Implementation of the F-Gas-Regulation in the grid of TransnetBW in the context of energy transition

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SUMMARY

In March 2024, the European Commission released the new F-Gas-Regulation aiming to discourage the use of F-gases with high global warming potential, to prevent leakages from equipment, to enhance sustainable growth and to stimulate the development of new technologies. From all F-gases being approached, this paper deals with the SF_6 only. Regarding the SF_6, the new regulation brought the needed clarity for the grid operators, showing how long the commissioning of SF_6-equipment is still possible and what SF_6-alternatives are allowed.

TransnetBW published in 2022 its own strategy describing the procedure to select, test and introduce SF_6-free equipment in its high voltage and extra high voltage grids. This strategy foresees only equipment with natural origin gases as SF_6-alternatives (GWP<1) as they are safer and more sustainable.

This paper describes how the new F-Gas-Regulation influences the strategy of TransnetBW regarding the selection and introduction of SF_6-free equipment in its grid. It also shows the progress and the gathered experience from pilot projects on 420 kV level and from the roll-out on 123 kV level respectively.

KEYWORDS

SF_6-replacement, environment, health, safety, emission reduction, substation equipment, sustainability, sustainable equipment, F-gas-free

1 TransnetBW strategy to select and introduce SF_6 alternatives

Transnet BW published its own strategy on how to select and gradually introduce SF_6 alternative gases in the high voltage (HV) and extra high voltage (EHV) grid [1]. The elaboration of the strategy was based on drivers such as, political context in Germany and in Europe, market development and internal experience from pilot projects on alternative gases. The strategy proposes a differentiated approach based on voltage level and equipment category and includes two phases: a trial phase to test products (Table 1, light green), and a standard implementation phase, which implies the deployment of natural origin gases-based (NOG) equipment as "first option" before SF_6 apparatus (Table 1, dark green). A product will remain in the "light green" phase, if that specific product can be delivered by a single manufacturer only. This way a monopoly situation and dependency of one manufacturer are avoided. Further, it has been decided, that only type tested products are accepted.

According to this strategy, TransnetBW will focus on the AIS equipment of the HV grid firstly and will move towards higher voltage levels, depending on how fast the NOG-equipment is developed and made available to the market. On one hand this approach limits the technical risks related to the product development itself (design, field distribution etc.). On the other hand, it allows TransnetBW to faster replace a faulty NOG-based piece of equipment in case of teething problems, as an AIS circuit breaker (CB) or instrument transformers (IT) can easily be replaced one-to-one on the existing foundations.

Based on the favorable market situation with NOG-based equipment from at least two manufacturers, TransnetBW decided to install 123 kV IT and CB for AIS as the first option starting 2023, excluding the SF_6 equipment. In parallel all projects are assessed, to identify the possibility of further trials with 123 kV GIS, 420 kV IT, CB and GIS, respectively. Based on this step several tons of SF_6 have already been prevented from coming into service.

For the time being the 420 kV NOG based CBs are still under development. TransnetBW is already in close contact with two manufacturers and searches already for locations to adequately test the new, innovative CBs as live tank for AIS and in GIS.

Table 1. Strategy to stepwise replace SF_6 against natural origin gases (NOG)

		2023 - 2026	2027-2030	Starting 2031
110 kV Grid	Instrument transformers and circuit breakers for AIS			
110 kV Grid	GIS			
380 kV Grid	GIB and instrument transformers for AIS			
380 kV Grid	GIS and circuit breakers for AIS			
Projects in execution and existing assets are not considered in this strategy. Projects will be executed as contracted. Existing assets will be operated „as is" till the end of their technical life. SF_6 and spare parts are required for their repair and maintenance.				

Installation of NOG-Equipment as standard products

On-site testing of NOG-Equipment within trial projects

2 Release of a new F-Gas-Regulation

The European *Green Deal* and the *fit for 55*-Program are meant to take us by 2050 to a climate neutral Europe. In Germany the climate neutrality needs to be achieved by 2045 and the German climate law shows the way to get there. In order to achieve these goals, the European Commissioned revised and released several regulations and laws. For the grid operators the most important one is the F-Gas-Regulation, which underwent its second revision and was released on March 11, 2024. Its main objectives are to discourage the use of F-gases with high GWP, to prevent leakage from equipment and proper end of life treatment of F-gases in all applications, and to enhance sustainable growth, stimulate innovation, and develop green technologies by improving market opportunities for alternative technologies. It clearly describes which gas mixtures can be used without any restrictions, and it provides derogations for other cases. Table 2 offers an outlook on these aspects.

Table 2. Requirements of the F-Gas-Regulation for the SF_6-alternatives (according to Art. 13)

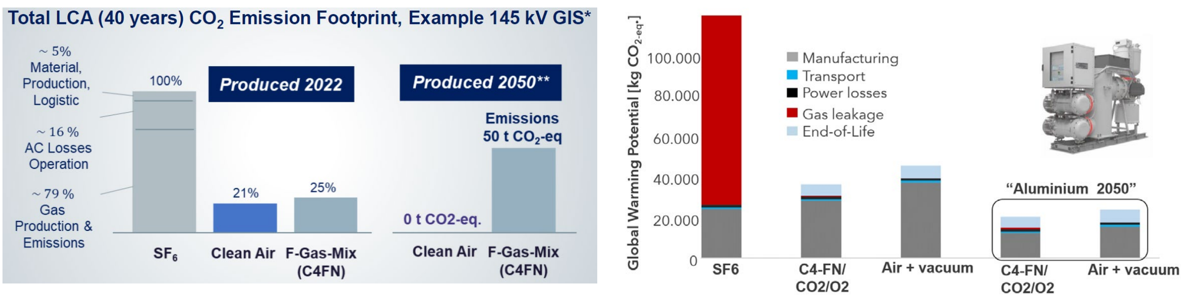
Medium voltage	≤ 24 kV	All F-Gases	01.01.2026
	> 24 kV…≤ 52 kV	All F-Gases	01.01.2030
High voltage	> 52 kV…≤ 145 kV, 50 kA	F-Gases GWP ≥ 1	01.01.2028
	> 145 kV or > 50 kA	F-Gases GWP ≥ 1	01.01.2032

Table 2 shows a strong alignment between the TransnetBW strategy and the F-Gas-Regulation. From TransnetBW perspective, this encourages a faster phase-in of the NOG-based equipment.

For those market segments wherefore NOG-equipment is still not available, the Regulation provides with derogation (Art. 13. Par.11, Art. 13. Par.12,) making possible the commission of equipment containing SF_6-alternatives based on gas blends with a GWP <1000. Another derogation is based on the eco-design directive (Art. 13. Par.15.). However, this directive still does not apply to switchgear. Furthermore, today it is unclear whether the existing eco-design directive will be reviewed and extended. Therefore, the authors do not take this derogation into consideration further in this paper. Nevertheless, TransnetBW is looking into the LCA of the equipment and the latest research is presented in the chapter 3 of this paper.

3 TransnetBW Research on LCA

Intensive discussions have taken place around the true CO_2-footprint of equipment based on different SF_6 alternatives, as well. Indeed, not only the gas leakage during erection, operation and scrapping leads to CO_2 emissions. There are plenty of other contributors, which needs to be considered, to elaborate a trustful life cycle analysis (LCA). An important contributor is the production of the aluminium from bauxite, which is a very energy-consuming process. This factor is especially important for the N_2/O_2-based equipment, as it is larger by design, due to the limited dielectric strength of the natural origin gases. This fact needs to be compensated by larger dimensions of equipment and by an increased gas pressure. Figure 1 presents the LCA results of two important GIS manufacturers, whose equipment relies on N_2/O_2 and vacuum interrupter (Manufacturer A – left) and a gas mixture based on C4-FN, CO_2 and O_2 (Manufacturer B – right). The results refer to a 145 kV GIS and an equipment lifetime of 40 years. Both manufacturers assessed not only its own product, but the competitor solution as well. Especially interesting from TransnetBW's perspective is the evolution of the LCA in the future. If today the use of more aluminium leads to considerable emissions due to its production, this CO_2-source will significantly decrease by 2050, when the power used by industry is supposed to be 100 % climate neutral. Based on this fact, the LCA proposed by the Manufacturer B shows almost similar CO_2 footprint results for both technologies. This study clearly indicates that despite of deployment of more material, the NOG-based equipment has a sustainable future.



Manufacturer A – relies on N_2/O_2 and vacuum interrupter [2]

Manufacturer B – relies on a gas mixture based on C4-FN, CO_2 and O_2 [3]

Figure 1. Life cycle analysis of 145 kV GIS of two European manufacturers

Another study of TransnetBW refers to the $CO_{2\text{-Äq.}}$ of two 420 kV combined IT (one filled with SF_6 and one with N_2/O_2) of the same manufacturer (Figure 2 - left). The calculation of the product carbon footprints (PCF) is based on OpenLCA-Software and the emission factors come from the Ökoinvent data base. The conversion factors were taken from the IPCC2013 report for a time span of 100 years (GWP 100). Five phases of the product life cycle such as, raw materials extraction and prefabrication, manufacturing of the product itself, installation, operation and end of life were considered for the LCA calculation. The shipment of the prefabricated to the factory were assigned to the manufacturing phase, while the shipment of the IT to the site and all required materials including the N_2/O_2, where assigned to the installation phase. The operation losses throughout the equipment lifetime were associated to the operation phase. The end-of-life phase includes all emissions related to the shipment of the equipment including its pole, concrete foundations etc. to the specialised recycling centre. The results concerning the $CO_{2\text{-eq}}$ emissions in all these phases are summarised in the Figure 2-right.

The first conclusion to draw is that, through the deployment of the NOG-IT, an overall reduction of the $CO_{2\text{-eq}}$ of about 23 % (mostly *Scope1* emissions) in comparison to the SF_6-IT is achieved. This reduction is directly related to the SF_6 emissions during operation and during the production of the SF_6 itself.

Secondly it can be noticed, that according to today's power mix over 70 % of the $CO_{2\text{-eq}}$ come for both ITs from the power loses during the operation phase. The continuous increase of green energy in the grid leads to the continuous reduction of the Scope 2 emissions, heading to 0 by 2045. Thus, it remains only the Scope 3-emissions which gives the PCF. Taking into consideration that, the manufacturers and their suppliers will also benefit from the greener power mix it results in a further reduction of the PCF. Under these circumstances only the deployment of SF_6-alternatives based on NOG enables the achievement of the lowest possible emissions level (close to zero).

TransnetBW intends to look into the LCA of further equipment such as AIS circuit breakers and GIS following the same procedure. The results will be shown in a future paper.

4 Grid expansion under the F-Gas-Regulation

As presented in chapter 2, one of the purposes of the new F-Gas-Regulation is to limit the $CO_{2\text{-eq}}$ emissions. However, by the time when SF_6 will be banned on all voltage levels, the amount of SF_6 in operation and the absolute quantity of leaked gas will increase due to the grid expansion required by the energy transition. Under these circumstances, there are two ways to limit the installation of SF_6: to phase-out SF_6 as fast as possible and to limit the installation of GIS, which requires large amounts of such gas.

The first way is the only solution to sustainably reduce the SF_6 emissions. To do so, the grid operators can choose between two alternative concepts. The first one is F-gas-free and based on NOG (N_2/O_2, vacuum interrupter or CO_2/O_2). The second alternative concept is based on F-gases, such as fluoronitrile (C4-FN, GWP = 2750), listed in the Annex 3 of the above-mentioned regulation. As presented in the chapter 1, TransnetBW decides to go for NOG only. The C4-FN-option is an emergency option which will be considered only when NOG equipment has not been offered. This is a way to always be compliant with all requirements of the F-Gas-Regulation.

The second way to limit the amount of SF_6 is to avoid the installation of the GIS (to be commissioned before 2028 and 2032 respectively) whenever possible by investing in land acquisition, relocating substations when they need to be renewed etc.

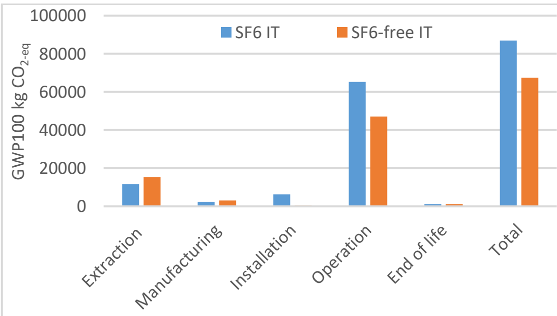


Figure 2. Comparison of PCF between all phases of an SF_6 and an N_2/O_2-IT

4.1 Grid expansion strategy

TransnetBWs grid expansion strategy foresees the AIS-concept as the first option in case new substations must be built or existing ones need to be renewed. This strategy also foresees the green-field instead of the brown-field construction, where the in-service substation needs to be step-by-step decommissioned and replaced.

Besides a less complex maintenance, repair and extension concepts, the AIS offers another significant advantage especially relevant for (at least) this decade. It allows the system operator to optimize the investments costs by choosing the most suitable and legal conform award strategies (turn-key vs. multi-contractor). In the case of AIS-concept the project scop can be easily split into several packages such as: primary and secondary planning and design, civil work execution, equipment delivery, equipment installation and commissioning etc. Through smaller packages a larger market can be addressed, leading to more competition which in turn implies important commercial advantages.

Although the AIS-concept offers significant advantage, it cannot be deployed at locations where a limited space is available. At these locations the GIS-configuration will be considered.

4.2 Know-How based on own projects

TransnetBW decided from the very beginning to consider only gas mixtures with a GWP ≤ 1 as SF_6 alternatives [1, 4]. Obviously, due to the missing request of SF_6-free equipment on 420 kV level, there were no such products available on the market in 2016 (Chicken-Egg-Problem). Consequently, the next major step was to identify those manufacturers, willing to start the development based on climate neutral gas mixtures.

4.2.1 Experience with F-gas-based gas blends

The first project aiming to support the development of an SF_6-free, double busbar, 420 kV GIS was awarded by TransnetBW in 2018 and taken into operation, as scheduled, in 2021. It has all passive components (indoor and outdoor) filled with a climate neutral gas mixture based on C5-FK, N_2 and O_2. The project is comprehensively described in [4].

Despite of a highly sophisticated GIS design from service continuity and accessibility perspective, the handling of such gas mixtures in this substation remains an extremely challenging task. As the SF_6-handling devices are not compatible to the C5-FK-gas mixtures, two sets of service carts, gas analysers, leakage detectors etc. were required. Additionally, the C5-FK-gas mixtures were prepared on-site before pumping them into the gas compartments. This is a complex task, which requires not only adequate mixing-devices, but a high level of expertise, as well.

Another challenge of this configuration is the difficulty to decide on how much gas mixture needs to be stored on site for repair or refilling. It needs to be considered that, in gas form a high number of cylinders are required in order to store a relatively small amount of gas. The number of gas bottles can be strongly reduced by gas compression, which in turn leads to the liquefaction of the gas mixture. Therefore, its homogenisation before toping up a gas compartment is mandatory. This step requires the use of an additional service devices and special expertise.

4.2.2 Experience with NOG-Equipment

TransnetBW awarded within a major grid infrastructure project the construction of probably the largest 420 kV GIS in Germany with 33 bays (including extension bays) – Figure 3. Alone the gas insulated busducts (GIB) of this switchgear account for more than 4000 m. Considering that the failure risk of the GIB is relatively low [5] in comparison to other switchgear elements (circuit breaker, disconnecting and earthing switches, instrument transformers), TransnetBW decided to test another SF_6 alternative with GWP<1, but this time, based on N_2/O_2 exclusively. Considering a gas mass of 4 kg/m of GIB at the operating pressure, it results that this measure leads to an SF_6 saving potential of about 16 t, which represents approx. 6,5 % of the total amount of SF_6 in the grid of TransnetBW.

Similarly, to the project presented above, the development of the NOG-based GIB was started after the project has been awarded. To mitigate the risks associated with the development of new products, several measures were agreed on together with the manufacturers.

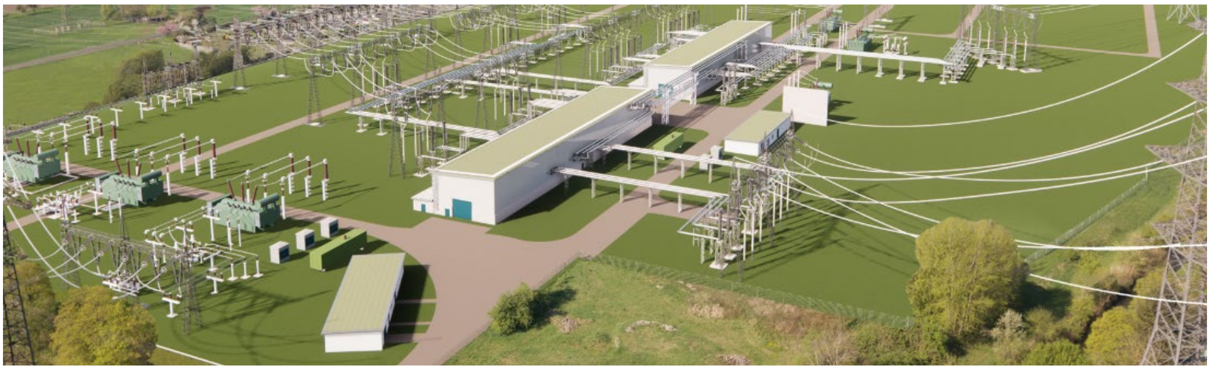


Figure 3. Design of the GIS with N_2/O_2-based GIBs

TransnetBW was allowed to witness the development progress and the quality tests in the factory. Additionally, TransnetBW, as end user, had had the chance to step out of the contract and to choose the SF_6-GIB, if challenges during the development had been faced. A time span of 36 months was set between the project award and the point of no return. After this milestone, the NOG-based GIB had to be accepted. On the other hand, to avoid delay of the civil works, TransnetBW committed to pay for the larger concrete foundations right at the beginning of the project. The larger foundations are required by the NOG-based GIB which are larger (diameter of 60 cm) and heavier than the SF_6 GIBs (diameter of 40 cm). A detailed project description is available in [2].
Gas handling aspects were discussed during the product development and the reduced complexity in comparison with the handling of F-gas-based blends was confirmed. The GIS modules can be topped up directly from commercially available gas cylinders. As this NOG-based gas mixture is a standard commodity, there is no need for its homogenisation before the filling process, which implies only the connection of the cylinders to the gas compartment over a universal pressure regulator. The same cylinder can be used for all pieces of equipment relying on N_2/O_2 gas mixtures (GIS, GIB, instrument transformers, AIS circuit breakers). From TSO perspective the simple and safe handling provides significant advantages, such as, less gas handling equipment, no need for additional mixing, shorter lead times, simplified procurement, logistic and storage, less resources and knowledge etc. This gas mixture can be released into the atmosphere, speeding up the gas works. Special safety equipment and procedures are only required, if heavily arced gas needs to be handled, i.e. only after internal arc faults or making of short circuit currents with make-proof earthing switches [2].
An open point is represented by the possibility to detect leakages on site. After installation the tightness of the GIS will be tested by filling the bays with helium following a well-known factory procedure. However, the detection of leakages during service remains a challenge. There are still no devices, which basically can detect air leakages in air. However, the manufacturer presents in [2] some practical methods meant to overcome this challenge.

4.3 Risks and Challenges

4.3.1 Coming regulations

The inventor and manufacturer of the C4-FN announced end of 2022, that it will exit the manufacturing of all PFAS (per und poly fluoroalkyl substances) by the end of 2025. Among these products are the C4-FN and the C5-FK [6]. However, the production of these substances has been taken over by some Asian manufacturers. All PFAS are highly persistent in the environment. Their release and mobility in water and air causes contamination to ground and drinking water. Certain PFAS are known to accumulate in the bodies of living beings and cause toxic effects. Certain PFAS are moreover toxic for reproduction and can harm the development of foetuses. Several PFAS have been demonstrated to cause cancer [2]. Therefore, there is at the European level an initiative intending to limit and respectively to ban the PFAS-based substances respectively. Presently the consultations are taking place, and a release of the regulation is expected by the end of 2030. It is unclear which PFAS will be restricted and for what applications. Therefore, deploying only equipment based on NOG as SF_6-alternative will prevent investments in technologies which can be potentially prohibited in the future.

4.3.2 Environmental health and safety aspects

The personnel safety and health are the highest priorities of TransnetBW. In this respect the NOG-based equipment provides highest advantages. The main core advantages are: GWP<1; extremely stable; environmental protection, health and safety (EHS) at work as gas handling are simple and with lowest risks and lowest safety measures compared with other SF_6 alternatives. Regarding EHS, the decomposition products are also of prime importance. Only with NOG there are no toxicological aspects to be concerned about, when operating high voltage products [2]. Consequently, NOG can be released into the atmosphere. Special safety equipment and procedures are only required, if heavily arced NOG needs to be handled, i.e. only after internal arc faults or making of short circuit currents [7].

In addition, there have been studies published showing that the by-products of C4-FN-based gas mixtures have a higher toxicity than the SF_6 by-products [8]. Other lab study reports on reproducible chemical reactions between C4-FN and gas moisture, resulting in crystal formation, despite of a technically dry gas with desiccants. The formation of polar crystal was observed especially in C4-FN, CO_2, O_2 mixtures being operating down to -10 °C [9].

4.3.3 Market availability and reliability

In the last years the development of AIS-IT und AIS-CB based on C4-FN and GIS based on C5-FK has been stopped and such products are not available on the market any longer. Their manufacturers changed their strategies and started the development based on other technologies. This led to stranded assets at the utilities as the equipment is already in the grid. The safe operation of such equipment over decades is difficult and involves very high costs. Therefore, from TransnetBW perspective it is of high importance to avoid such investments and to install sustainable equipment only. This target can be only achieved by working closely together with manufacturers with sustainable roadmaps whose equipment is meant to remain on the market over decades.

5 Phase-out SF_6, phase-in F-gas-free alternatives

In 2018, TransnetBW started a long journey to replace SF_6 in its electrical equipment with more sustainable solutions. The natural origin gases (NOGs) or gas mixtures with a GWP ≤ 1 have been preferred as SF_6 alternatives from the beginning. Based on experience from own projects, market analysis and considering the latest requirements by policymakers, TransnetBW published its own strategy on how to replace SF_6 only with NOG-based alternatives in 2022. This strategy is being carefully considered in all grid expansion projects, in order to ensure the availability of equipment and avoid delays in its implementation. Thes strategy is compliant with the present F-gas-Regulation requirements.

Based on this strategy, TransnetBW stopped installing SF_6-equipment below 123 kV in 2023. Since then, several NOG-based instrument transformers (ITs) and circuit breakers (CBs) have been installed and have been working flawlessly. Selecting NOGs as an alternative to SF_6 is seen as both a sustainable and future-proof solution. NOGs are safer to handle, with lower operation costs and lower toxicity of the by-products in comparison to other alternatives and SF_6. Furthermore, NOGs are not prone to be affected by incoming regulations (new revision of F-gas Regulation, PFAS Regulation etc.).

Due to the very good experience gathered with SF_6 instrument transformers (ITs), their replacement with NOG-based ITs rather than oil-insulated ITs is preferred by TransnetBW. They match the existing configuration of the substation (bay width) and only the foundations may need to be reinforced in some cases. Currently, there are about 120 oil-ITs (123 and 420 kV) in operation in the TransnetBW grid which are approaching their technical end of life and are planned to be replaced with SF_6-free ITs based on N_2/O_2 over the coming years. The selection of NOGs in insulation systems provides for synergy effects in terms of grid operation and maintenance, as both prequalified manufacturers use the same gas mixture. The same gas handling devices can thus be used for gas quality checks, refilling can be performed from the same cylinder, no additional expertise is needed etc.

With regard to CBs, there are two technologies on the market which are compliant with the TransnetBW strategy and current F-gas-Regulation. The first one is based on N_2/O_2 as insulation medium and a vacuum interrupter for arc quenching. The second technology uses a gas mixture of CO_2 and O_2 for both insulation and arc quenching. CBs using technologies of this type are already on the market for up to 123 kV and most applications are already covered. On the 420-kV level, there are currently pilot projects being initiated at TransnetBW to install new NOG-based CBs as well. It is planned to use both technologies (N_2/O_2 with vacuum interrupter and CO_2/O_2) and commissioning is scheduled for 2027. As far as 420-kV GIS is concerned, this remains the ultimate solution for those cases where an AIS substation cannot be accommodated. However, a NOG-based GIS remains the first option ahead of other solutions based on F-gases. The decision will be taken on a case-by-case basis in order to avoid delays in grid expansion and to remain compliant with the F-gas-Regulation at any time.

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