Grid Solutions

g³ THE SF_6-FREE SOLUTION IN PRACTICE

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In August 2014, GE unveiled g^3 (g cubed), its ground-breaking solution for replacing SF_6 in high-voltage equipment. Since then, g^3 products have been installed successfully in several countries (Figure 1), and g^3 lifecycle assessments have underscored the huge environmental benefits of the new gas mixture.

Figure 1: CERIUS' F35-72.5 kV g^3 gas-insulated substation, including six circuit-breaker bays, is located in Denmark

g^3 Equipment Portfolio

For about 50 years, SF_6 has provided the high-voltage equipment industry with good service, thanks to its exceptional arc-quenching and voltage-withstanding capabilities. Now, with the sustainability of the planet becoming an overriding, universal concern, the power transmission sector is looking for a replacement.

This is due to the global warming potential (GWP) of SF_6 being 24,300 times higher than that of CO_2, and the fact that it remains in the atmosphere for 1,000 years. Moreover, its atmospheric concentration has increased by 20% over the past five years.

The time is now to find and scale the adoption of a reliable and sustainable SF_6 substitute. After several years' of research, GE has done just that, with its g^3 solution – a gas mixture made up of CO_2, O_2, and a small percentage of an additive to increase the performance. This revolutionary gas mixture has the power to reduce the gas impact on climate change by 99%, in comparison to SF_6.

This performance is achieved through only limited modifications to the original equipment up to 245 kV. The breaker remains a single-chamber, self-blast breaker, using the same spring drive, and an overall unchanged footprint.

The g^3 equipment portfolio to date ranges from 145 kV gas-insulated switchgear (GIS), to 420 kV gas-insulated lines (GIL) (Figure 2), a 145 kV live tank breaker. All subsequent products will be made for g^3 and released to the relevant industry in their g^3 version. Such was the case with the latest developments shown at CIGRE in 2018 where the new 72.5 kV GIS and 145 kV live-tank circuit breaker were introduced.

Figure 2: A 420 kV gas-insulated line filled with g^3 at National Grid's new Sellindge substation in the UK

Figure 3: SF_6-free 145 kV live tank circuit breaker using g^3 switching medium installed at Groupe e's substation in Switzerland.

Grid operators globally who are concerned about the environmental impact of their operations have chosen the SF_6-free, g^3 technology from GE, ultimately reducing both their overall physical and economic footprint. g^3 adoption is increasing, given its equally reliable performance in comparison to SF_6, and the tremendously vital environmental benefits it delivers.

From SF_6 to g^3 gas: A Smooth Transition

Customers do not have to be concerned about mixing the g^3 components on site. Delivery of g^3 is just like that of SF_6, so the user is not required to combine the different components of the gas mixture. Instead, GE has established partnerships with leading industrial gas suppliers, including Air Liquide, DILO, Inventec, etc. These gas handling experts have developed specialized equipment and processes for g^3 mixing. They ensure the precise percentages of the different elements when transferring to cylinders, which are then shipped either to the customer factory or directly to the site.

Each large B50-size cylinder contains approximately 22 kg of the gas mixture in liquid state, and is used for large volumes such as GIS and GIL applications. The mixture is also available in gas form in 2 kg cylinders for gas-to-gas operations, such as topping up or filling instrument transformers. GE's partners have also developed special gas carts (for both small and large volumes) for the filling and recovery of gas mixtures, similar to the SF_6 equipment standards that users are already familiar with (Figure 4). A typical GIL or GIS installation can require anywhere between 10 and 50 B50 cylinders (Figure 5).

Figure 4: Air Liquide's g^3-filling cart in service at a National Grid site in the UK

Figure 5: g^3 cylinders being delivered to the customer site

For liquid-to-gas transfers, homogeneity of the gas mixture must be achieved to ensure the right ratio of the CO_2, O_2, and the additive. Specialized service carts enable this process, without operator interaction, by heating the cylinders through an automated process of induction or resistive heating (Figure 6). This is the only significant change when compared to SF_6 gas handling, where heating was required only in cold climate conditions.

Figure 6: g^3 cylinder with warming system

The same devices used for monitoring SF_6 gas purity and humidity have been adapted for g^3 oversight applications, now designed to verify the percentage content of g^3 components. Operators have been using these same tools for the past 40 years. Although they have been adapted, the principles are the same.

Figure 7: WIKA g^3-gas quality analyzer and a DILO g^3-gas quality analyzer

End-of-Life Management

Disposal and recycling are important concerns for grid operators. Since there are insufficient quantities of the g^3 mixture around today to warrant recycling, all decomposed products are disposed of by specialized partner companies. Any new gas can be re-used in the mixing plant. This highlights a clear parallel with SF_6 in its early days, when disposal was the norm as well. Over time, processes were introduced to separate the components, and now, even polluted products can be recycled. The same is expected to happen with g^3. GE is currently investigating two different approaches to recover the additive, both of which have shown some promise for the recycling and re-use of those mixture components in the future.

Lifecycle Assessment: A Positive Comparison

According to EU green procurement guidelines, the environmental impact of the whole product throughout its complete lifecycle should be evaluated in the sourcing and procurement phase (as opposed to only considering the gas global warming impact).

Lifecycle assessments (LCA) were performed on 420 kV GILs and 145 kV double busbar GIS – both SF_6-based and g^3-based – to compare their results. The aim was to evaluate:

- the reduction of impact on climate change, considering not only the gas itself, but the complete product over its whole lifecycle, from raw material extraction to end-of-life;
- the environmental impact of the g^3 solution on the other environmental indicators, compared to SF_6.

The assessments were carried out according to ISO 14040 and 14044 using SimaPro 8.3.0. and the International Life Cycle Data (ILCD) method, covering 16 environmental impacts, including climate change, ozone depletion, resource depletion, and toxicity, among others. The following entries were taken into account:

- manufacturing, including all materials contained in the complete switchgear bays, and accounting also for surface treatments and painting
- transportation (1,000 km on the road and 6,000 km on the sea)
- 40 years of service use, considering both power losses and gas leakages
- The end-of-life phase, taking into account that the gas is removed from the GIS and treated separately

Comparative LCA of 145 kV GIS with SF_6 and with g^3

In Figure 8, the results for the 145 kV GIS show that, compared to the SF_6 version, the SF_6-free product had a significantly lower negative impact on climate change (72.5% reduction) and resource depletion (18% reduction), respectively.

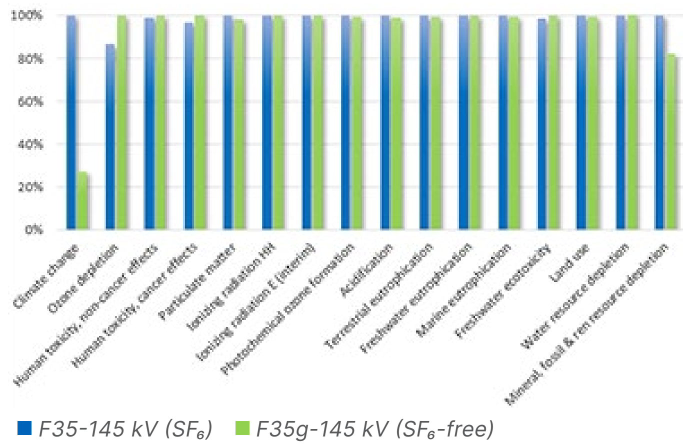


Figure 8: LCA comparison of F35-145 kV (SF_6) in blue, and F35g-145 kV (SF6-free) in green

With respect to the climate change indicator reduction of 72.5%, it is worth considering that aluminum (due to its production process) has the largest impact in the GIS manufacturing phase. Aluminum represents 65% of the product using SF_6, and only 4.4% more in GE's SF_6-free version. One of the main specifications for g^3 product design was to keep the same equipment size at equivalently-rated voltage. Had the GIS been designed any larger, the impact on climate change would have been even greater.

In terms of g^3's global warming potential, it has a GWP reduced by 98% compared to SF_6. When applied in the GIS, the GWP of the gas is further reduced by 99%, simply because the necessary gas mass of g^3 for one bay is half the necessary mass required for SF_6.

The g^3-GIS yields a 15% increased impact on ozone depletion. This is due to the greater use of polytetrafluoroethylene (PTFE) material in the circuit breaker to cope with the characteristics of the alternative gas. However, since PTFE quantities are very low, this increase is negligibly small (only 2.8 g of CFC-11 equivalent over the whole life cycle).

On the other 13 indicators, the difference is less than 5% between all other indicators, keeping them in the range of uncertainty of the LCA analysis. In other words, these environmental indicators remain virtually unchanged compared with those of state-of-the-art SF_6 GIS.

Comparative LCA of 420 kV GIL with SF_6 and 420 kV GIL with g^3

For the 420 kV GIL, the results in Figure 9 show that the use of g^3 brings about a considerable reduction in environmental impact, compared to the SF_6 product:

- for global warming, there is a reduction of 96% in environmental impact. This is an overall improvement, taking all parameters into consideration. The gas global warming effect specifically is reduced by 99.3%
- on all other environmental indicators, there is an average reduction of 14%.

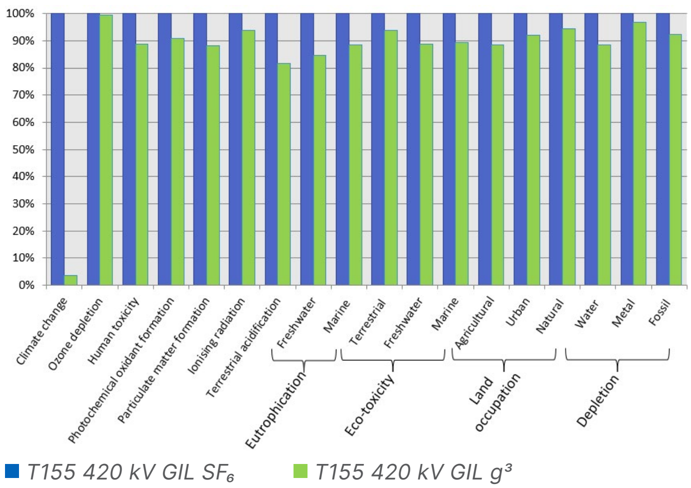


Figure 9: LCA comparison of 420 kV GIL with SF_6 (in blue) and 420 kV GIL with g^3 (in green)

While ozone depletion shows a minimal increase, g^3 - using the additive C_4F_7N in combination with CO_2 and O_2 as background gases - has a major positive impact on climate change and resource depletion indicators. In brief, g^3 offers the same technical performance as SF_6, with an environmental impact reduction of 99%.

g^3 Case Studies

At the time of writing, 22 utilities have opted for GE's SF_6-free HV equipment:

- 16 sites with 145 kV GIS, totaling 100+ bays with circuit breakers;
- One site with 420 kV GIS, totaling 9 bays with circuit breakers;
- Eight sites with 420 kV GIL, for over 5,000+ meters of gas-insulated lines;
- Four sites with 13 145 kV live tank circuit breakers

UK – England

The first g^3 products to be energized (in April 2017) were the 420 kV GIL at National Grid's new Sellindge substation in southeast England. Around 40 B50 cylinders were used, totaling more than 750 kg of the g^3 gas mixture. This represented approximately 38,000 liters distributed across 15 compartments, using the Air Liquide gas cart. The GIL equipment was filled during the winter, with ambient outdoor conditions around 10 to 15°C. The process was slightly longer than with SF_6, since the gas mixture needed to be heated by the gas cart's heating belt. However, on-site filling was carried out in parallel with other installation operations and equipment commissioning (Figure 10). The filling activity progressed normally, and the gas insulated lines have now been in operation for over a year and a half.

Figure 10: g^3-filling of the 420 kV GIL at National Grid's Sellindge substation, UK

UK - Scotland

Another g^3 project in the UK, a 420 kV GIL application for Scottish Power's Kilmarnock substation (Figure 11), was installed under harsh conditions, with heavy rain, snow, wind, and temperatures below 0°C. This was a test of the gas-handling process which, with gas carts made for indoor and outdoor conditions, progressed smoothly under the severe weather conditions. For this project, it was necessary to recover the gas mixture in the bushing – down to 0.5 bar – to reduce the pressure in the bushing for connection to the overhead lines. It was returned, intact, to the cylinders in liquid form. Once the connections were made, it was returned to the GIL at the right mixture percentages. This enabled the team to validate the process of gas filling, recovery, and re-filling in three different compartments.

Figure 11: g^3-filling under harsh weather conditions of the 420 kV GIL for Scottish Power's Kilmarnock substation, UK

Switzerland

This project using g^3 gas was delivered and tested onsite in March 2018 at an Axpo site in Switzerland (Figure 12). It features four bays of three-phase encapsulated 123 kV GIS and can operate, just like SF_6-GIS, down to -25°C. It was the first project featuring a circuit breaker using g^3 as the arc-quenching medium.

The gas mixture was delivered onsite, premixed in cylinders. The filling or evacuation procedure is similar to the procedure with SF_6 directly from the cylinder. A g^3-dedicated gas handling cart is used to fill or recover the gas from/to the GIS compartment (Figure 13). Gas quality analyzers, densimeters, filling valves, and the sealing system are adapted to g^3, but work the same way. Even the maintenance cycles remain the same. The site was energized in August 2018 (Figure 14).

Figure 12: Axpo's Etzel substation in the Swiss Alps

Figure 13: DILO's g^3-service cart used at Axpo's Etzel substation

Figure 14: 123 kV GIS with g^3 installed and energized at Axpo's Etzel substation in 2018

France

RTE, the French transmission system operator, ordered seven GIS bays at 72.5 kV rated voltage for its substation at Grimaud in France (Figure 15). This project is so far the largest F35 GIS, with g^3 gas installed at the customer site in September 2018. A dedicated g^3 service cart containing a cylinder heating facility was used to fill the GIS. The gas handling of g^3 is similar to the gas handling of SF_6; it needs an additional step of heating the cylinder to bring the mixture from liquid into the gaseous phase. After filling, the C_4F_7N content, O_2 content, and humidity in each compartment was confirmed using a g^3 analyzer (Figure 7).

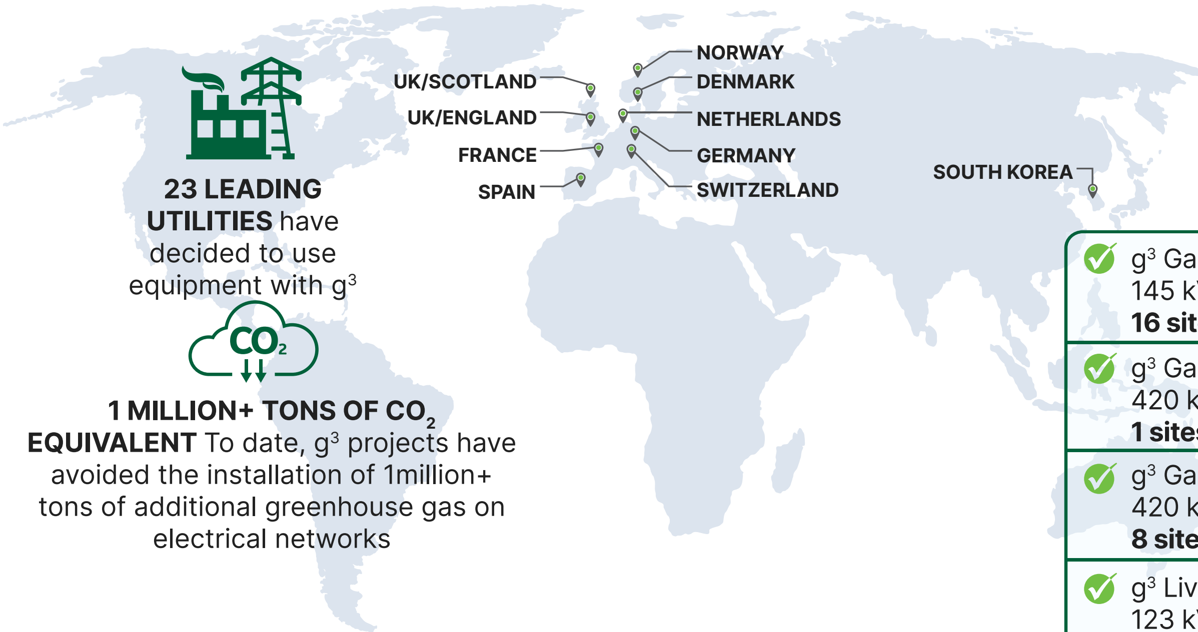
Figure 15: 72.5 kV F35 GIS using g^3 installed in RTE's Grimaud substation in France

Conclusion

These first applications demonstrate that the g^3 gas handling tools work reliably, even under adverse weather conditions, and that the gas filling process compared to SF_6 is practically unchanged.

Various g^3 projects are currently in their execution phase. They demonstrate how straightforward g^3 high-voltage products can be implemented throughout the manufacturing, engineering, project execution, installation, and commissioning phases. As shown in Figure 16, GE's g^3 products have already been adopted by 23 different utilities around the world.

g^3 Adoption



23 LEADING UTILITIES have decided to use equipment with g^3

1 MILLION+ TONS OF CO_2 EQUIVALENT To date, g^3 projects have avoided the installation of 1million+ tons of additional greenhouse gas on electrical networks

- g^3 Gas-Insulated Substations
  145 kV, -25 °C
  16 sites - 100 bays
- g^3 Gas-Insulated Substations
  420 kV, -25 °C
  1 sites - 9 bays
- g^3 Gas-Insulated Lines
  420 kV, -25 °C
  8 sites - 5000+ meters
- g^3 Live Tank Circuit-Breakers
  123 kV, -30 °C
  5 sites – 14 CBs

Figure 16: g^3 worldwide adoption

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