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Moving Towards Carbon-Neutral High-Voltage Switchgear by Combining Eco-Efficient Technologies

Michael GATZSCHE[1]
Ueli STRAUMANN[1]
Patrick STOLLER[1]
Moritz BÖHM[1]
Saskia BUFFONI-SCHEEL[1]
Henrik LOHRBERG[2]
Manuel NAEF[1]
Freddy VON ARX[1]
Adrian SKEA[1]

Hitachi Energy
Switzerland[1], Germany[2]
michael.gatzsche@hitachienergy.com

SUMMARY

The transition towards a carbon-neutral energy system is a strong motivation for system operators and equipment manufacturers to also reduce the carbon footprint of equipment in the power grid. Specifically, for high-voltage switchgear, there are three main sources for CO_2 equivalent emissions:

- Gas losses: CO_2 equivalent of insulating gas that escapes to the atmosphere
- Grey energy: necessary for material production and transportation of the equipment
- Power losses due to Joule heating by operating current

Today, high-voltage switchgear mainly uses sulfur hexafluoride SF_6 as insulating and arc quenching medium. For more than 50 years, due to its excellent technical properties, SF_6 technology has enabled compact and reliable substations. However, SF_6 has a high global warming potential GWP = 23 500, which means over a 100-year period each kilogram SF_6 released to the atmosphere makes the same contribution to global warming as 23 500 kg CO_2. The high GWP leads to the fact that gas leakage is the main portion of the carbon footprint of SF_6 gas-insulated switchgear, even with a high standard of sealing technology and gas-handling procedures [14]. At the same time the concentration of SF_6 in the atmosphere is increasing annually [11]. Much of this is due to the expanding installed fleets of gas-insulated switchgear, which release increasing volumes of SF_6 as they age if they are poorly maintained.

This is the main motivation for developing eco-efficient switchgear based on SF_6 alternative technology, for ensuring its acceptance by users and that it quickly becomes a significant fraction of newly installed equipment. Manufactures and users have decades of experience in applying SF_6 based technology and in making it a highly effective and reliable technology. Thus, it is beneficial if a large portion of this experience can be applied to the new technology.

Regarding the installed base, in many cases equipment will reach its natural end of life and will be decommissioned and replaced by new eco-efficient equipment. However, as the design life of

switchgear is usually around 50 years, an alternative solution will need to be found for much of the equipment installed today, which contains SF_6, to avoid either the high write-off cost of early replacement or the cost of continuing SF_6 management.

In this contribution we assess the dielectric and switching performance of eco-efficient gas mixtures for application in high-voltage gas-insulated switchgear, as well as the effect the choice of gas has on the technical performance (size, scalability) of the products. Based on this initial assessment we identify a gas mixture based on C4 fluoronitrile (C4-FN) as the suitable basis for two key applications to lower carbon footprint:

- New equipment **eco GIS**: Design of a complete gas-insulated switchgear (GIS) including circuit breakers, disconnectors and fast-acting earthing switches based on a common platform C4-FN/CO_2/O_2 gas mixture.
- Installed base **retrofill**: Gas-insulated lines (GIL) where SF_6 is replaced onsite with a C4-FN/N_2/O_2 gas mixture without changing any primary equipment.

Based on the two target applications we detail the performed technology development and qualification with a focus on:

- Materials
- Health and safety
- Gas handling
- Life cycle assessment (impact category global warming)

Derived from the technology basics we describe equipment ratings and properties for new equipment—a 420 kV eco GIS—as well as a retrofill solution for the installed base, including first return of experience.

KEYWORDS

SF_6 alternatives, gas-insulated switchgear, GIS, transmission, switching, material compatibility, gas handling, health and safety, retrofill, sealing material, installed base

1 Introduction

In this contribution we compare eco-efficient SF_6 alternatives, current state of technology development and how the gas mixture used influences equipment design and carbon footprint based on the example of high-voltage gas-insulated switchgear. With a focus on gas mixtures containing the components carbon dioxide (CO_2), nitrogen (N_2), oxygen (O_2) and C4 fluoronitirile (C4-FN) we assess:

- technical performance for insulation,
- technical performance for switching in circuit breaker (CB) and non-CB applications,
- interaction with materials,
- operational health and safety and gas handling,
- life cycle assessment (LCA) with a focus on impact category global warming.

Derived from the basic technology, we describe two solutions for 420 kV, including first return of experience for:

- New equipment **eco GIS**: Design of a complete GIS including circuit breakers, disconnectors and fast-acting earthing switches based on a common platform C4-FN/CO_2/O_2 gas mixture.
- Installed base **retrofill**: Gas-insulated lines (GIL) where SF_6 is replaced on-site with a C4-FN/N_2/O_2 gas mixture without changing primary equipment.

2 Dielectric Design

In this section the performance of different gas mixtures is compared, following the concept shown in [13], but presented in more detail here.

Scalability of eco-gas solutions

In compressed gaseous insulation, inception of discharges is decided locally, typically at the scale of millimeters or even smaller. To prevent such inception of discharges in an economical manner, gas insulated systems are typically designed to yield only slightly inhomogeneous fields. Larger inhomogeneity typically occurs exclusively at defects and imperfections, such as mobile particles, scratches of surfaces and surface roughness.

In many cases the field distortions resulting from such defects can be described as follows:

- In case of larger defects, the field distortions are so far ranging that discharges incept at relatively low background fields in the form of partial discharges, which do not cross the entire insulating gap.
- In case of smaller defects (e.g., surface roughness), at inception, the voltage and background field are so high that a discharge will propagate across the entire insulating gap.

Thus, local discharge inception and the background field are decisive for breakdown. Special scaling, or more simply put a “performance hole” which can become dominant for longer gap lengths or higher voltages in the case of atmospheric air exposed to slow front voltages (switching impulses), does not play a role for SF_6 or the eco-gas-candidates considered as the insulating medium for high-voltage switchgear. Therefore, excessively high field strengths must be prevented from occurring across all voltage ranges, and the corresponding design limits remain practically the same over all voltage ranges, provided that the production environment and the quality of the manufactured equipment remains similar. As mentioned, in the case of smaller defects, the inception of partial discharge will result in sparkover and failure of the insulation. Therefore, (the local) discharge inception limits the performance of rough surfaces. Such inception occurs when the Streamer-criterion

$$\boldsymbol{K_{\mathrm{st}}} < \int_{\gamma} \boldsymbol{\alpha(E(x), p)\,\mathrm{dx}} \quad , \qquad (1)$$

is fulfilled, with α being the net ionization coefficient, K_{st} the Streamer-constant, γ the path along the field E and p the pressure of the gas.

As one of the consequences, the performance of gases, measured through parameters such as the withstand field $E_{\mathrm{w}}(p_o)$ at pressure p_o, does not rise linearly with the pressure p. To account for this, commonly used power-laws such as

$$\boldsymbol{E}_{\mathrm{w}}(\boldsymbol{p}) = \boldsymbol{E}_{\mathrm{w}}(\boldsymbol{p_o}) \left(\frac{\boldsymbol{p}}{\boldsymbol{p_o}}\right)^{\boldsymbol{k}} \quad , \tag{2}$$

with exponents $k < 1$ have been established [18]. In the following $k = 0.75$ will be used.
In connection with insulating higher voltage levels, practically the same design rules hold as for lower voltages. These circumstances make eco-gas insulated switchgear scalable with regard to addressing different voltage ranges: Holding the performance of the insulation media constant, voltage and resulting geometrical size are related linearly. Similarly, gaseous insulation with lower performance for a given voltage level, may be compensated by a corresponding linear scaling of the geometrical size of the equipment. Compensation of lower performance by pressure increase, however, is hindered by the fact that there is a less then linear change in withstand voltage with pressure.
In connection with such scaling, the question arises, whether the resulting designs based on the insulation performance of the specific (eco-)insulation gases are acceptable in terms of size. This aspect is highlighted in the following section.

Equivalency of eco-gas solutions
The performance of clean and smooth surfaces insulated with eco-gases or SF_6 (as present, for example, in dielectric type tests of new equipment) is limited by streamer inception. The net ionization coefficients for several gases are depicted in Figure 1.

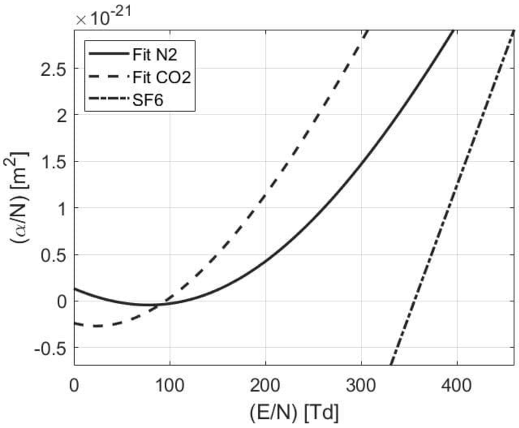

Figure 1. Comparison of density reduced net ionization coefficients α/N for N_2 and CO_2 (polynomial fit) and SF_6 (using linearized approach as used in textbooks, such as [17]) in dependence of the density reduced electric field E/N.

Evaluating the net ionization coefficients for certain pressures (or densities) shows that with increasing pressures, the curves shift towards higher field strengths. Adding electron-attaching additives to N_2 or CO_2, such as C4-FN, roughly results in lowering the curves and increasing their slope.
As a consequence, the net ionization coefficients of the different gases and gas mixtures at pressures yielding the same E_{crit}[1] are roughly similar. Thus, the streamer-criterion and therefore the performance of the different gases insulating rough electrodes may be approximately compared solely based on E_{crit}. By applying this approach, we define the SF_6-equivalency of a given eco-gas insulation by the pressure at which SF_6 would yield the same E_{crit}. The flatter slope of the net ionization coefficient in case of the pure carrier gases CO_2/O_2 and N_2/O_2 requires a correction by some percent (yielding somewhat larger performances) – this correction is adopted in the following.
Based on this concept of SF_6-equivelancy, together with utilizing (**2**), different eco-gases may be benchmarked. Such a comparison is shown in Figure 2, normalized to 450 kPa SF_6, a typical minimum functional pressure of GIS.

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[1] denoting the field, where the net ionization coefficient becomes zero

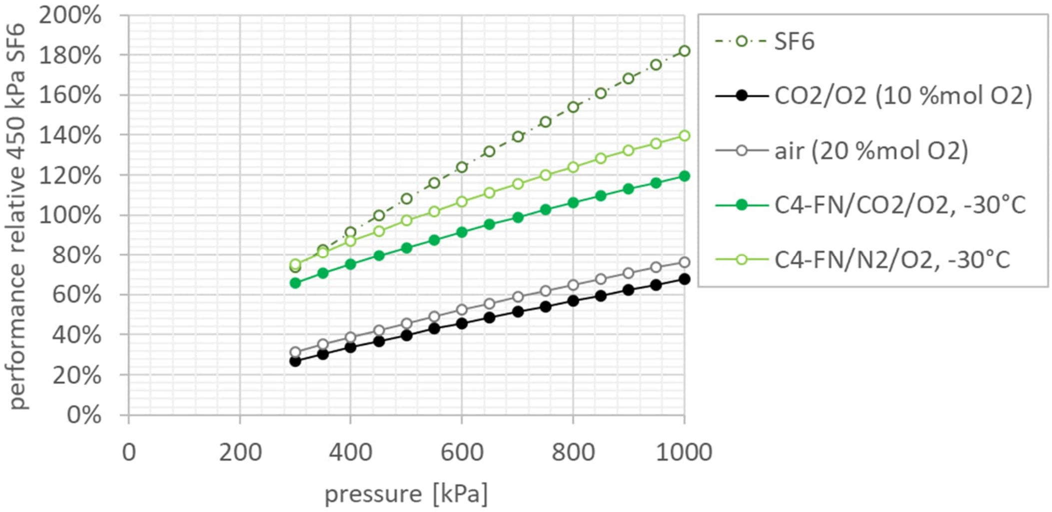


*Figure 2. Comparison of dielectric performance (i.e., withstand voltage or withstand field) of SF_6 and eco gas mixtures in clean insulation systems, with surface roughness being typical for GIS. This comparison bases on the concept of SF_6-equivalency (i.e., considering the performance of SF_6-insulation at pressure yielding the same E_{crit}). The pressure-dependence of the SF_6-performance is provided by the power law (**2**). The E_{crit}-values needed to establish the SF_6-equivalency of typical eco gases are taken by fitting the experimental data from [8] and [9]. The C4-FN based gas mixtures are defined to have a dew temperature of -30°C.*

The addition of the strongly electron-attaching C4-FN to N_2/O_2 or CO_2/O_2 yields a considerable increase of E_{crit}. For a technical reference application like a GIS busduct with 450 kPa SF_6-insulation (100 % performance in Figure 2), an eco-gas insulation with equivalent dielectric performance can be found based on C4-FN/CO_2/O_2 or C4-FN/N_2/O_2 mixtures and requiring a reasonable increase of the pressure. For the design of the equipment this would mean that the same dimensions as in the SF_6 reference application can be used.
Using an insulation gas with poorer performance, such as N_2/O_2 (air), on the other hand, results in the need to increase the size of the equipment to insulate the electrode system properly. This may (partly) be compensated by significantly increasing gas pressure; however, the less than linear performance increase with pressure must be considered (Eq. (2)).
Another aspect of SF_6 alternatives is the performance of the eco-gas in the presence of defects, such as metallic particles. The stability of switchgear in presence of such defects is checked in type tests in connection with dielectric integrity tests, which are performed after mechanical endurance tests or some power tests of switches and circuit breakers. Breakdown initiated by such defects is more complex and cannot be related simply to E_{crit}. As consequence, when substituting SF_6 in existing SF_6-insulated GIS designs with an eco-gas or gas mixture, design changes can provide a more optimal solution.
Understanding, considering and coordinating the performance of clean electrodes as well as the influence of defects will increase the reliability of electrical equipment in type, factory (i.e. routine) and commissioning testing and, most notably, in operation. Such reliability and stability also will reduce gas emissions due to less gas handling and less use of material (less material needs to be scrapped or replaced if fewer repairs are needed). Increased reliability and stability thus also significantly reduce the CO_2 footprint (section 6) of electrical equipment.

Summary of Dielectric Performance

Based on the dielectric performance assessment, gas mixtures containing C4-FN are suitable SF_6 alternatives for gas-insulated switchgear that allow to keep the compact dimensions of SF_6 based equipment. C4-FN/CO_2/O_2 is the optimal candidate for complete eco GIS including switching devices (see section 3 on switching performance). C4-FN/N_2/O_2 is the best candidate for retrofill application of non-switching components, because the same dielectric performance as SF_6 can be reached with minimal pressure increase. A big advantage is that design rules in use for SF_6 today can be adapted to C4-FN/CO_2/O_2 and C4-FN/N_2/O_2, which ensures scalability and reliability of the technology.

3 Switching

$C4\text{-}FN/CO_2/O_2$ gas mixtures have strong current interruption performance in addition to their good dielectric properties. The arc-extinguishing capability of these mixtures, combined with the good dielectric performance discussed in the previous section, enables the design and construction of compact, efficient, and reliable switching devices, including circuit breakers, fast-acting earthing switches, and circuit breakers. The same gas mixture used in passive components can be used for switching and short-circuit current interruption.

Circuit Breakers

Circuit breakers face the most severe conditions in the high voltage power grid—they must be capable of closing on ("making") and interrupting a range of different short-circuit faults. In addition, they are required to switch loaded and unloaded lines and cables, shunt reactors, and capacitor banks during routine operation. The short-line fault represents a fault that often plays a defining role in the design of a circuit breaker: it requires interruption of the high short-circuit current that results when a section of transmission line is short-circuited, followed by the steep rise of a transient recovery voltage that results from travelling waves on the transmission line. Several laboratory studies have been carried out to assess the short-line fault performance of circuit breakers that use SF_6 alternatives, including CO_2 and C4-FN, CO_2, and O_2 mixtures [1,2,3]. The short-line performance of CO_2-based circuit breakers is significantly better than that of breakers based on N_2/O_2, but it does not reach the performance of SF_6 in gas circuit breakers that have been optimized over many years for that gas [4,5]. CO_2 and SF_6 differ significantly in their physical properties. SF_6, for example, has a lower speed of sound than CO_2, and its temperature-dependent adiabatic constant also differs from that of CO_2. By taking into account these inherent differences between the two gases, the arc zone of a CO_2 or $C4\text{-}FN/CO_2/O_2$ circuit breaker can be modified to achieve better current interruption performance and to satisfy the required short-circuit current ratings [3,4]. While the short-line fault performance is largely defined by the ability of the circuit breaker to rapidly cool the arc zone during a current-zero crossing and to interrupt the current, several other important fault types must also be considered in the design of a circuit breaker. For example, the IEC 62271-100 standard defines terminal fault test duties designed to cover a range of other fault conditions in the high voltage power grid. In those test duties, the circuit breaker is typically able to interrupt the current more easily than during a short-line fault test duty. However, the subsequent transient recovery voltage can rise to higher levels than after a short-line fault test. Therefore, these test duties test the ability of a circuit breaker to rapidly cool and restore the dielectric strength of the arc zone after the current is interrupted and while the voltage rises across the opening contacts. For two of these test duties, the T10 and the T30 test duties, with 10 % and 30 % of the rated short-circuit current, respectively, addition of a high dielectric strength additive, such as C4-FN, significantly enhances the dielectric recovery and the interruption performance [2]. To further improve current interruption and to achieve the same performance as in an SF_6 circuit breaker a modest increase in the gas flow used to cool the arc is sufficient [6].

Non-Circuit Breaker Switching Devices

While circuit breakers face the largest range of and the severest requirements on current interruption performance, disconnector-earthing switches and fast-acting earthing switches also play an important role in ensuring reliable and efficient operation and maintenance of the power grid. These two switching devices operate under less severe conditions: they must interrupt or switch lower currents, and the voltage that arises across them after interruption of a current is typically much lower than under the conditions in which circuit breakers operate. The most severe switching case with regard to current interruption faced by either one of these test devices is arguably the switching of electromagnetically induced currents by the fast-acting earthing switch. A disconnector-earthing switch, on the other hand, must switch higher currents during bus transfer switching operations, but is stressed by much lower voltages during such operations. A disconnector-earthing switch must also perform bus-charging switching operations (as defined in the IEC 62271-102 standard), but in this case, while the voltages across the switching gap can be very high, the currents to be interrupted are very low compared to those faced by a fast-acting earthing switch interrupting an electromagnetically induced current. Both fast-acting earthing switches and disconnector-earthing switches that use SF_6

have contact opening speeds that are typically an order of magnitude lower than those of a circuit breaker. These devices both generally draw a free-burning arc between the opening contacts. Under certain free-burning arc conditions the current interruption performance of CO_2 and C4-FN/CO_2/O_2 gas mixtures is not as high as that of SF_6 [7]. However, the introduction of gas flow to cool the arc, together with an increase in the opening speed, significantly enhance the current interruption performance of these SF_6 alternatives. In fact, such changes permit the interruption of electromagnetically induced currents by a fast-acting earthing switch [7]. A simple example of a design change that can be made to improve the current interruption performance of a fast-acting earthing switch is given in Figure 3.

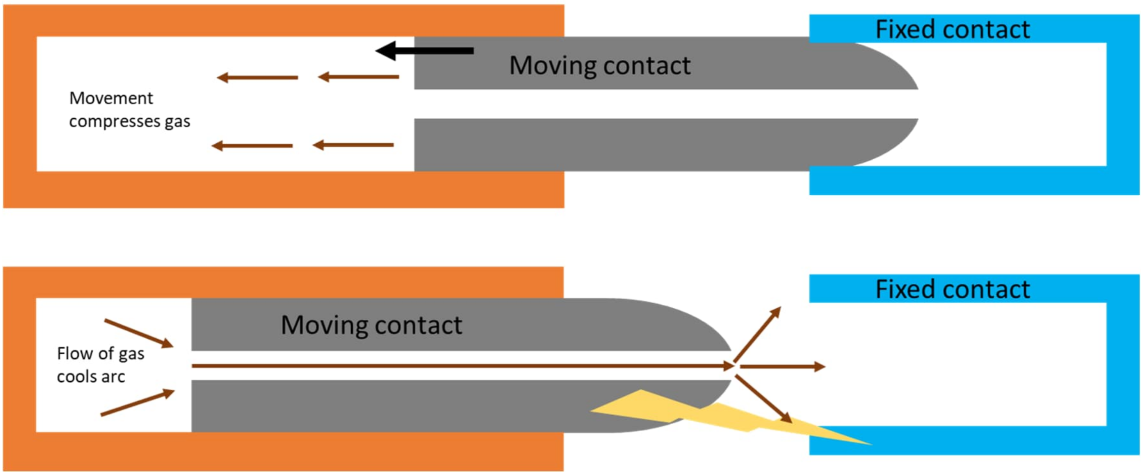


Figure 3. Sketch of the concept used to create gas flow and effectively extinguish an arc in a fast-acting earthing switch.

Summary of Switching Performance

By taking advantage of reliable, time-tested SF_6 circuit breaker technology and adapting it to the properties of C4-FN/CO_2/O_2 mixtures, circuit breakers, fast-acting earthing switches, and disconnector-earthing switches can be designed to address the full range of voltage and current ratings for the power sub-transmission and transmission networks. For example, a C4-FN/CO_2/O_2 based gas-insulated switchgear circuit breaker with a rating of 420 kV is in development, together with a fast-acting earthing switch and disconnector-earthing switch for the same voltage rating.

4 Materials

To ensure a product's reliability over its lifetime, extensive tests were performed to ensure the materials used in switchgear are stable and do not degrade or cause degradation to the C4-FN based gas mixture. The base for the choice of materials is SF_6 based gas-insulated switchgear where vast experience in material qualification as well as long-term operational stability has been demonstrated.

Test procedure.

Materials are tested in-situ using metal autoclaves for 4-20 weeks at temperatures between 85 and 135°C. The gas composition is regularly measured with a suitable gas-analyzer, such as a fourier-transform infrared (FTIR) spectrometer or a mass spectrometer (MS). From the measured decomposition rates, simple lifetime models and estimates can be derived for individual materials and, if the quantity of materials is known, even entire gas compartments. Finally, testing on a module level over several months allows realistic estimation of the behavior of materials in combination over the lifetime of the product. Testing on a module level has the advantage that the functionality of the modules after thermal aging can also be verified, e. g. by a dielectric condition check or a mechanical endurance test.

Elastomers
Elastomer gaskets or seals are critical components for the functionality of HV switchgear. Natural rubber (NBR) or Ethylene-propylene-diene (EPDM) rubbers have been used successfully for decades, and extensive experience, lifetime models and qualification procedures are available.
Gasket materials are critical for several reasons: they keep the insulation gas inside the device, ensuring operational performance, while protecting the switchgear from the outside environment. On the outside, gaskets are subject to atmospheric stresses: corrosion, ozone, and water, to name just a few. On the inside, the gaskets are in continuous contact with insulating gas and, in cases of circuit breaker compartments, decomposition products produced by arcing. Furthermore, gaskets offer the most likely pathway for water ingress into HV switchgear.

New equipment eco GIS – Choice of elastomers for C4-FN/CO_2/O_2
For mixtures with CO_2 carrier gas, EPDM gaskets are not the first choice due to the higher relative permeation rates for CO_2 compared to O_2 and N_2 [19]. A suitable alternative is buthyl rubber (IIR/XIIR). IIR exhibits high resistance to environmental ageing and has significantly better permeation properties compared to EPDM, especially grades that are halogenated (XIIR). Arrhenius-type lifetime-models were created for different IIR materials based on compression-set and stress-relaxation-tests. These models conservatively ensure performance for the total product lifetime taking into account compression-set, temperature and lifetime [15], [16].

Installed base retrofill – assessment of installed elastomers for C4-FN/N_2/O_2
For mixtures based on N_2/O_2, EPDM gaskets can be used without need to exchange if the EPDM grade itself does not exhibit any detrimental reactions with the SF_6-alternative gas mixtures.
Testing of elastomers follows the same process outlined earlier. To reflect the application of elastomers under compression, the material samples are compressed by 25% between aluminum holders fixed with stainless steel bolts during the material compatibility testing; see Figure 4.

Figure 4 EPDM after 4 weeks at 100°C in C4-FN / O_2 / N_2 mixture

In a comparative experiment, standard EPDM O-ring segments (d ~10mm) were aged, and the compression set [20] determined after ageing in air and in a C4-FN/N_2/O_2 mixture (1 bar air vs. 2 bar C4-FN/N_2/O_2) gave a compression set after 1000 h at 100°C, which is in line with other EPDM materials used in HV switchgear.
To assure that prior exposure of EPDM to SF_6 does not influence its performance with C4-FN/N_2/O_2 mixtures, comparative tests were also carried out for gaskets taken from old installations during service overhauls. For example, a gasket with 25 years of prior service time (in an SF_6, indoor installation) exhibited a compression set after ageing with a C4-FN/N_2/O_2 gas mixture, that was

similar to the compression set measured for new EPDM. For gaskets which have been in harsh outdoor service, especially if not maintained properly, initial degradation due to thermal ageing should be assessed.

Other materials.
There are other materials that have been assessed and tested according to the procedure described above, for example coatings, lubricants, and insulation materials. Metals are inherently non-hygroscopic and therefore can be considered inert in the presence of C4-FN based gas mixtures.

Material choice for switchgear with C4-FN based gas mixtures
We can summarize that with the described material qualification procedures we were able to qualify a complete range of materials for designing C4-FN/CO_2/O_2 insulated eco GIS, with only minimal adaptations to the material used in today's SF_6 equipment (e.g. seals). Additionally, for the scope of gas-insulated lines with C4-FN/N_2/O_2 for retrofill application in the installed base, we were able to confirm the suitability of the installed material including seals.

5 Operational health and safety and gas handling

The development of eco-efficient technology based on C4-FN gas mixtures should not only be a big leap for the environment by reducing CO_2 emissions, but it should also have a strong focus on the operational health and safety of people working with the gas.
Safety data sheets serve as a basic source of information when assessing the risks of handling different substances. The manufacturer provides regional safety data sheets for the C4-FN gas mixtures used in its GIS for each country where the C4-FN mixture is introduced. Also, the safety data sheets cover all states of the gas mixtures, ranging from "technical grade" to "heavily arced".At first glance handling a gas mixture like C4-FN/CO_2/O_2 made from three components may appear more complex compared to handling pure SF_6. For this reason, great effort was made by the switchgear equipment manufacturers as well as 3rd party suppliers to develop an efficient gas handling concept. Detailed gas handling instructions are provided together with the operating manual as a guidance by the switchgear manufacturer; many concepts, procedures, and best practices, as well as personal protective equipment and safety precautions, are similar to those used in established SF_6 gas handling

Initial filling during installation
During installation of the substation, large volumes of the C4-FN gas mixture need to be provided with the required composition and they need to be filled into the gas compartments within a reasonable time. Several concepts were studied, for example mixing the gas directly on site from the pure components (C4-FN, CO_2, N_2, O_2) and working with premixed gas that would be prepared in advance. From the comparison of different solutions regarding logistics, economic and ecologic aspects as well as complexity on-site, preparing the gas mixtures directly on-site was identified as most beneficial. A powerful gas mixing and filling device that can mix the gases and directly pump them into the GIS compartments will be used. In a continuous mixing and filling process, the high flow rate of 12 m^3/h is reached.

The filling device is highly automated, guiding the user step–by-step through the filling procedures, and supervising the entire process. Choosing the settings for the required gas mixture is very easy, since the gas mixture is encoded in a QR-code. During the filling procedure, the QR-code is scanned, and the filling device directly adjusts the settings. The gas connections have a different thread M48x2 (SF6: M45x2) to avoid mixing C4-FN mixtures with SF_6. With these measures, the possibility for errors during the handling processes is reduced to a minimum. This concept offers the flexibility needed for efficient filling with C4-FN mixtures.

Figure 5: Filling with C4-FN mixture

Gas tightness inspection
All permanent connections (between subassemblies) that are made on site are checked carefully for gas tightness using leak detectors, whereas transport units (subassemblies of the GIS that are pre-assembled in the factory) are tested for gas tightness during routine testing in the factory. For C4-FN mixtures the measurement procedures are the same as for SF_6 filled equipment.

Gas quality checking
After filling with the C4-FN mixture, it is best practice to measure the gas quality using a portable gas analyzer that is directly connected to the gas compartments. The portable gas analyzer measures the percentage proportion of each component of the gas mixture, as well as the humidity. This is again comparable to checking the gas quality when handling SF_6.

Gas monitoring during operation
All gas compartments that are filled with C4-FN mixture are equipped with density monitors of the same type as used for SF_6, which have a a reference gas chamber. The reference gas is adapted to the specific C4-FN gas mixture or for SF_6.

Gas handling during service and maintenance
For service purposes, when only limited amounts of gas need to be handled, a gas handling cart is used. It combines all the functions that are typically needed for handling gas (gas recovery, topping-up, evacuation). Filling gas with a service cart requires that the C4-FN mixture is prepared in advance. Premixed gas can be supplied by third party suppliers. When large amounts of C4-FN gas mixture must be refilled, the high-volume filling device (as described above) can be used for this purpose.

End of life
The switchgear manufacturer aims to provide an eco-efficient product that is sustainable over the entire product life cycle. Used C4-FN gas mixtures typically shows only small amounts of by-products after normal operation of the GIS. At the end of life of the equipment, the gas is recovered from the GIS and compressed in a storage container. It should then be sent for recycling, where the C4-FN can be extracted, purified, and reused. Gas disposal by incineration is also possible but should be avoided with the aim of reducing waste whenever possible.

6 LCA Gas-Insulated Switchgear

Life cycle assessments (LCA) investigate the environmental impacts related to a product or system during the complete life cycle of production, use and maintenance and end-of-life (cradle to grave). This includes the impact of energy and resource consumption and of emissions.
The goal of the following considerations is to quantify the impact of using an alternative gas on the ecological footprint of a GIS in term of greenhouse gas emissions. The basis of the calculation is one

unit (double bus bar bay with 100 m gas-insulated lines as exit to the overhead line) of a 420 kV GIS produced in Europe. At the end of life, non-fugitive materials are either landfilled, destroyed, or recycled. Credits for recycled materials are not included. Although LCA in principle is a multidimensional impact approach, only global warming potential will be discussed here. The most relevant inventories (resources used in production, emission during usage etc.) of a GIS using SF_6 as insulation gas are material, gas losses and power losses.

Amongst materials, typically aluminum is by far the most important with regard to greenhouse gas emissions, followed by steel of different types. In this LCA we considered primary aluminum manufactured using conventional smelting technologies. Due to the long lifetime of aluminum products, closed recycling loops for aluminum are only possible if the total amount of aluminum used in new products is reduced. The availability of aluminum produced with renewable energy sources is limited, too. Hence, it is important to focus first on reduction of resource usage and second on alternative sources. The gas losses portion of the carbon footprint is dominant for SF_6 insulated GIS, because SF_6 has a high global warming potential of GWP = 23 500.

LCA for new equipment eco GIS C4-FN/CO2/O2
For a new installation of a GIS using SF_6 alternatives like C4-FN/CO_2/O_2 (GWP < 300, base data from [10, 12]) or air (GWP = 0), the impact of gas losses on carbon footprint are virtually eliminated as CO_2 equivalent leaked gas is reduced by 99% to 100% for new equipment. Other, less relevant inventories are transport of components and product, resources used in assembly, testing, installation, commissioning, and maintenance and finally recycling. Most variable inventories are gas losses and power losses. Gas losses depend to a large extent on careful equipment maintenance, namely corrosion protection, and strictly adhering to correct gas handling procedures. In addition, accidental losses can play a role. While electrical resistance is rather stable, power losses depend on load profiles.
Figure 6 shows a comparison of the global warming impact of two GIS designs, one using SF_6 (a), the other using C4-FN/CO_2/O_2 (b). Assumptions included a 0,5% yearly leakage rate and 800 A constant primary current. Total greenhouse gas emissions estimated were 7 110 t_{CO2e} and 540 t_{CO2e}. Different use scenarios are listed in Table 1.

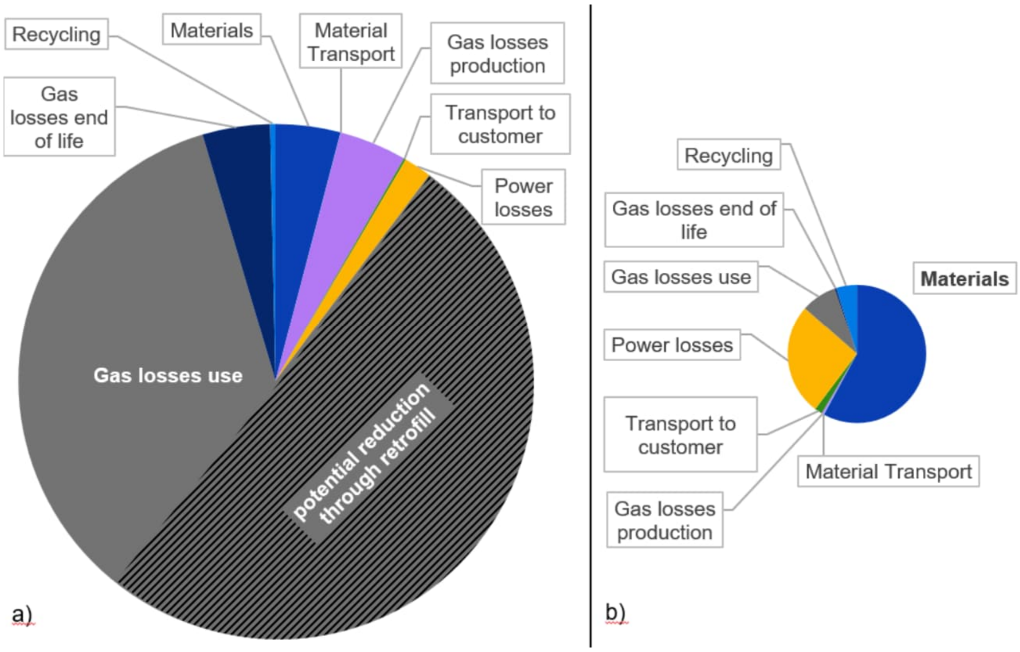


Figure 6. Life cycle comparison of a 420 kV GIS bay with 100 m GIL filled with SF_6 (a) and C4-FN/CO_2/O_2 (b)

According to the design study for the eco GIS with C4-FN/CO_2/O_2, the remaining carbon footprint is dominated by production of materials (40% to 55%), but also other causes for emissions are related to size and weight of the bay, namely transport and recycling. An additional impact to be considered by the user is the energy needed for creating, air conditioning and maintaining civil works, which also depend on the size of the equipment. Buildings accounted for 19% of global energy-related GHG

emissions (including electricity-related), approximately one-third of black carbon emissions, and an eighth to a third of F-gases in 2010 [12], indicating that this impact is significant, too.
According to the design study, the material impact of an eco GIS with C4-FN/CO_2/O_2 is almost equal to SF_6 equipment. Considering dielectric performances as shown in Figure 2 it is evident that any further reduction of GWP of the insulation medium (e. g. by using air with GWP = 0) will inevitable be over-compensated by increased material use. Therefore, we conclude that a C4-FN/CO_2/O_2 gas mixture is the optimum to reduce the overall greenhouse impact of new gas insulated switchgear.

Leakage rate	**Nominal current**	**Reference SF6 GIS** bay and GIL: SF6	**eco GIS** bay and GIL C4-FN 3.5 mol%/ CO_2 86.5 mol%/ O_2 10 mol%	**retrofill** bay: SF_6 GIL: SF_6 replaced with C4-FN 10 mol%/ N_2 85 mol%/ O_2 5 mol%
		t_{CO2e}	t_{CO2e}, (delta to SF_6 ref.)	t_{CO2e}, (delta to SF_6 ref.)
0,5% / a	800 A	**7 110**	540 (-6 566)	3 357 (-3 748)
0,5% / a	400 A	**7 040**	460 (-6 579)	3 292 (-3 748)
0,1% / a	800 A	**2 270**	500 (-1 770)	1 524 (-750)

Table 1. Global warming potential of different use scenarios of a 420 kV GIS bay and 100 m GIL with SF_6, eco GIS with C4-FN/CO_2/O_2 and retrofill of GIL with C4-FN/N_2/O_2

LCA impact of Retrofill of installed base with C4-FN/N_2/O_2
The C4-FN/N_2/O_2 (GWP < 1 000) gas mixture allows "retrofilling" and replacing the SF_6 (GWP = 23 500) in the passive gas-insulated lines of existing gas insulated switchgear. Retrofilling leads to a reduction of almost 99 % of the CO_2 equivalent of the compartments where the gas is swapped. The reduction of the CO_2 equivalent is larger than one would expect from a pure comparison of GWP values which are given per unit of mass. One has to take into account also that the eco gas mixture has much lower mass than the SF_6 gas which fills the same compartment. Thus, for an existing installation, most of the future emissions of the retrofilled compartments can be avoided. Depending on the length of the GIL/exits in the specific project and the point in time after installation when the retrofill is performed a significant share of the total CO_2eq emissions of the substation can be avoided. In the example of Table 1 / Figure 6 (420 kV GIS with 100 m GIL) this share is up to 59 % of total gas losses (in case of C4-FN/N_2/O_2 retrofill directly after initial commissioning with SF_6)

7 New equipment eco GIS: complete switchgear based on C4-FN/CO_2/O_2

C4-FN/CO_2/O_2 has good performance for insulation (section 2) and interruption (section 3) and is thus suitable for the design of circuit breakers, disconnectors, fast acting earthing switches, as well as all passive GIS modules. Material qualification procedures exist and with small adaptations (e.g. seals) to the material used in today's SF_6 equipment, equipment that is stable over the long term can be designed (section 4).
For the gas mixture definition, low C4-FN content and a slightly increased total pressure allows a combination of low condensation temperature (outdoor applications −30 °C), dielectric performance similar to SF_6 at typical pressures (e. g. 450 kPa) and CO_2 eq reduction of the insulating gas by 99 % (section 6). Similar dimensions for C4-FN/CO_2/O_2 equipment can be achieved as for typical SF_6 equipment [13], which is beneficial, especially for installations with restricted space requirements or in case of retrofit for existing substations. CB/non-CB as well as indoor/outdoor devices can be designed using the same gas mixture; thus, all equipment in one substation can be filled with the same mixture, which is beneficial from a gas handling perspective. Together with the gas handling concept (section 5) this allows users to build on the decades of experience with SF_6 for safe, efficient, and reliable gas handling.
HV GIS based on C4-FN/CO_2/O_2 technology has lowest overall lifecycle CO_2 eq emissions compared to air with vacuum circuit breaker and SF_6 [3]. Thus, we have shown that C4-FN/CO_2/O_2 is an eco-efficient and scalable alterative to SF_6 for metal-encapsulated high-voltage switchgear. Currently, a complete GIS for a rated voltage 420 kV incl circuit breaker is under development. For the transmission level, where large volumes of insulating gas are used, this will allow a fast transition to

eco-efficient equipment and contribute to efficient reduction of CO_2 eq. emissions and be an important step towards carbon neutral HV switchgear.

8 Installed Base Retrofill: Gas-insulated Lines Based on C4-FN/N_2/O_2

Ecological and Economic Motivation

Regulation has led to improvements in both new equipment and maintenance of older fleets of switchgear containing SF_6. However, with the prospect of further increases in penalties for CO_2 equivalent emissions, the long-term ownership and operation of SF_6-based switchgear will become a serious financial burden. This has led many operators with large fleets of SF_6-based switchgear to look for solutions to eliminate this risk. As the design life of switchgear is usually around 50 years, much of the equipment installed today, which contains SF_6, will need to find an alternative solution to avoid either the high write-off cost of early replacement, or the cost of continuing SF_6 management. Here, replacing the gas, not the equipment, can offer a viable solution.

Retrofill will eliminate the emissions of SF_6 and the associated carbon footprint (section 6) and avoid the costly decommissioning and replacement of equipment which still has an economic design life. It offers the double advantage in eliminating the risk of ongoing and future penalties for emissions, while at the same time extracting the highest financial benefit from equipment investments by enabling them to be operated to the end of their design life or even longer. Here retrofill offers an optimal solution since the process is fast and effective and will not require extended outages.

Technical description of retrofill

The retrofill solution was qualified for most of the passive gas compartments of a 420 kV GIS design. It involves exchanging the gas and leaving the primary equipment in place (details see Table 4). The concept is based on the dielectric performance of C4-FN/N_2/O_2 (Figure 2), which can deliver equivalent insulation performance to 4-5 bar SF_6 with an increase of less than 10% in filling pressure. For the specific 420 kV GIS design this pressure increase is still lower than the design pressure of the existing equipment. Additionally, the EPDM seals predominantly used in the installed base have good tightness for the N_2 carrier gas (section 4). The feasibility of this concept was proven by performing material compatibility tests according to section 4 and type tests (ratings Table 2, tests Table 3).

For the 420 kV GIS design the retrofill qualification was completed for the passive gas compartments, which typically contain around 50% of the installed SF_6, but can vary significantly, depending on the length of the GIL. Therefore, this portion of the SF_6 can be removed and replaced with C4-FN/N_2/O_2. the retrofill solution could potentially remove over 1 000 tons of SF_6 from currently installed switchgear of this 420 kV GIS design. Looking beyond this specific design, the potential amount of SF6 to be removed from the installed base can be increased by extending the retrofill concept including qualification measures to further voltage levels.

Table 2: Ratings of 420 kV retrofill gas-insulated lines

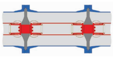
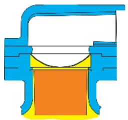
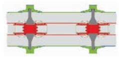
Rated nominal voltage U_m	420kV (440 kV 60 min)
Power frequency withstand voltage	650 kV (r.m.s. value)
Rated Switching/Lightning Impulse withstand voltage	1 050 kV / 1 425 kV (peak value)
Rated current at 40°C (50Hz, 60Hz)	4 000A 5 000A
Rated short time withstand current/duration	63 kA / 3 s
Rated peak-withstand current (peak value)	171 kA
Temperature range Indoor/Outdoor	**- 30° / + 40°C** (+55°C @ 4 000A)

Table 3: Type tests with C4-FN/N_2/O_2 for retrofill of 420 kV GIS components

Designation	Reference
Dielectric tests	IEC 62271-203, § 6.2 & IEC 60137
Continuous current test	IEC 62271-203, § 6.4 and 6.5 & IEC 60137
Low and high temperature test and gas tightness test	IEC 62271-203, § 6.102 and 6.8 & IEC 60137

On-site work procedure
In addition to replacing SF_6 with C4-FN/N_2/O_2, unique gas filling points will be installed to prevent mix-ups or the use of the wrong gas. The desiccant and gas density monitoring devices will also be replaced with equipment optimized for the C4-FN/N_2/O_2 gas mixture.

Table 4: Onsite Work Procedure for Retrofill

	 © DILO GmbH	 © DILO GmbH				 © Air Liquide / Laurent Lelong	 © DILO GmbH	
SF6 GIL	Gas quality measurements & no leak confirmation	Reclaim SF6 & Store or disposal of SF6	Exchange density monitor	Exchange gas filling point	Exchange desiccant	Gas mixing and filling	Gas quality measurements	**retrofill GIL**

Pilot project
In 2021, the first retrofill was successfully done at an installation in Richborough in the United Kingdom. This is the world's first replacement of SF_6 in existing high voltage equipment and 755 kg of SF_6 were removed from approximately 75 m of GIL and replaced with a C4-FN/N_2/O_2 mixture. The quality of execution for the pilot project was proven with the on-site tests as shown in Table 5.

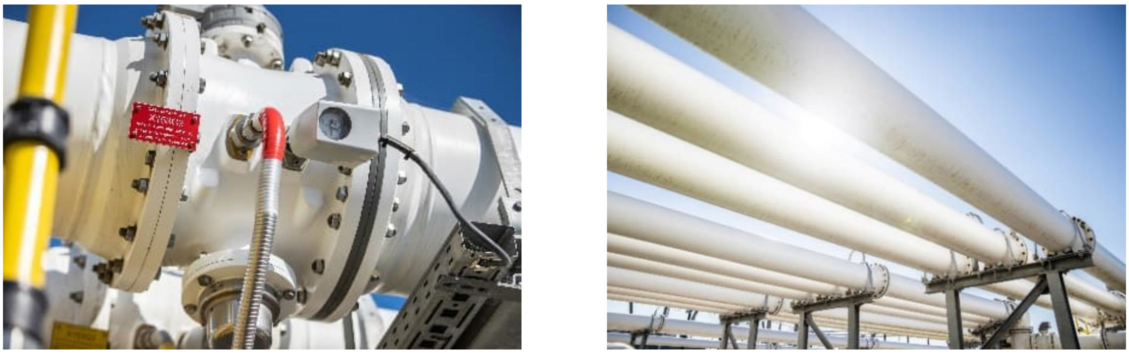


Figure 7: 420 kV GIL at Richborough UK where first Retrofill was performed

Table 5: On-site tests for the retrofill 420 kV pilot installation in Richborough

Designation	**Reference**
Dielectric tests	IEC 62271-203, § 6.2 & IEC 60137
Tightness tests	IEC 62271-203, §10.2.101.5
Verification of wiring	IEC 62271-203, §10.2.101.6
Gas analysis	IEC 62271-203, §10.2.101.7

9 Conclusions

Eco-efficient solutions for significantly reducing the carbon footprint of HV switchgear can be designed by using C4-FN-based gas mixtures. C4-FN/CO_2/O_2 mixtures represent a solution for the full platform of HV switchgear. They have excellent dielectric and arc quenching properties and can lead the way to an industry standard for new equipment. C4-FN/CO_2/O_2 enables manufacturers and users to build on decades of experience with SF_6 in dielectric design, gas circuit breaker technology, material choice, operational health and safety and gas handling. An optimal solution for the installed base using C4-FN/N_2/O_2 mixtures was developed and implemented to quickly replace large volumes of SF_6 in GIL of existing installations and significantly reduce future CO_2 eq emissions.

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