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420 kilovolts SF_6 gas-insulated substation

LifeGRID aims at developing a 420 kV/63 kA **SF_6-free** High-Voltage (HV) Circuit Breaker (CB) using **GE's g³ gas** to create the solution for SF_6-free HV **gas-insulated substations**

INTRODUCTION

Increasing urbanization, thus power consumption, is a trend that continues to grow. Electricity consumption is expected to more than double between now and 2050. Electrical grids must be adapted to face this trend. Power transmission system operators need to add high voltage electrical substations, replace existing ones, or upgrade to higher voltages. To supply urban zones with electricity while limiting the use of costly land, compact gas-insulated substations are used. They are so called because they incorporate all electrical apparatuses necessary in the substation in a sealed system that is insulated in a gas. For over half a century, sulfur hexafluoride (SF_6) gas has been used due to its excellent insulating and switching properties. Due to this design, the substation is compact and can be housed in a building or installed underground, making it almost invisible to the public.

SO, WHAT?

The temperature at the surface of the Earth rises during the day due to solar radiation and falls during the night as heat is lost due to infrared radiation. Greenhouse gases (GHG) are gases in the atmosphere that absorb and emit this thermal energy, leading to increased temperatures of the atmosphere. This process is the fundamental cause of the greenhouse effect.

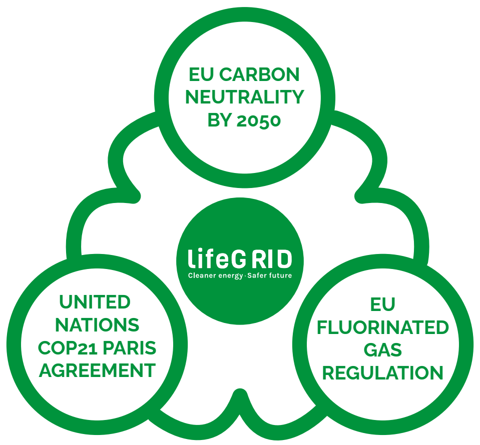
The most important GHG in the atmosphere are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, such as SF_6. Accumulation of atmospheric GHG contributes to energy entrapment and increased temperature on the planet. Global warming since the mid-20th century has predominantly been due to GHG emissions from human activities. The average annual temperature for the European land area over the last decade (2011-2021) was around 1.95˚C above the pre-industrial level, which makes it the warmest decade on record. Predictions about the average global warming rates by 2100 depend on the emission scenarios used. The Intergovernmental Panel on Climate Change (IPCC), which assists the United Nations on a scientific level, expects an average temperature increase on Earth of between 0.3 and 1.7 ˚C by 2100 compared to the period 1986-2005 (with the most ambitious scenarios for emission reduction) and 2.6 to 4.8˚C (for the less ambitious scenarios).

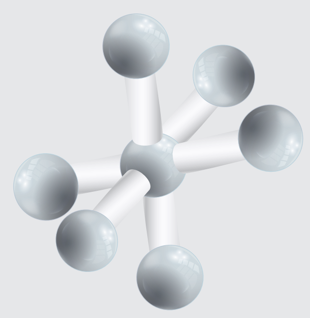
The IPCC has been alerting the public about the impact, adaptation, and vulnerability of climate change. The consequences are already extensive and widespread, both on land and in the ocean.

In Europe, the main risks identified relate to extreme climatic events such as droughts, floods or tornados, as well as local extinction of species, the disappearance of certain natural habitats, and the introduction and expansion of invasive species. The observed changes are expected to have serious impacts on our ecosystems, but also on the human socioeconomic sectors and human health and well-being. The IPCC emphasizes the urgent need to implement an ambitious mitigation and adaptation policy worldwide, which will determine the scale of the risks of climate change in the second half of the 21st century and beyond. These events show that climate change is a pressing concern of our society and that there is an urgent need to reduce GHG emissions to avoid the most adverse impacts of climate change.

Compared to CO_2, CH_4, and N_2O, the contribution of SF_6 to the overall GHG effect is small (less than 1%). However, given its high atmospheric lifetime and global warming potential (GWP), every source of SF_6 emission has a disproportionally large impact on global warming. In addition, F-gas emissions have risen by 60% since 1990 – in contrast to all other GHG, which have been reduced.

The potential for emission reduction in the high voltage industry is further underscored when you look at the quantity of SF_6 installed worldwide: approximately 10 000 tons are installed each year, with 80% concentrated in the high voltage power transmission industry. It is thus evident that, to fulfil the EU's climate goals, the use of potent GHG gases such as SF_6 must be prevented, and the adoption of alternative dielectric gases must be supported. Elimination of SF_6 from current use in the industry is therefore an absolute priority.





The issue with SF_6 gas

Due to its strong insulating and arc-quenching properties, SF_6 is widely used in substation equipment with the transmission industry accounting for approximately 80% of the world's usage. SF_6 belongs to the fluorinated gas family or F-gas. Identified as a potent greenhouse gas by the 1997 Kyoto Protocol, SF_6 is estimated to contribute 25,200 times more emissions than CO_2 when leaked and can remain in the atmosphere for up to 3,200 years.

LifeGRID in line with EU's plan

The LifeGRID project fully complies with the regulations and initiatives aiming to limit global warming.

At the European level:

The new European Green Deal claims to make Europe the first climate-neutral continent by 2050. As an intermediate step, the EU is targeting to reduce its GHG emissions by 55% in 2030 (vs. 1990).

> F-gas regulation (2014) in force
The regulation on fluorinated gases intends to reduce the use of greenhouse gases, including SF_6. It plans a cut by 2/3 by 2030, compared to 2014.

> The new F-gas regulation
As alternatives to SF_6 start to be available, the regulation is likely to propose a ban of SF_6 in switchgear. A report on SF_6 alternatives, issued by the EU commission, in September 2020 was highlighting fluoronitrile mixture benefits when it comes to performances and equipment size.

The story of an **ambition**

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LifeGRID: An initiative serving the climate

THE TARGETS

Our business objective is to help electrical utilities to get rid of SF_6 gas on their HV networks, thus moving them to environmentally friendly options like g^3 gas. To achieve this target, we must demonstrate that it is feasible to cover all main voltage ranges with g^3 technology. Our LifeGRID project is a key part of this ambition.

The main objective of the project is to replace SF_6 in HV circuit breakers embedded in gas-insulated substations (GIS) with a more sustainable alternative, GE's g^3 gas. The technical feasibility is already demonstrated at the 145 kilovolt (kV) level. However, the challenge is to scale it up to the highest voltage level in Europe, which is 420 kV. Ultimately, this will demonstrate that an SF_6-free European network is possible.

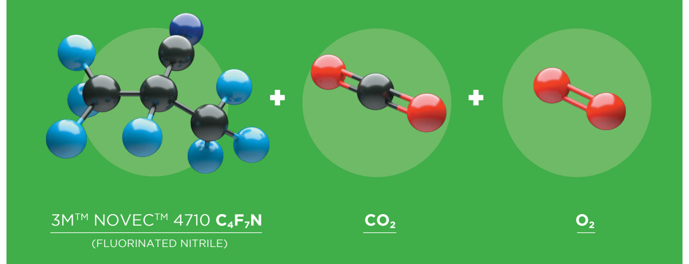
However, going to higher voltages/currents requires an innovative combination of gas mixture fine-tuning and component adaptations (mainly the circuit-breaker interrupting chamber) to show capabilities for a fully-integrated future-proof SF_6-free GIS circuit breaker at higher ratings. It also requires a better understanding of the behavior of the g^3 gas mixture and its by-products that occur when the circuit breaker is switching. In fact, as an electrical arc occurs during switching, the temperature in the equipment increases drastically, bringing the molecules into a plasma stage leading to the decomposition of the gas mixture.

The cost of the final breaker, as well as the time to market and the duration of the project also need to be considered to best define the solution.

Finally, a life-cycle assessment of the new g^3 circuit breaker should be carried out to evaluate its positive global impact on the environment. The results will be officially made available in an Environmental Product Declaration (EPD). This will help utilities assess the global impact of their future 420 kV substation projects.

About GE's g^3 gas

GE's alternative to SF_6 is g^3 insulating and switching gas, representing the culmination of a decade of research and development by its teams in France, Germany, and Switzerland in collaboration with 3M Company. The g^3 gas mixture is based on carbon dioxide, oxygen, and 3M™ Novec™ 4710 Dielectric Fluid from the 3M fluoronitrile family. Fluoronitrile was identified by GE's Grid Solutions R&D experts as the most suitable additive to CO_2 and O_2 to reach the targeted environmental benefit of an alternative to SF_6, without compromising the equipment's technical performance and footprint. As a result, the contribution of the gas to global warming is reduced by 99% compared to SF_6.



What is a GIS circuit breaker?

GIS or gas-insulated substations are protective equipment dispatched all along the electrical grid. A GIS is composed of gas-insulated bays and busbars (lines).

The HV circuit breaker inside the GIS bay, the focus of our project, is one of the main electrical components of the bay. In case of a problem on the grid, the circuit breaker cuts or redirects the power through another path to avoid blackouts. LifeGRID's 420 kV g^3 GIS CB development has been realized by GE's Grid Solutions Research Center in Villeurbanne, near Lyon, France. The circuit breaker's SF_6 mass represents roughly 25% to 30% of the SF_6 used in a single bay.

The other SF_6-free bay components and the gas-insulated line were developed in parallel by GE's team in Aix-les-Bains, France.

BRNO UNIVERSITY OF TECHNOLOGY

INP FROM IDEA TO PROTOTYPE

THE METHOD

A circuit breaker ("CB") consists of mechanical switching devices that connect and break current circuits (operating and fault currents) and carry the nominal current in closed position. They are used for protection purposes and eliminate overcurrent, overload, and short circuits, helping to prevent damage to the substations and the electrical network.

To demonstrate its ability to work properly, a CB must meet standard specifications in several areas, such as dielectric withstand, heat rise, mechanical endurance under extreme climatic conditions, and breaking fault currents.

This last item is the most critical part in the development of a CB as it combines many inter-connected physics, linked to the creation of an arc during the switching operation. Indeed, fluid mechanics, heat transfer, and radiative and plasma control are critical technical topics that lead to specific behavior inherent to CB operational conditions. It is of utmost importance to keep this phenomenon under control to ensure reliability and electrical endurance.

To do so, several design adjustments of the breaking chamber must be done to accommodate g^3 properties, which are different than SF_6. Those adjustments are defined by simulation along with full-scale breaking tests, as simulation is not completely predictive.

ELABORATION OF A MULTI-PHYSICS MACROSCOPIC NUMERICAL SIMULATION MODEL

Numerical simulations are an innovative way to save money, time, and unnecessary assessment on physical components, thus embedded carbon. However, the results provided by the models must be corroborated by real-life test results to be validated.

Under breaking conditions, metallic contacts of the CB are opened, leading to the creation of an electrical arc, which is necessary to dissipate the energy stored on the grid. The local temperature at the core of this arc can approach 30,000 °C. Due to the dissociation and ionization of the insulating gas between the electrodes, plasma is created. The latter includes elementary particles, being a mixture of the insulating gas and fluorocarboned gases as a consequence of the Teflon-coated part's erosion. Throughout the breaking, significant heat transfer occurs. The composition, temperature and local pressure (which can reach hundreds of bars) define the plasma. The cooling of the arc is operated through thermal convection, natural conduction, turbulent conduction, and radiation losses that involve the erosion of the Teflon parts.

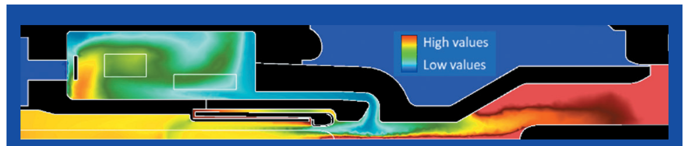
Detailed analysis of switching operation, including the device design, can be obtained by magneto-hydrodynamic simulations. The corresponding models use thermodynamical properties, transport, and radiative absorption coefficients for g^3 in the initial stages, as well as for gaseous products that appear due to decomposition during the arcing and recombination processes in the post-arc phase.

Within this project, various mixtures consisting of C_4F_7N (3M's Novec 4710) (from 3.5% to 10%), CO_2, O_2, and C_2F_4 in a temperature range from -23 °C to 40,000 °C and pressure range from 0.01 to 150 bar have been considered. Working with different mixture definitions was important for the validation phase since results can be analyzed in their variations and compared with study results for specific mixtures like pure CO_2.

The calculations of the gas mixture properties demand specific equipment and very powerful computers. That is why this part of the project was attributed to our two academic partners, the Faculty of Electrical Engineering at Brno University (BUT) in the Czech Republic and Leibniz Institute for Plasma Science and Technology of Greifswald (INP), in Germany.

BUT was in charge of the determination of the plasma composition, the detailed thermodynamical, and radiative data. INP worked on the transport properties, namely dynamic viscosity, thermal conductivity, and electrical conductivity for g^3 gas with various admixtures of CO_2, O_2, and C_2F_4. The understanding of these arc properties, such as the amount of energy transferred by conduction, convection of the Joule effect within the plasma, and between the arc and surroundings, is crucial.

As a result, a completely new database of gas properties in specific conditions was created and was applied on the numerical modelling in the circuit breaker. For that purpose, GE engineers worked with Computational Fluid Dynamics (CFD) methodologies as implemented in existing numerical analysis solutions such as ANSYS. They integrated the gas properties database and performed the configuration of a model to do the realization of the simulations and adjust the CB design.



Modelling of the arc in the interrupter

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CIRCUIT BREAKER DESIGN

In the first phase of the project, one major decision had to be made: should we keep the 420 kV single breaking chamber design in use today with SF_6 or move to a double-breaking chamber design (2x245 kV)?

420 kV CBs switching means dealing with significantly higher energy levels. The existing g^3 gas data for 170 kV CBs could not be applied directly to solving the 420 kV CB design problem. Accordingly, a decision was made to develop a double-chamber 420 kV 63 kA circuit breaker made of two 245 kV 63 kA CBs in series. The additional benefit of this design helps prepare for the future design of the 245 kV CB.

In order to determine the technical adjustments needed to reach 245 kV 63 kA with g^3 gas, our first approach was to perform breaking simulations using the g^3 gas properties obtained during the action working on the elaboration of the multi-physics numerical mode.

In total, more than 1,400 calculations on more than 70 different designs were necessary to figure out which technical adjustments had to be made to achieve this project successfully. This led to the assembly of 12 different prototypes and the demonstration of the main performances according to international standards.

This proved the feasibility of the g^3 technology to reach the highest voltage levels and allowed us to pursue the demonstration at full-scale 420 kV level.

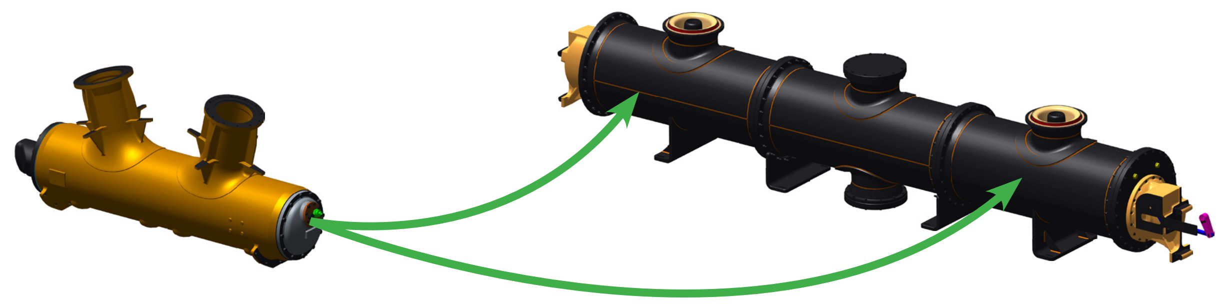
Full-scale electrical endurance assessment at the CERDA laboratory, Villeurbanne, France

During this phase, the contribution of our first customer, SSEN Transmission, was tremendous, bringing customer insights and expectations, participating to the definition of the specification. This phase also witnessed the most demanding type tests to validate the proper operation of the CB once integrated in the GIS.

INTEGRATION OF THE TWO 245 KV INTERRUPTER IN THE FULL-SCALE DOUBLE-CHAMBER GIS CB

After the design optimization was performed on 245 kV - 63 kA chamber, we focused on the realization of a pilot of a 420 kV 63 kA double chamber g^3 GIS circuit breaker in order to have an in-depth integration assessment of the apparatus based on utility requirement.

Extensive work on CAD design was performed on the 420 kV - 63 kA double chamber mock-ups to integrate the 245 kV interrupter design and define the best architecture and tank design to connect the two chambers together. During this phase, we built 10 prototypes that we submitted to the tests defined by the IEC standards.



245 kV single breaking chamber — 420 kV double breaking chamber

In March 2022, GE was very proud to announce the first SF_6-free 420 kV g³ GIS circuit breaker during a virtual seminar in front of 90 utility and industry representatives and colleagues.
Since then, the final prototypes have been tested. The post-LifeGRID project began in October 2022 with the integration of the double chamber circuit breaker into the gas-insulated substation while the industrialization team in Aix-les-Bains, France, prepare the manufacturing process of the other 420 kV bay components. Commercial release of the SF_6-free GIS with the g³ circuit breaker is planned for 2023.

ENVIRONMENTAL IMPACT MEASUREMENT

It is important to remember that the CB is not the final product, but one of the components embedded in the substation. This means that the evaluation of the environmental and socio-economical impact can only be partial. We will need one more year until the integration of the CB into the GIS has been completed to measure the total impact of the new 420 kV g³ GIS. This life cycle assessment (LCA) will be part of the post-project dissemination plan.
To evaluate the environmental impact, specifically the CO2 equivalent emissions of our project, we proceeded to an LCA of the g³ CB to compare it with the results of a SF_6 CB.
The importance of the LCA was highlighted on the EU Commission website by T&D Europe, the European association representing the Transmission and Distribution industry, in its feedback on the EU latest "F-gas" regulation draft: "The Members and Associates of T&D Europe would like to remind that the Life Cycle Assessment (LCA) method according to ISO 14040/44 is the state-of-the-art tool to evaluate the impact of products and systems on the environment. The GWP of the gas alone does not enable to assess the global carbon footprint of the electrical switchgear."

However, the EU is targeting the carbon emissions on the continent. That is why we needed to evaluate the impact of our future SF_6-free GIS (including our LifeGRID CB) in terms of g³ gas losses and compare them to SF_6 losses.

To do so, we can consider the Kintore substation that will be the first project benefiting from the new 420 kV g³-GIS. Replacing the SF_6 gas with the g³ gas will help avoid the emission of some 29,000 tons of CO_2e. Now, let us consider the impact of the installation or the first 100 g³ GIS bays in the coming years. These 100 bays alone will save the emission of more than 326,000 tons of CO_2e.

Test witnessing by Matthew Barnett from SSEN Transmission in May 2022

Kintore
350,000 tons less CO_2e
on SSEN Transmission's grid in Scotland

Scottish & Southern Electricity Networks
TRANSMISSION

SSEN Transmission joined our LifeGRID project in 2020. Since then, the Scottish utility has worked closely with GE to help best specify the performance of the new SF_6-free circuit breaker.

To support their decarbonization goals, SSEN Transmission awarded a contract to GE's Grid Solutions for the delivery of the world's first SF_6-free 420 kV g³ gas-insulated substation to be installed at Kintore in Aberdeenshire.

The installation of GE's nine bays of 420 kV g³ GIS and roughly 2 km g³ GIL at Kintore supports SSEN Transmission in getting closer to its carbon reduction targets by building the transmission infrastructure necessary to connect and transport large quantities of renewable energy. It also prevents the addition of about 350,000 tons of CO_2 equivalent on the Scottish grid.

Finally, this contract is a major earning of our project as it will help us to reach stage 4 of LifeGRID: cooperating with a high-voltage network operator to set up a pilot. This is a major step before we can replicate the technology on other European transmission networks.

SOCIO-ECONOMICAL IMPACT

As the integration of the CB and the industrialization process of the GIS start in October 2022, commercialization of the full SF_6-free GIS is planned for 2023. This means that the return-on-investment can only begin in 2024 with the first installations at customer substations. The successful achievement of the LifeGRID project and the availability of the 420 kV g³ GIS bay at the end of 2022 have already motivated several utilities in Europe to specify an SF_6-free alternative in their calls for tender for 420 kV substation projects, which allows us to see an increasing interest in the technology and a high sales potential in the coming years. We received our first contract for nine g³-GIS bays from SSEN Transmission in December 2020.

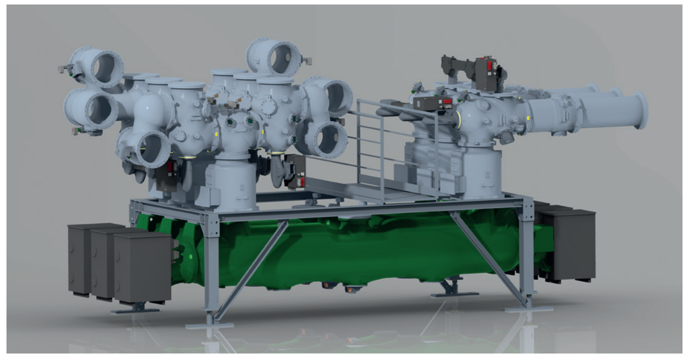
In addition, we have entered into a cross-licensing agreement with another major manufacturer in Europe during the project, which will help the standardization of our g³ gas technology, and thus of SF6-free, alternative gas equipment. Meanwhile, other HV GIS manufacturers are also showing interest in the g³ technology, the only one allowing them to reach 420 kV at the time-being. In addition to the high voltage field, a medium voltage (MV) equipment manufacturer is also planning to develop submersible switchgear based on a g³-like gas mixture.
In parallel, Nexans, a cable manufacturer, has begun to develop and launch AC and DC g³ gas-insulated cable terminations.

NEXT STEPS

The main action after the end of the project is to complete the integration of the circuit-breaker compartment into the 420 kV g³ GIS bay that was developed in parallel and prepare the industrialization process. Commercialization of the full g³ GIS bay is planned in 2023. Production and delivery of the first nine bays dedicated to SSEN Transmission's Kintore Substation are planned in 2024.
In parallel, thanks to the confidence of the EU LIFE Programme into our g³ technology, we have launched two new LIFE projects, namely LIFE SF6-FREE HV CIRCUIT BREAKER and LIFE SF6-FREE GIS. Both projects are about applying the expertise and knowledge acquired during the LifeGRID project to downscale the technology to the 245 kV voltage level, for which no SF_6-free solution is available yet.
In the first three years after the end of this project, we plan to continue to proactively communicate the project's next key achievements. We will proudly announce the launch of the full 420 kV g³ GIS bay, the next contracts, but also the first delivery, the first energization at the Kintore substation through press releases and news segments on GE's Grid Solutions website and on the project website, www.lifegrid.eu. We also plan to continue to participate in exhibitions showing the interrupter and have our R&D experts sharing the expertise acquired during the project with their peers in the power industry. Finally, once the LCA of the complete GIS bay is completed, we will update our g³ app, allowing those interested to be able to calculate the reduction of the CO_2e of their future substation with our 420 kV g³ GIS bays and busbars. And finally, we anticipate continued exchanges with regulators, standardization bodies, and policy makers to help them set new rules and standards allowing the EU to decarbonize its electrical grids as quickly as possible.

LifeGRID interrupter exhibited at the CIGRE booth

LifeGRID team with the 420 kV g³ GIS mock-up



GE's SF_6-free T155g 420 kV GIS bay with LifeGRID's g³ circuit-breaker

This strong communication/dissemination strategy emphasizing the best practices of the LifeGRID project will help us establish new collaborations with industrial players, as well as European associations in order to further develop the g³ product portfolio and complete it in 2026 to cover all European voltage levels. This will help electrical utilities move away from SF_6 and achieve their carbon reduction targets faster.

CONCLUSION

The positive impact and awareness raised by the LifeGRID project is clear considering that we have achieved the development of a g^3 GIS circuit breaker at 420 kV, the most challenging voltage level in Europe, opening the door for a full deployment of an alternative to SF_6. The involvement of SSEN Transition was a determining factor. In contracting GE for the delivery of the 420 kV SF_6.-free GIS for the Kintore Substation, SSEN helped attract the attention of other utilities and equipment manufacturers. In addition, another company in Europe selected g^3-like mixtures to develop its HV equipment. Also essential was the confidence placed by the EU Commission's LIFE Programme as they co-funded an additional project in 2020 (development of a g^3 life tank circuit breaker at 245 kV) and another one year later (development of a 245 kV g^3 GIS). Finally, the fact that we were able to exhibit our 420 kV SF_6-free solution with g^3 gas at CIGRE in Paris in September 2022 was a strong signal to all in the industry (equipment manufacturers, electrical utilities, standardization bodies, and regulators) that the gas technology is the right solution to remove SF_6 completely without delay from electrical grids in Europe and – in the future - worldwide. The adoption of the solution by the utilities continues to increase, allowing the replication of the LifeGRID results through all of Europe and beyond.
The LifeGRID project fully contributes to achieving the objectives of the European Union to reduce EU's carbon footprint by 55% before 2035.

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Think Grid Magazine/Grid Sustainability

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PROJECT NAME
LIFEGRID

SUMMARY
The LifeGRID project aims at developing a 420 kV-63 kA SF_6-free high voltage circuit breaker using GE's g^3 gas to create the basic solution for SF6-free high voltage gas-insulated substations.
This project is a key step to help develop other high voltage switching equipment and, with their deployment, decarbonize high voltage electrical grids.

PARTNERS
The core of the project is based at GE's Grid Solutions research center in Villeurbanne, France. Collaboration partners are the Faculty of Electrical Engineering at the Brno University of Technology (Czech Republic) and the Leibniz Institute for Plasma Science and Technology (Germany). They developed the properties data base of the g3 gas mixture.

PROJECT LEAD PROFILE
Born in Selestat, Yannick Kieffel received his PhD in Physics from the University of Grenoble in 2001. Currently CTO of the HV Products product line, he began his work on an alternative to SF_6 in 2008 and announced GE's SF_6-free solution, the g^3 gas, in 2014. Since then, he has been supporting product development based on this new gas.

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