hitachi, and Siemens.

3.1.6 Toshiba

Toshiba offers a single 72.5 kV "origin-gas" breaker system under the Aeroxia brand. This system is manufactured and marketed in Japan. However, the technology was developed in partnership with Meiden, with the intent to develop an 84 kV option in the future. After deployments in Japan, the stated intent is to market the product globally (Toshiba Energy Systems & Solutions Corporation, Meidensha Corporation 2021). Toshiba was mostly removed from consideration for this survey due to its limited offerings and focus on Japan.

3.1.7 Meiden

Meiden produces non-SF_6 equipment using dry-air and vacuum technology. Currently, they offer 145- and 72.5 kV vacuum breakers. This company manufactures in the U.S. and has partnered with Toshiba to develop this technology. The two companies commercialized first in Japan and then in the rest of the world. These systems are currently available in the US, with at least one deployment for GVEA, located in Fairbanks, Alaska.

3.2 Summary of Manufacturer Interviews

In addition to a product and manufacturer survey, additional questions were explored informally with the manufacturers' representatives during the T&D Institute of Electrical and Electronics Engineers trade show. The questions explored were:

- What are your supply chain bottlenecks for the manufacturing of non-SF_6 equipment? I.e., what components are the most expensive/ difficult to procure?
- If demand were to increase significantly for non-SF_6 equipment, how long would it take to ramp up production to meet demand?
- Do you have U.S.-based manufacturing and assembly capability for non-SF_6 equipment? If not, what would it take to increase your U.S.-based capabilities?
- Is there a sufficient base of labor with sufficient skillsets to support the U.S.-based manufacture of non-SF_6 equipment?

- What is the anticipated lifetime for non-SF_6 equipment? How does this compare to SF_6 equipment?
- What are your typical lead times for non-SF_6 equipment? Are these getting shorter or longer?

The responses have been aggregated into a general response under each question. When a specific response diverged significantly from the common responses they were identified and attributed as appropriate.

Question 1: What are your supply chain bottlenecks for the manufacturing of non-SF_6 equipment? I.E., what components are the most expensive/ difficult to procure?

All manufacturers interviewed indicated the supply chain is currently robust enough to provide all materials and components needed to build their non-SF_6 products and keep their production lines fully employed. New technologies under development are unknown, but there was a sense of confidence that the components for new products could be properly sourced. None of the people interviewed expressed concern over their supply chains. The open-source information collected did not indicate any issues with raw materials or procuring components for building non-SF_6 high-voltage equipment. Some manufacturers mentioned a mild concern with single-source suppliers in their supply chains but were actively working to mitigate those risks (no specifics were given on "single-source suppliers"). Normal business operations in the supply chain results in business divisions being sold and purchased, new divisions being stood up, or products being divested, etc. The standard corporate churn requires manufacturers to constantly manage the supply chains for their products, which they all do. One noteworthy consideration is that 3M has decided to discontinue NOVEC gas. The manufacturers indicated that this is not a concern because there are other suppliers in the market capable of providing this material.

Question 2. If demand were to increase significantly for non-SF_6 equipment, how long would it take to ramp up production to meet demand?

Every manufacturer had the same initial response to this question. That answer was "it depends." Every manufacturer of high-voltage non-SF_6 equipment already on the market has experienced a significant increase in orders. Manufacturers that previously installed only dozens of projects now have hundreds of orders queued. Orders for SF_6-free GIEs are coming from many utilities in states that currently regulate the use of SF_6 or plan to do so in the future. The backlog for non-SF_6 equipment is because order volume has increased quickly in a short amount of time. The total capacity of the manufacturers' production lines is the bottle neck. With the very recent and significant uptick in orders, there is a concerted effort to find and develop production efficiencies or innovative methods to increase output with existing production capabilities. The manufacturers indicated that these efforts can potentially increase production rates by 20–30%.

Additional production beyond the 20-30% would generally require construction of new manufacturing facilities. Costs on the order of $1 billion were suggested for standing up a new production facility, although any numbers suggested were strictly notional. The manufacturers expressed concern about overbuilding production capacity to meet a rapid transition and then being unable to use that capacity long term. The general approach taken by most of the manufacturers is to observe the growing market demands resulting from the electrification of developing nations, the decarbonization of the developed world, new construction driven by data centers and other organic growth factors and trying to match their production capacity to the sustained long-term demand. One notable exception is Hitachi. Their non-SF_6 technology is close enough to their SF_6 equipment that their production lines can produce both systems. This gives them the capability to shift their production capacity over to non-SF_6 equipment quickly, or as the market dictates. The Hitachi approach of developing their non-SF_6 systems assembly to be interoperable with their SF_6 production line was a brilliant move that could very quickly provide a competitive advantage in the non-SF_6 market if demand continues to push wait times further.

Question 3. Do you have U.S.-based manufacturing and assembly capability for non-SF_6 equipment? If not, what would it take to increase your U.S.-based capabilities?

Yes, mostly. Hitachi, GE, Meiden, Mitsubishi, and Siemens have U.S. manufacturing capabilities in addition to a collection of overseas capabilities. Toshiba is in Japan. Increasing its U.S. manufacturing capacity is based on the business case for doing so, the current approach is to improve production and efficiency for existing production lines. Meeting global market demand is going to be an effort that will leverage the full scope of existing global manufacturing capabilities. Some of the manufacturers have indicated their intent to expand in the U.S. (Toshiba Energy Systems & Solutions Corporation, Meidensha Corporation 2021), but the scan did not identify and any new production facilities in development.

Question 4. Is there a sufficient base of labor with sufficient skillsets to support the U.S.-based manufacture of non-SF_6 equipment?

Yes, manufacturing has been performed in the U.S. for years, skilled labor can perform the work and train additional people to do the same. The people we talked to did not seem deeply concerned about the labor market. There was a sense of confidence that they were able to maintain production and grow it if necessary. Although there was a general sense of needing to manage the workforce in a way that is stable, sustainable for production, business, and jobs.

Question 5. What is the anticipated lifetime for non-SF_6 equipment? How does this compare to SF_6 equipment?

The new non-SF_6 technologies are anticipated to last for 50 years or more and to have greatly reduced maintenance costs. This approximately compares to a life expectancy of 30–50 years for SF_6 equipment. The actual life expectancy is determined by maintenance and service history. New non-SF_6 technologies are supposed to last through many more full-current faults than traditional SF_6 equipment. This was a point of pride for the folks we talked to. An SF_6 breaker can tolerate 5–6 full-current faults while the non SF_6 equipment was advertised with much higher numbers: dozens to hundreds. The absolute proof of more than 50-year durability will only be available 50 years from any installation; however, the comparative testing in tandem with the service histories since the initial installations of the first non SF_6 systems makes a compelling case that the new technology will provide the durability claimed.

Question 6. What are your typical lead times for non-SF_6 equipment? Are these getting shorter or longer?

The longest lead time provided by a manufacturer for an existing technology was roughly 3 years. The shortest was 1 year (for a 145 kV vacuum breaker system). All the other leads times fell between these two numbers; however, as orders increase and production improvements are made, the lead times are variable. Several of the manufacturers indicated that utility customers were beginning to share infrastructure development plans out as far as 10 years. This is a strategy to reduce risk in the supply chain and to mitigate lead-time challenges for both the utilities and manufacturers.

3.3 Analysis

The key enablers for non-SF_6 technologies are the manufacturers developing the technology needed to build the grid without SF_6. In this group, the three standout companies are Siemens, GE, and Hitachi because they have the widest range of product options and are pushing non-SF_6 technologies to higher voltages. The other companies reviewed can be seen as key enablers for broadened production capacity.

As utilities like PG&E deploy a voltage-based phase-out approach, the demand for non-SF_6 products will continue to grow. As new technologies are made available, early adopters will continue phasing out deployment of SF_6 equipment in near-real time with each new technological development. The manufacturers are preparing new technologies and looking for ways to improve production capacity for current demand while keeping a very careful eye on upcoming regulations. To mitigate long lead times, some utilities are sharing 10-year development plans with the manufacturers, thus reducing procurement risks for utilities while also taking risk out of the manufacturers' production plans.

Uncertainty regarding the timing and structure of future regulations is one signal leading to caution in the manufacturing and utility sectors. Industry professionals know something must be done, but the companies in this market want less risk. A logical, phased regulatory role out would give manufacturers the clarity they need to make investment decisions about production capacity and enable utilities to plan and coordinate long lead procurements. The complexity and uncertainty for new equipment comes with regulation timing, phase-in timelines, available technology, and maturity of the supply chain.

Ramping up capacity with existing production lines should be able to generate 20–30% greater output. Additional output would likely require building new facilities. The one exception is Hitachi, which can convert current SF_6 production capacity over to non-SF_6 equipment production. These increases are not sufficient to replace the current volume of SF_6 equipment being deployed, and certainly not enough to meet future demands. Additional non-SF_6 production capacity will need to be developed while current SF_6 production capacity will need to be abandoned. This must occur in times when demand for both SF_6 and non-SF_6 equipment exists to decarbonize developed nations and support the needs of developing ones. Converting or abandoning SF_6 production lines at this point would likely delay decarbonization efforts and could result in a cascade of negative economic impacts.

The current deployment rate for non-SF_6 equipment spans a range for the different manufacturers. Some are deploying ~1/3 of their new systems as non-SF_6 while others are deploying ~1/10. Some have new technologies that are not online yet. The Prescient Strategic Intelligence economic analysis indicates the non-SF_6 market is about 1/3 of the total global market right now and is likely to stay at approximately 1/3 of the market for the next 6 years. The two markets are projected to grow in tandem (P&S Intelligence 2023). The likely deployment rates for non-SF_6 equipment over the next 5–10 years will grow a little faster than the deployment of SF_6. Unfortunately, the SF_6 systems installed over the next 10–20 years will likely remain installed until the end of the equipment's service life and the greenhouse impacts of SF_6 will remain, even if it only leaks 1% annually.

Manufacturers are having no difficulty sourcing the materials they need to assemble their products, nor are there any specific monopolies that restrict production. The bottleneck is the production lines themselves, which have already ramped up from dozens of orders to hundreds in the last year.

The demand is coming from both foreign and domestic utilities that are being regulated to reduce or eliminate SF_6 or from utilities that anticipate elimination or heavily regulation of SF_6. Lead times primarily result from the demand for non-SF_6 switchgears. If this demand endures, it will provide a powerful motivation to develop the capacity to meet the demand. A good set of regulations could provide the stable backdrop needed for both utilities and manufacturers to make meaningful strides toward removing SF_6 from the electric power grid.

3.4 Assessment of Domestic Manufacturing Potential

The domestic manufacturing potential for the U.S. is promising. A significant number of systems have been developed and are commercialized; however, nothing above 420 kV is currently available. The technologies needed to replace SF_6 entirely do not exist. Between now and 2027, systems up to 550 kV are being developed and will be made available by the manufacturers. However, even with those technologies online, there will still be no options for the 765 kV portions of the transmission system.

Current technology options cannot fully replace SF_6 right now, and the new technologies mapped out on the development pathways by manufacturers will not create all the technology needed to eliminate the need for SF_6. It is critical to recognize a complete ban on SF_6 would be crippling. Over 60% of the GIS market is below 220 kV; this is where most non-SF_6 technology is competing, making a phased approach to voltage a reasonable option for restricting SF_6.

The three companies with the most-comprehensive product offerings (Hitachi, GE, and Siemens), all manufacture in the U.S. With sustained U.S. market demand increases, the case for investing in U.S. production capacity will grow stronger. The production-line interoperability that Hitachi has built into their systems gives them the ability to switch their entire capacity from SF_6 to non-SF_6 very quickly. That transition is going to be based entirely on the orders for non-SF_6 gear that Hitachi receives.

4. Conclusion

The current challenge for reducing SF_6 is a rapid expansion of global demand for electrical-power systems and infrastructure. Due to current demand, both SF_6 technology and non-SF_6 technology are being deployed into the world's power grids. While non-SF_6 technology deployments are growing, SF_6 deployments are growing at nearly the same rate. By 2030, both categories will have nearly doubled. The continued growth of SF_6 deployments is environmentally problematic. The critical questions to ask are what is being or can be done, and who can do it.

Utilities. Some utilities have been proactive in coordinating long-term plans with manufacturers to mitigate risks for both parties. This is a good practice that should be promoted to encourage investment by manufacturers in new production capacity and get non-SF_6 equipment to the utilities in a timely manner. The utilities that were reviewed are not averse to purchasing non-SF_6 equipment to build out new infrastructure or replace retiring equipment where the new technology would fit and perform the needed function. There is, however, uncertainty about how potential new regulations might penalize utilities or delay critical projects.

Manufacturers. Manufacturers believe the demand for new non-SF_6 and SF_6 equipment will continue to grow, but they want to watch the market carefully to match capacity with demand. A mismatch could be extremely detrimental. Predictability in the regulatory space would provide needed clarity regarding SF_6 phase-out or partial phase-out requirements and timelines. New regulations would need to recognize production capacity, technologies available, technologies in development, and technology not projected in development plans. The PG&E approach has been aggressive and was motivated at least in part by the SF_6 regulatory environment in California. A careful look at the voltage based SF_6 phase out is a good indicator of how such a process could potentially be accomplished in the rest of the U.S. Manufacturers will need to retire SF_6 capacity and replace it with non-SF_6 capacity. If demand for SF_6 equipment endures, retiring profitable production capacity is a step a manufacturer cannot take economically. The other option is to increase the cost of SF_6 to the point that only non-SF_6 equipment is reasonable for any utility to purchase. Either way, eliminating SF_6 will require forces external to the natural market to be applied.

The Department of Energy (DOE). DOE could develop an SF_6 phase-out roadmap in coordination with utilities and manufacturers that could be tailored for states and Environmental Protection Agency policy makers. This map would act as a base line for developing logical regulatory approaches to reduce or eliminate SF_6. The DOE could also partner with manufacturers to develop new technologies that would improve production using existing capacity, or to develop extra high-voltage non-SF_6 insulated switchgears.

5. Works Cited

[1] 3M. 2021. "3M™ Novec™ 5110 Insulating Gas." Accessed May 20, 2024. https://multimedia.3m.com/mws/media/1132123O/3m-novec-5110-insulating-gas.pdf?&fn=3M-Novec-5110-Insulating-Gas-TDS-FINAL_R6.pdf.

[2] 3M. 2022. "Technical Data: 3M™ Novec™ 4710 Insulating Gas." Accessed May 16, 2024. https://multimedia.3m.com/mws/media/1132124O/3m-novec-4710-insulating-gas-tech-data-sheet.pdf?&fn=Novec-4710-Insulating-Gas-TDS_R13.pdf.

[3] Ficheux, A., A. E. Laruelle, and M. Walter. 2021. "White Paper: g^3: The SF_6-Free Solution in Practice." Accessed May 20, 2024. https://resources.grid.gevernova.com/SF6-free-solutions/white-paper-g3-the-SF6-free-solution-in-practice#main-content.

[4] Devins, J. C. 1980. "Replacement Gases for SF_6." IEEE Transactions on Electrical Insulation EI-15(2): 81-86. https://doi.org/10.1109/TEI.1980.298243.

[5] Manna, D., R. Bess, and D. Ghosh. n.d. "Role of Hybrid SF_6 Switchgears Towards Sustainability." Accessed May 16, 2024. https://www.tamco.com.my/index.php/role-hybrid-SF6-switchgears/.

[6] Dilo. 2023. "History and Evolution Of SF_6 Gas." Accessed May 20, 2024. https://dilo.com/blog/article/history-and-evolution-of-SF6-gas#:~:text=SF6%20gas%20history%20as,electrical%20transmission%20and%20distribution%20industry.

[7] Electrical4U. 2020. "SF_6 Gas or Sulfur Hexafluoride Gas Properties." Electrical4U. Accessed May 01, 2024. https://www.electrical4u.com/sulfur-hexafluoride-SF6-gas-properties/.

[8] Yedinak, E., K. Lentijo, and I. C. Kizilyalli. 2023. Eliminating SF_6 from Switchgear. In Direct Current Fault Protection, by Z. John Shen, Daniel W. Cunningham Isik C. Kizilyalli, 409–427. Springer.

[9] Entergy. 2023. "Entergy Mississippi, Siemens Energy work to create cleaner power grid." Accessed May 20, 2024. https://www.entergynewsroom.com/news/entergy-mississippi-siemens-energy-work-create-cleaner-power-grid/.

[10] Eversource. 2023. "Carbon Neutral by 2030." Accessed May 20, 2024. https://www.eversource.com/content/residential/about/sustainability/carbon-neutrality.

[11] Eversource. 2024. "Our Company." Accessed May 29, 2024. https://www.eversource.com/content/residential/about/our-company.

[12] GE Vernova. 2024. "g^3 G3- GE's SF_6 SF_6Alternative For High Voltage Applications." Accessed May 20, 2024. https://www.gevernova.com/grid-solutions/hvmv_equipment/catalog/g3/.

[13] GE Vernova. 2021. "GE and Hitachi ABB Power Grids sign landmark agreement to reduce environmental impact in the electrical transmission industry." Accessed May 20, 2024. https://www.gevernova.com/grid-solutions/press/gepress/ge-and-hitachi-abb-power-grids-sign-landmark-agreement.htm.

[14] GE Vernova. 2023. "g3 Roadmap." Accessed May 30, 2024. https://www.gevernova.com/grid-solutions/products/reference/g3-roadmap-infographic-gea-33147f-202309-r31.pdf.

[15] GE Vernova. 2024. "SF_6 and g3 Gas-Insulated Solutions." Accessed May 30, 2024. https://www.gevernova.com/grid-solutions/hvmv_equipment/gis.htm.

[16] Gräf, T. 2019. "Operational Aged Switchgear with the Age up to 50 Years – Investigations, Testing, Results – Considerations for Design and Operation of New Switchgear." In proceedings of the 21st International Symposium on High Voltage Engineering, Budapest, Hungary, August 26–30, 2019. Springer. pp 417–428.

[17] GVEA. 2022. "GVEA Purchases the World's First Eco-friendly 145kV Vacuum Circuit Breakers." Accessed May 20, 2024. https://www.gvea.com/news-releases/gvea-purchases-the-worlds-first-eco-friendly-145kv-vacuum-circuit-breakers/.

[18] Heimbach, M. 2023. "Now Ready: SF_6-Free Solutions for Sustainable Power Grids." Accessed May 20, 2024. https://www.world-energy.org/article/33680.html.

[19] Hitachi. 2024a. "Accelerating the transition towards a carbon-neutral energy future." Accessed May 30, 2024. https://www.hitachienergy.com/us/en/products-and-solutions/high-voltage-switchgear-and-breakers/econiq-eco-efficient-hv-portfolio.

[20] Hitachi. 2024b. EconiQ retrofill for gas-insulated lines ELK-3, 420 kV. Accessed May 20, 2024. https://www.hitachienergy.com/products-and-solutions/high-voltage-switchgear-and-breakers/econiq-eco-efficient-hv-portfolio/econiq-retrofill-gil-elk-3-420kv.

[21] *Hitachi. 2024c. "EconiQ™ Eco-efficient high-voltage portfolio." Accessed May 20, 2024. https://library.e.abb.com/public/90d5981897264d29b1832ae9974d8a5a/EconiQ_HV_portfolio_9AKK107992A1307_AF22_EN.pdf?x-sign=f%20mygn8/4FdkFCxVQlLxzRZm8b8pF9Scx9AudAN4SaN8UMWsMkEsPNkbkeHmlfRS.*

[22] *Hitachi. 2024d. "North America leads the way in the journey toward an* SF_6*-free world." Accessed May 20, 2024. https://www.hitachienergy.com/news/features/2024/03/north-america-leads-the-way-in-journey-toward-SF6-free-world.*

[23] *Hitachi. 2021. "The Big Switch: A game-changing technology towards a carbon-neutral future." Accessed May 20, 2024. https://www.hitachienergy.com/about-us/events-and-webinars/2021/the-big-switch-a-game-changing-technology-towards-a-carbon-neutral-future.*

[24] *Loizou, L. et al. 2023. "Application of* SF_6 *Alternatives for Retro-filling Existing Equipment." CIGRE Science & Engineering 27: A3.10103. https://cse.cigre.org/cse-n027/application-of-SF6-alternatives-for-retro-filling-existing-equipment.html.*

[25] *Maloney, P. 2020. "Traverse City Light and Power becomes first utility to deploy* SF_6*-free circuit switchers." Accessed May 27, 2024. https://www.publicpower.org/periodical/article/traverse-city-light-and-power-becomes-first-utility-deploy-SF6-free-circuit-switchers.*

[26] *Meiden America . 2019. "Meiden America Switchgear, Inc. delivers world's first ecofriendly 145kV dead tank vacuum circuit breaker, free of harmful* SF_6 *gas." Accessed May 20, 2024. https://www.meidenamericaswitchgear.com/news-releases/blog-post-title-one-fd4ea.*

[27] *Myhre, G., D. et al. 2013. "Anthropogenic and Natural Radiative Forcing." In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment , by T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, Stocker, 659-740. Cambridge, United: Cambridge University Press.*

[28] *P&S Intelligence. 2023. "Global Gas Insulated Switchgear Market. Market Assessment, Prescient & Strategic Intelligence." Prescient & Strategic Intelligence 12496: 320. https://www.psmarketresearch.com/market-analysis/gas-insulated-switchgear-market.*

[29] *Parnell, D. 2024. "An Introduction to Gas Insulated Electrical Substations." Accessed May 16, 2024. https://www.cedengineering.com/userfiles/E03-043%20-%20An%20Introduction%20to%20Gas%20Insulated%20Electrical%20Substations%20-%20US.pdf.*

[30] *Simmonds, P. G. et al. 2020. "The increasing atmospheric burden of the greenhouse gas sulfur hexafluoride (SF_6)." Atmospheric Chemistry and Physics 20(12): 7271–7290. https://doi.org/10.5194/acp-20-7271-2020.*

[31] *Rak, T. 2020. "PG&E Phases Out SF_6 in HV Substation GIS." Accessed May 20, 2024. https://www.tdworld.com/substations/article/21121380/pge-phases-out-SF_6-in-hv-substation-gis.*

[32] *Siemens Energy. 2024. "Siemens Energy Blue Portfolio." Accessed May 30, 2024. https://p3.aprimocdn.net/siemensenergy/88bb59e4-f5d2-4d57-aefa-b0840170f33f/2020-08--Siemens-Energy-Blue-portfolio-customer-presentation-EN-DAM-version-pdf_Original%20file.pdf.*

[33] *Siemens Energy. 2020. "Siemens Energy Commissions First Emissions-Free, Clean Air Circuit Switcher." Accessed May 20, 2024. https://www.siemens-energy.com/us/en/home/press-releases/siemens-energy-commissions-first-emissions-free-clean-air-circuit-switcher.html.*

[34] *T&D World. 2024. "Eversource Completes $190 Million Eastern Connecticut Reliability Program." Accessed May 20, 2024. https://www.tdworld.com/smart-utility/article/21284766/eversource-completes-190-million-eastern-connecticut-reliability-program.*

[35] *T&D World. 2022. "Hitachi Energy, Eversource Install EconiQ 420-kV Circuit Breaker."Accessed May 20, 2024. https://www.tdworld.com/smart-utility/article/21250056/hitachi-energy-hitachi-energy-eversource-install-econiq-420-kv-circuit-breaker.*

[36] *T&D World. 2018. "PG&E to Use SF_6-Free High-Voltage Products From Siemens." Accessed May 20, 2024. https://www.tdworld.com/overhead-transmission/article/20972022/pge-to-use-SF_6-free-high-voltage-products-from-siemens.*

[37] *Uchii, T. et al. 2022. "Recent Development of SF_6." Accessed May 20, 2024. http://www.cigrecolombia.org/Documents/Memorias/Paris%20CIGRE%20Session%202022/2.Presentations/4.Poster%20session/A3%20Posters/10643.pdf.*

[38] *Toshiba. 2024. "The Permanent SF_6-free Solution." Accessed May 16, 2024. https://www.global.toshiba/content/dam/toshiba/ww/products-solutions/transmission/products-technical-services/substation-equipment/pdf/TOSHIBA_AEROXIA_Brandbook_20220803.pdf.*

[39] *Toshiba Energy Systems & Solutions Corporation, Meidensha Corporation. 2021. "Toshiba and Meidensha to develop GIS jointly using natural origin gases." Accessed May 27, 2024. https://www.global.toshiba/ww/news/energy/2021/06/news-20210621-01.html.*

[40] *United Nations. 1998. "Kyoto Protocol to the United Nations Framework Convention on Climate Change." Accessed May 16, 2024. https://unfccc.int/resource/docs/convkp/kpeng.pdf.*

[41] *Tamco. n.d. "WHITE PAPER: Role of Hybrid* SF_6 *Switchgears Towards Sustainability." Accessed May 20, 2024. https://www.tamco.com.my/index.php/role-hybrid-*SF_6*-switchgears/.*

[42] *Widger, P., and A. Haddad. 2018. "Evaluation of* SF_6 *Leakage from Gas Insulated Equipment on Electricity Networks in Great Britain." Energies 11(8): 2037. https://doi.org/10.3390/en11082037.*

[43] *Wolf, G. 2023. "The Power Grid's Gas Problem." Accessed May 20, 2024. https://www.tdworld.com/substations/article/21263945/the-power-grids-gas-problem.*

[44] *Zhaolun Cui et al. 2024. "Recent progresses, challenges and proposals on* SF_6 *emission reduction approaches." Science of The Total Environment 906(9): 167347. http://dx.doi.org/10.1016/j.scitotenv.2023.167347.*