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F-gas-free Natural-Origin Gases, for MV GIS, to manage your sustainable grid

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SUMMARY

Sulphur hexafluoride (SF_6) is widely used in electrical switchgear equipment at both medium and high voltage (HV > 52 kV). In medium voltage gas-insulated switchgear (GIS) SF_6 gas is predominantly used as an insulating medium as well as interrupting medium for load-break switching applications. With its Global Warming Potential (GWP) of 24300 times higher than CO_2, it's one of the strongest greenhouse gases. When emitted into the atmosphere, often during decommissioning, SF_6 gas stays in the atmosphere for 1000 years and contributes to global warming.

Various regulatory bodies like the European Commission, California Air Resources Board (CARB) call for alternatives to SF_6 gas. This led to various alternatives from different manufacturers [1]. They have different characteristics and handling needs compared with today's SF_6. Natural-origin gas (NOG) use only components of the natural air (N_2, O_2, CO_2) they have no Ozone Depletion Potential (ODP = 0) and a very low GWP ≤ 1.

The focus of this paper is to highlight key requirements that an SF_6 alternative switchgear shall have and how NOG fulfil them. It reports on the first UK installation of a NOG switchgear ring main unit in Glasgow, SPEN and other pilots up to 24 kV in Europe.

Keywords

GIS, SF_6 alternatives, synthetic air, clean air, vacuum interrupter, digitalization, GWP

1 Introduction

What do regulations say? The Montreal Protocol, adopted on 16 September 1987 regulates the production and consumption of nearly 100 man-made chemicals referred to as ozone depleting substances (ODS). Through the 1997 Kyoto Protocol, the industrialized countries (responsible for over 70% of the global emissions of "greenhouse gases") have committed themselves to reduce their emissions. SF_6 gas was listed in the Kyoto protocol as one of the six greenhouse gases subject to monitoring, due to its high Global warming Potential (GWP). Dec. 2015, in the Paris Convention, 195 member states agreed to reduce climate-damaging greenhouse gases under the United Nations Framework Convention on Climate Change (UNFCCC) as of 2020. Based on this framework the industrialized countries have established regulations on such gases over the past years. The California Air Resources Board (CARB) Regulation for Reducing SF_6 Emissions from Gas Insulated Switchgear is effective since January 1, 2022. For Medium Voltage (MV; ≤ 52 kV) switchgear it defines the following Phase-Out Dates:

Table 1. Phase-Out Dates for SF_6 GIE with Voltage Capacity ≤ 38 kV

Configuration	Voltage Capacity (kV)	Short-Circuit Current Rating (kA)	Phase-Out Date
Aboveground	< 38	All	January 1, 2025
	38	All	January 1, 2028
Belowground	≤ 38	< 25	January 1, 2025
		≥ 25	January 1, 2031

Over the last years the GWP figure have changed. The difference between CARB (which links to an Electronic Code of Federal Regulations (eCFR) [1], 22,800, also used in C37.20.9(2019)) and the EU F-gas regulation (25,200) is obvious. The final IPCC6 report shows now in its supplementary material [2] a different number for the SF_6 GWP: 24,300. Due to some labelling requirements and CO_2 taxations in various countries, a harmonization of these figure is required.

The European Commission has drafted its proposal of the third revision of the Fluor (F-) Gas regulation on April 5th, 2022 [3]. SF_6 is now planned to be regulated. Market evaluation has given the Commission the opinion, that there are valuable alternatives available, that fall under two categories: the first having a GWP below 10 and the second a GWP between 10 and 2000. Any gas above this threshold shall be banned, anything below GWP of 2000 needs to be checked if alternatives below GWP = 10 are available. In March 2023 the parliament came to a final opinion on the F-gas Regulation. Based on the proposal of the leading Committee on the Environment, Public Health and Food Safety (ENVI) they proposed a ban for all fluorinated gases. This proposal needs to be discussed with the EU members states within the next months. *NOG* with a GWP < 1 fall under this threshold. As they also don't use any F-gas they are therefore future safe for any further adjustment of this or any further F-gas regulation. Drafted regulation foresees a ban date for up to 24 kV on January 1. 2026 and 1. of January 2028 below 52 kV.

2 Why Natural-Origin Gases are the best alternative?

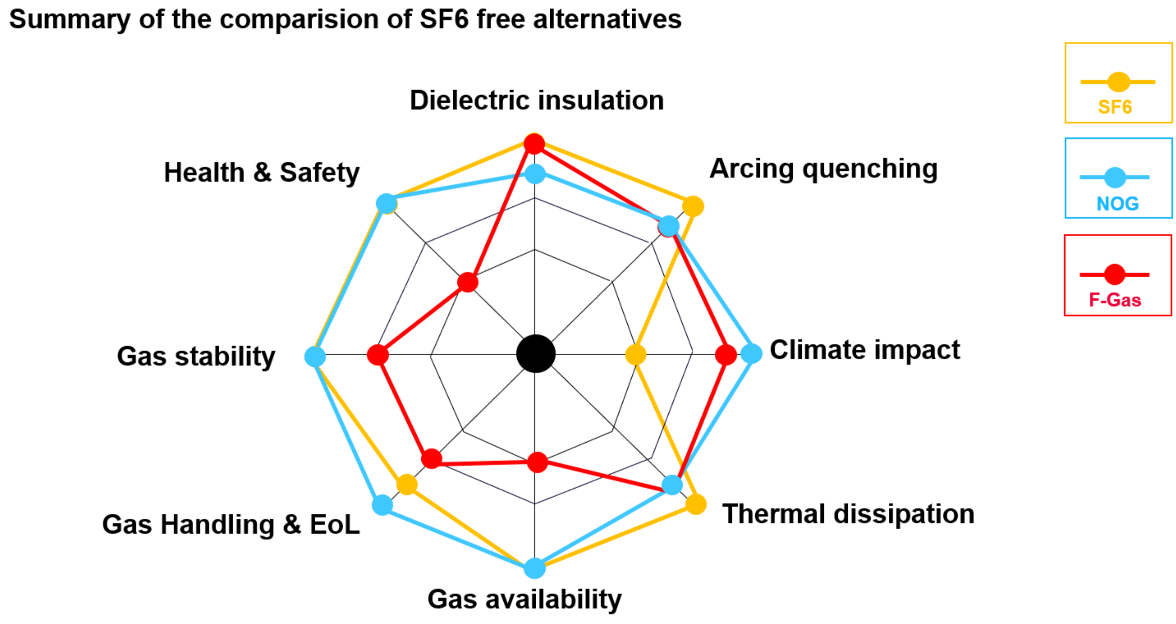

Figure 1: Main parameters to decide on SF6 Alternatives [White paper]

Finding an alternative to SF_6 that can exactly match its properties is not possible as a single gas compound. The focus of recent research activities on SF_6 alternatives is either on only natural-origin gases or fluorinated gas compounds with natural-origin gases as carrier gases. The F-Gas alternatives currently under discussion according to IEC62271-4 are C4-Fluoronitrile (C4-FN) and C5-Fluoroketone (C5-FK).

Any potential alternative must have a lower GWP and be compliant with the strict criteria that current switchgear must meet. These requirements are discussed in the following section.

2.1 Sufficient dielectric strength

It is one of the important features of a switchgear that ensures reliable operation of the equipment throughout its lifetime, at all requested temperatures. SF_6 has excellent dielectric properties which applies for ambient temperatures ranging from -40°C to 55°C. Temperatures below -25°C are typically requested in arctic and mountainous regions. On the other hand, none of the alternatives can match with excellent SF_6 properties at a given pressure except GWP.

The authors from [4] performed a series of tests on various simplified arrangements and a variety of gas mixtures at different pressure levels. A rod to plate with 30 mm gap arrangement, showed the respective results (figure 1). It is evident that C4-FN showed similar results as SF_6 and both C5-FK and natural-origin gases are lagging at the chosen pressure levels.

It is concluded in these investigations [4] with various arrangements that natural-origin gases show improved withstand voltages up to 43% when the pressure rises from 1.3 bar to 1.8 bar absolute and offers further potential at higher pressures to fulfil the insulation level for rated voltages up to 40.5 kV. The filling pressures of existing SF_6 switchgear is in the range of 0.5 bar (rel.) up to 1.2 bar (rel.). For natural-origin gases higher filling pressures ranging from 0 bar (rel.) to 3 bar (rel.), depending on the voltage level and internal design within the hermetically sealed vessels, are required. An optimized switchgear design with E-field uniformity measures and right selection of pressure with rigid structure of housings based on tests and simulations [5], will achieve for medium voltage switchgear same technical ratings as of SF_6 switchgear.

As space in Compact Substations and within cities is limited, similar dimensions and footprint as with SF_6 are required and can be achieved with NOG.

2.2 Arc quenching

For the arc quenching and current interruption capability in MV switchgear, vacuum circuit breakers (VCB) have been used for decades, proving their reliability in SF_6 gas insulated switchgears. For primary distribution switchgear alternative gases are used only as insulating medium, keeping VCBs for current interruption.

For secondary distribution switchgear, load current interruption is done in SF6 gas. For SF6-free switchgears, this calls for two options. Either use the same alternative gas for load current interruption or implementing a vacuum interrupter for load break switching applications.

The heart of the new ring-main-unit switchgear is the innovative load-break switch with vacuum interrupter in the auxiliary path. The Siemens load break switch uses a specially designed vacuum interrupter which is used to quench the switching arc of load breaking current. Functions like switching ON, main current flow, short-circuit making capability and meeting the isolating distance requirements are implemented in NOG. The compact dimension of this switch enables compact switchgear design by using the same operating principal as known from SF_6 switchgear.

2.3 Climate impact

The sole reason for searching alternatives for SF_6 gas is because of its considerable effects on climate change due to its high GWP of 24,300. This means the alternatives shall not in any case create another detrimental effect on environment.

NOG like example N_2, O_2 & CO_2 have no Ozone Depletion Potential (ODP=0) and a very low GWP $\leq$ 1. Furthermore, they are extremely stable, non-toxic, non-flammable and suitable for all operating temperatures. Their climate impact is also very low during operations or at the end of life, presenting no risks when released into the atmosphere.

The F-gas alternatives on the other hand like C4-FN have a GWP of ~ 2750 and when used in mixture

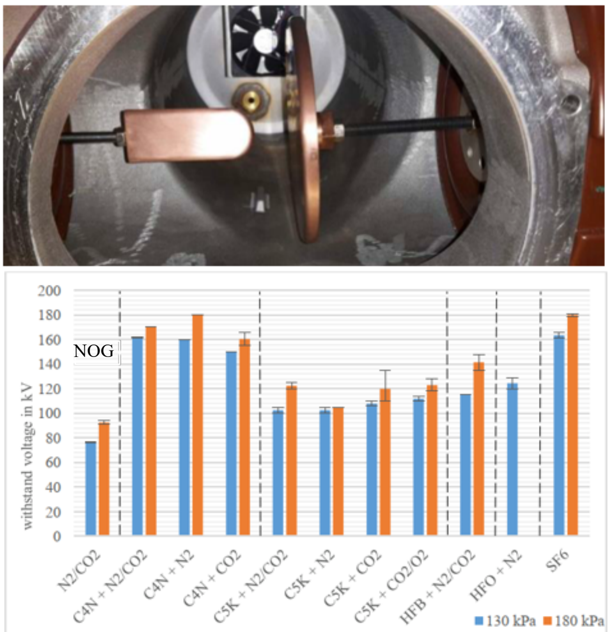

Figure 2: Average withstand voltages for the given arrangement with 1.3 bar abs and 1.8 bar abs. pressure, only critical polarities.

with dry air, its GWP ~ 700 calculated based on formula in [3]. The C5-FK has a GWP < 1. With respect to C5-FK, when escaped or leaked into the air, it is demonstrated that even under the light energy it decomposes in air as illustrated in figure 3. In case of controlled release, the UV light is the driver and the principle decomposition path and the decomposition products are known. All decomposition paths end up in HF (hydrofluoric acid) (LC50: 630ppm) or CF3COOH (Trifluoroacetic acid - TFA) (Inhalation rat LC50: 10 g/m3. Investigated as a mutagen.). The molar yield of TFA for C5-FK is 100%.[6]

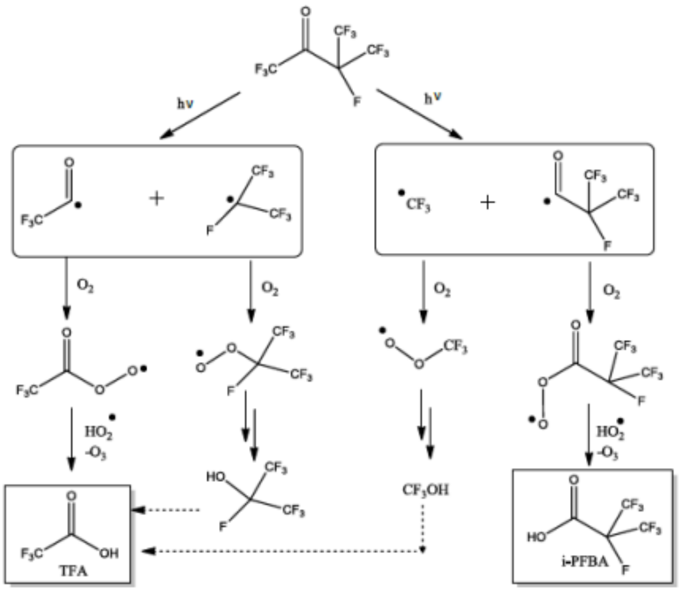

Figure 3: Atmospheric decomposition path of C5-FK after photolysis [7]

2.4 Thermal Dissipation and gas availability

Thermal dissipation of all the studied alternatives is reported to be lower than SF6. Therefore, a number of different optimizations are possible (s. Fig.4).

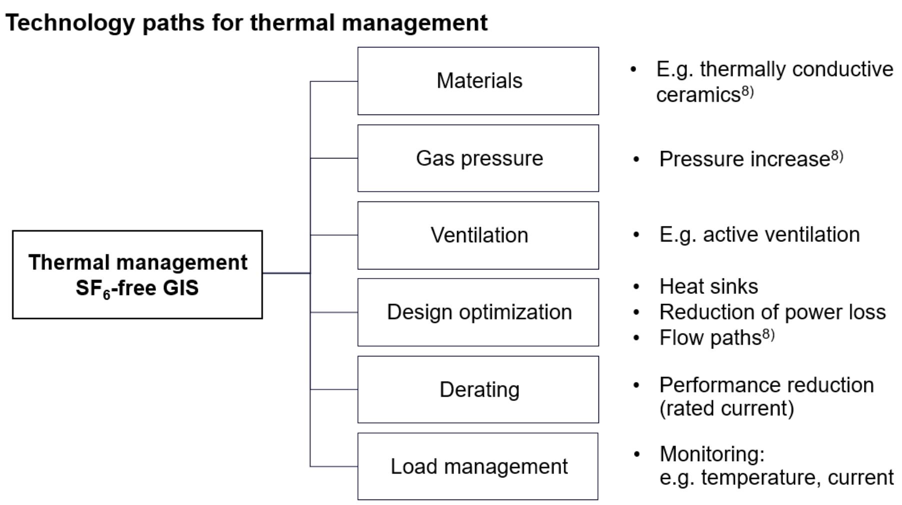

Figure 4: Technology paths for thermal management [8, 9]

With respect to gas availability, since NOG consists of natural air elements (N_2, O_2 and CO_2) it is not protected by patents. Therefore, there are numerous global providers who can deliver the gases in the requested mixing ratio. This prevents the monopoly position of a single gas producer (or few licensed producers) and allows to purchase the insulating gases at a low cost.

2.5 Gas stability

Gas stability is a key parameter to insure service life of 30 or 40 years. Natural-origin gases are very stable in presence of electrical field and has been used for decades in various other industry applications (e.g. AIS). SF_6 is a very stable gas that recombines itself naturally and rapidly after decomposition due to arc breaking or partial discharge. With respect to NOG, real field tests and first pilot experiences [10] have shown that no abnormalities were found and stable behaviour in service is observed. On the other hand, fluorinated gases with low GWP are not very stable and decompose quickly in atmosphere. For instance, the atmospheric lifetime of fluoroketone (GWP < 1) is only 14 days. This gas will decompose during arc breaking or partial discharge and will not recombine. Tests [15] made with a 14 litres tank with load break switch have shown that after 100 CO at 630 A / 24 KV, 51% of the fluoroketone initially present in the mixture (C5-FK + air) have disappeared, generating 25 different Fluorine by-product and an overpressure of 0.5 bar in the tank. All these by-products are toxic and protection of people should be made in case of leakage or end of life handling.

2.6 Health and safety

In addition to technical performances and environmental impacts, toxicity of alternative gases is a key parameter to consider during their validation process. According to [20] some toxicity properties such as acute toxicity, which describes the adverse effects resulting from a single exposure to a high concentration of a substance or by opposition, the chronic toxicity, which represents the development of adverse effects because of long-term exposure to low concentration of a contaminant are generally well documented in the literature. It makes possible a direct comparison of the new gas candidates with SF_6.

In parallel to this basic information, carcinogenic, mutagenic and reprotoxic (CMR) effects, bone marrow cytotoxic effects (cytotoxicity involves the death of cells), neurotoxic effects of the new candidates must also absolutely be well known in order to guarantee the longterm health of people who potentially may be exposed to these gases. The concerned people are operators on gases, users of equipment and public in case of accidental gas leakage.

For many years, these open questions for C5-FK and C4-FN are without any answer. Some publications have shown that the acute toxicities of these gases are more severe [11][12]. A recent paper has demonstrated that fluoronitrile is neurotoxic in the mouse brain [13] and teratogen (which causes malformation on an embryo) on rats [16]. If these gases are also used for current breaking, gas analysis [15] have shown that the quantities of by products are very high compared to SF_6 ones and the acute toxicity of this gas mixture with by-products is very high.

Another aspect must be taken into consideration: the future regulations about PFAS (Per- and PolyFluoroAlkyl Substances) which concerns C5-FK and C4-FN. Since 2020, initiatives have been taken in Europe and the United States of America to restrict the manufacturing, marketing and use of this group of substances. The European strategy on chemicals of October 14, 2020 also stated the restriction of all PFAS by 2025 through REACH regulation (Registration, Evaluation, Authorization and Restriction of Chemicals). A Draft Proposal was released on 7th. of February 2023 by the leading Countries Denmark, Germany, The Netherlands, Sweden, and Norway. The proposal also foresees a ban of these F-gases below 145 kV. Above 145 kV ban will start 5 years later [16]. The PFAS discussion shall be finished in 2025. In the current context of recurrent health scandals, switchgear manufacturers and users should pay more attention to safety risk while using the gases which have not demonstrated their harmlessness. Moreover, with increasing sustainability targets, the users cannot take the risk of installing switchgear with possible regulatory restrictions in the future.

2.7 Life cycle costs including gas handling and end of life treatment

In [17] Fraunhofer Institute for Energy Economics and Energy System Technology IEE has conducted a study to investigate the cost factors in the life cycle of MV switchgear. The scope of this study covers processes from procurement to disposal for GIS with insulating gases containing F-Gases as well as NOG insulating gases. The study was conducted between February 2021 and March 2022.

In the study, the costs of a medium-voltage switchgear with a typical number of switchgear panels in German public power networks, as well as the environmental impacts due to the different insulating gases or system types used are considered. The costs were determined for this exemplary switchgear system in common public supply networks. The aim was to compare market factors and environmental impacts.

The parameters included in the cost factors are changed within the observation period in order to capture their influence or share in the total costs. For the calculation of the life cycle costs, the LCC-CO_2 tool from the project « SMART SPP - innovation through sustainable procurement » was adapted and used with regard to the observation period and the CO_2 certificate price consideration.

The calculations are based on values from literature research and expert interviews among stakeholders on various aspects of the life cycle phases of planning, operation, and disposal of switchgear.

The lowest total costs were calculated for the NOG-GIS (s. fig. 5).

The main drivers are the costs due to energy losses (electricity price), the emission costs from electrical losses (CO_2 equivalents of the electricity mix) and the costs for the maintenance of the switchgear.

The costs of equipment, maintenance, energy loss, replacement, safety tests and documentation have been identified as cost factors that account for a large proportion of the total costs. The costs for documentation are low for switchgears without fluorinated gases.

For the alternative F-gases, documentation requirements corresponding to SF_6 have been assumed, but the legal requirements are currently interpreted differently. In the next few years, these may be clearly defined or changed. Maintenance is decisive for the cost difference between air-insulated and gas-insulated switchgear.

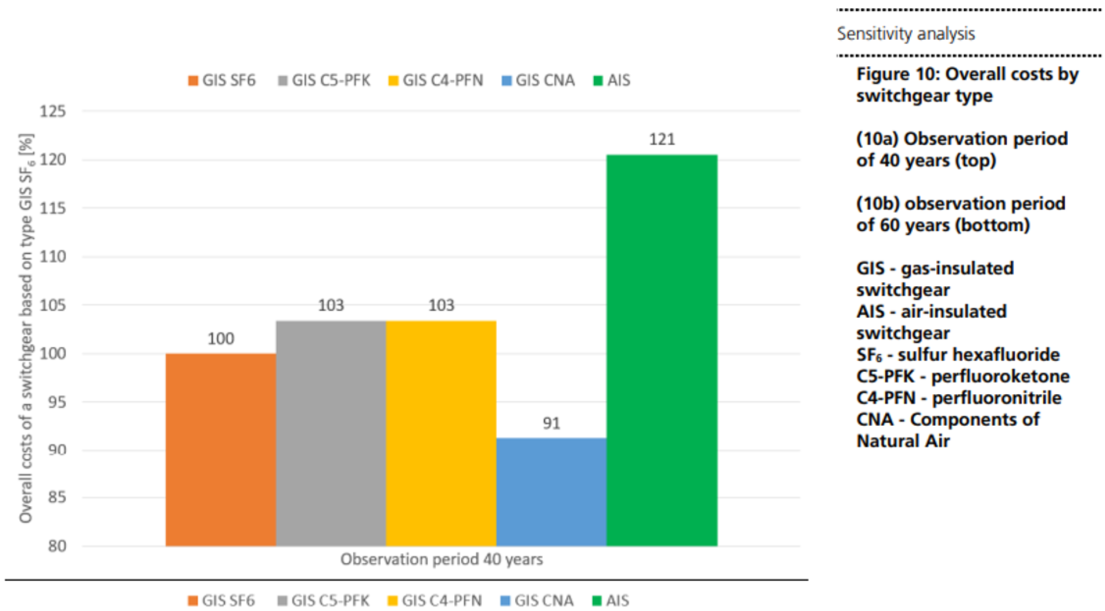

Figure 5: Cost comparison NOG vers. SF_6 and F-gas alternatives [17]

3 Innovations: Smart grids need measurements, how smart MV-GIS do support

The increasing feed in of renewable energies requires a comprehensive monitoring of current and voltage values especially in the secondary distribution grid in order to avoid grid congestions and overload of network components.

Today, currents and voltages are mainly measured using conventional current and voltage transformers. Especially in compact ring-main units is a demand for smaller geometry. Such alternatives to conventional current and voltage transformers, are the so-called non-conventional instrument transformers (NCITs). They are installed mainly as additional components at the switchgear's cables infeed or at its cable plugs. However, they are subject to constraints due to different cables, cable plug

Figure 6: SIBushing Design (with RJ45 plug)

technologies, and geometries. Therefore, the call for suitable, universal current and voltage sensors is getting evident. SIEMENS developed a new type C cable connection bushing (SIBushing) shown in Fig. 6 with an integrated Rogowski coil current sensor, a capacitive voltage sensor and a temperature sensor, which fulfil the requirements of IEC 61869-10 [18] and -11 [19] with regard to output signals and accuracy.

Measuring and evaluating current and voltage

To safeguard the NCIT's proper function over the entire switchgear lifetime, only passive components are used for the bushing design, avoiding any active electronics, which could result in a reduction of the service life due to its inherent failure probability by electronic stress. A capacitive divider for voltage measurement and a Rogowski coil for current measurement provide a measuring accuracy of 0.5%. Furthermore, the bushing contains a temperature sensor for a possible supervision of the cable connection. The current and voltage sensors can be connected to directional short-circuit indicators, multifunction protection devices, and even power quality and power measuring devices.

This innovative integration of the measuring functionality in the cable connection bushings is also a sustainable solution: It reduces the use of material and avoids additional installation space for current and voltage transformers, leaving the cable compartment unchanged.

4 On-site installation and operational experience across Europe (UK)

The UK's first 'blue GIS' installation using the 8DJH12 ring main unit. The RMU (RRL Block) with Siemens protection relays (7SR11), SICAM FCM, motor operated CB and switches was installed and commissioned for SP Energy Networks.

This is the first UK installation of a Siemens NOG switchgear ring main unit allowing the substation to operate free of sulphur hexafluoride (SF_6), which is commonly used as an insulator for electrical equipment in substations across the UK.

Scottish Power Energy Networks (SPEN) worked with Siemens to have the equipment delivered and installed at the Glasgow substation by the end of summer 2021, ensuring it will be in place by the time world leaders arrive in Glasgow for the landmark event, COP26.

SPENs key focus is to deliver a Net Zero path. In terms of sustainability one key focus area to reach Net Zero is, that together with their suppliers and contractors, they build up a sustainable supply chain to match a resilient network needs. SPEN will invest a total of £ 10 bn in the clean energy generation and networks infrastructure needed to help the UK decarbonise and reach Net Zero emissions.

SPEN currently own and operate 30,000 substations across areas in Scotland, Northwest England and Wales. The trial took place at a substation in MacLean Square in Glasgow, just across the River Clyde from the Scottish Event Campus (SEC), where the United Nations Climate Change Conference (COP26) took place in Autumn 2021.

5 Conclusion

NOG based MV Switchgear manufacturers represent major original equipment manufacturers in the distribution sector. Since more than 2 years they have released first natural-origin gas (NOG- N2, O2 and CO2) pilots .in various regions of the world. Mainly starting at lower levels, but each of them is committed to close the remaining gaps till ban dates are set into force. Those alternatives to replace harmful SF_6 gases are already available today as matured technologies and products due to extensive field experiences. This will help DSO's making their power grids clean and safe by ensuring the electricity system is free of F-gases. Additional investments to manage the increased demand for renewables are being executed.

The article demonstrates, that due to the technical solutions chosen, NOG is the best alternative to SF_6 gas in GIS switchgear, has lower life-cycle costs than alternative F-gases and with its digital add ons it is well prepared to manage grids closer to their limits, which will be needed to manage the sustainable energy transition.

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