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Paper Title: Pilot projects and ongoing activities in Japan for phasing out SF_6 gas

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SUMMARY

Currently, SF_6 gas is used in gas insulated switchgear and other equipment for both electrical insulation and arc quenching. However, SF_6 alternative gases are being discussed in Europe and North America from the viewpoint of preventing climate change since SF_6 gas has a high global warming potential of 25,200. In 2015, the United Nations General Assembly adopted 17 Sustainable Development Goals as international goals for the period up to 2030, and efforts are being made around the world to achieve the Paris Agreement target, 80% reduction in greenhouse gas emissions.

The percentage of GIS and GCB equipment that uses SF_6 gas as an insulating medium in TEPCO PG accounts for more than 90% of the total. Therefore, adoption of non-SF6 technologies is necessary to achieve carbon neutrality by 2050.

This paper reports on the process and evaluation results of the application of a GIS without SF_6 gas in the renewal of a 72 kV GIS. The pilot installation at the Fuchu Substation satisfied the seven requirements for replacement of SF_6 discussed in Japan. The equivalent carbon dioxide emissions are estimated to be reduced by 73% compared to the current SF_6 GIS.

KEYWORDS

SF_6 alternative, pilot project, natural origin gas, synthetic air, gas-insulated-switchgear, life cycle, greenhouse gas, carbon neutral

1 Introduction

Currently, SF_6 gas is used in gas insulated switchgear (GIS) and other equipment to insulate the equipment and interrupt the current. However, SF_6 alternatives are being discussed mainly in Europe and North America from the viewpoint of preventing climate change since SF_6 gas has a high global warming potential (100-year GWP) of 25,200 [1]. In 2015, the United Nations General Assembly adopted 17 Sustainable Development Goals as international goals for the period up to 2030, and efforts are being made around the world to achieve the Paris Agreement target, 80% reduction in greenhouse gas (GHG) emissions.

In October 2020, Japan declared that it aims to achieve carbon neutrality by 2050. Against this backdrop, the Ministry of Economy, Trade and Industry, in collaboration with other ministries and agencies, formulated the “Green Growth Strategy through Achieving Carbon Neutrality in 2050” [2]. Decarbonization of the power sector is a major component of the strategy where a 46% reduction in greenhouse gas emissions by 2030 compared to 2013 levels has been set as a goal for the entire industry. Also, in the power transmission and distribution sector, based on the development roadmap of SF_6 alternative gas switchgear as shown in Figure 1 [3], discussions have started among the Transmission and Distribution Grid Council (TDGC) members. This roadmap is proposed by the Japan Electrical Manufacturer’s Association (JEMA) which represents electric power equipment manufacturers within the TDGC. TEPCO PG is the first among Japanese utilities to introduce synthetic-air insulated switchgear.

This paper introduces the process that lead to the pilot project, evaluations of each SF_6 alternative solution, and operational matters compared to SF_6 gas equipment.

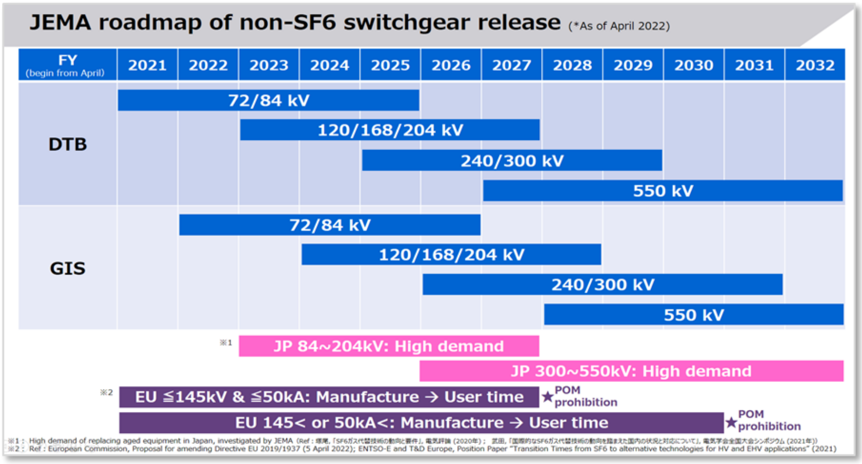


Figure1: JEMA's Development Roadmap[3]

2 Process leading to the pilot project

2.1 Motivation for applying SF_6 alternative switchgear

Figure 2 shows the percentage of TEPCO PG equipment that uses SF_6 gas. Figure 2 indicates that switchgear represented by GIS and GCBs accounts for more than 90% of the total equipment. Therefore, it is necessary to introduce SF_6-alternatives in order to reach “Green Growth Strategy Achieving Carbon Neutrality by 2050” objectives.

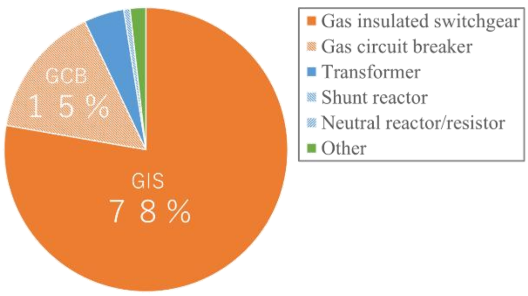


Figure 2: Percentage of SF6 equipment owned by TEPCO PG by in FY2021

As shown in Figure 3, the SF_6 gas-insulated switchgear in operation at TEPCO PG is aging gradually. Planned replacement is being implemented since the number of early-type GIS/GCBs that are over 35 years old is increasing. The maintenance period of early-type equipment has often expired, leading to replacement on a priority basis, for example, at the Fuchu substation.

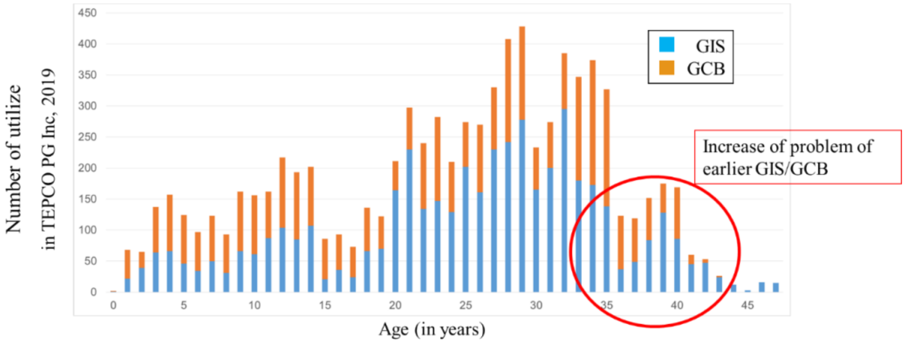


Figure 3: Age distribution of operating GIS and GCB in TEPCO Power Grid in 2019

2.2 Current actions of SF_6 alternative solutions within TEPCO PG

Each solution was evaluated based on the "Seven requirements". These are application guidelines developed through discussions of the SF_6 alternative gas study group, which was established in April 2016 by Japanese industry and academia [4-6]. The “Category” column of Table 1 outlines the seven requirements. As a result of the evaluation, from the viewpoint of accountability to stakeholders, the importance of environmental health and safety (EHS) and especially toxicity, was the top priority.

Table 1 : Evaluation of various gases against the "Seven requirements"

No.	Category	F-gas			Natural origin gas	
		SF_6	C4-FN mixture	C5-FK mixture	N_2/O_2 (synthetic air)	CO_2/O_2
1	**EHS;** GWP/TLV-TWA*	**25,200**(*1) / 1,000ppm	2,750(*1) / **65ppm**(*2)	1 / **225ppm**(*3)	0 / infinite	1 / 5,000ppm
2	**Service condition ;** liquefaction temperature	> -20 ℃	> -25 ℃	**> 5 ℃**	> -183 ℃	> -78.5 ℃
3	**Stable supply**	multi vendors	single vendor	single vendor	multiple vendors	multiple vendors
4	**Gas handling;** mixture and control	single gas	mixed gas	mixed gas	mixed gas	mixed gas
5	**Life cycle cost**	present standard	up (*4)	up (*4)	up (*4)	up (*4)
6	**Footprint**	present standard	same	same	up	up
7	**Voltage coverage;** GIS/GCB for insulation / switching(*5)	1000 kV / 500 kV	1000 kV / 420 kV	420 kV / 170 kV	420 kV / 145 kV	170 kV / 170kV

(*) EHS: Environment, Health and Safety, GWP: 100-year global warming potential, TLV-TWA (Threshold Limit Value - Time-Weighted Average) is the concentration limit for workers based on a lifetime of exposure. A lower limit implies higher toxicity.

(*) The GWP and TLV-TWA values represent pure gases. Therefore, for a practical gas mixture, GWP might be lower and TLV-TWA might be higher (less toxic).

(*1) Value referred from AR6 (IPCC Sixth Assessment Report) [1], (*2) Value for C5-FK [7], (*3) Value for C4-FK [7], (*4) Assumption of increase in cost resulted in the size-up and gas handling compared with SF_6 gas equipment, (*5) Current development status based on CIGRE TB 871 [8]

Currently, in the voltage class of 168 kV or lower, natural-origin gases (NOG, such as synthetic air, etc.) are the most suitable solution. NOGs can be released into the atmosphere without risk of poisoning or asphyxiation – permitting long-term confidence in EHS and zero gas supply risk. Therefore, TEPCO PG decided to apply the first Japanese GIS with NOG to Fuchu substation. This pilot solution is expected to be put into commercial production in the next few years according to JEMA's development roadmap shown in Figure 1. TEPCO PG also has replacement plans for additional 72 kV-GIS.

3 Typical considerations for Fuchu substation GIS replacement

3.1 Suitability according to the guideline “7 requirements” for SF_6 alternative technology

This section evaluates the suitability of the developed technology for specific replacement projects. Table 2 shows the results of the evaluation of the suitability of seven requirements for the natural-origin gas GIS to be applied to the Fuchu Substation.

In the evaluation, safety and environmental compatibility are the highest priority among the requirements. In addition, a vacuum interrupter is used in the circuit breaker, and the generation of decomposition gas due to short-circuit current interruption is considered to be extremely small. In the case of current interruption in the disconnectors and earthing switches, nitrogen oxide (NOx) are mainly generated as decomposition gases, but safety is assured similar to SF_6 gas equipment. Also, the environmental compatibility is satisfied since CO_2e emissions are expected to be reduced by 73% compared to SF_6 GIS. This assumes 40 years of lifetime operation from manufacturing to disposal, thus contributing significantly to the reduction of CO_2e emissions.

Table 2: Suitabilities according to the guideline “Seven requirements” for SF_6 alternative technology

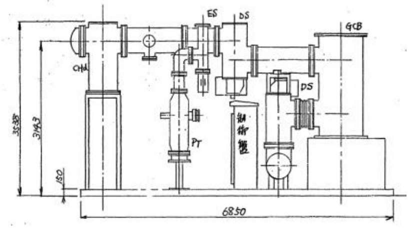
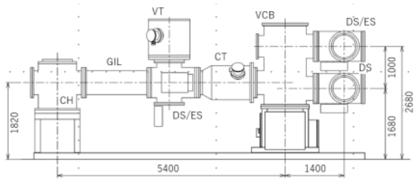
Requirements	Suitabilities
Environment Health Safety (EHS)	✓ No risk of poisoning or suffocation ✓ No decomposition gas generation due to short-circuit current interruption ✓ 73% CO_2e emission compared with SF_6 over a 40-year lifetime
Service condition	✓ Outdoor operation ✓ Liquefaction temperature is sufficiently low to allow operation in normal conditions as specified in the Japanese standard (JEC).
Stable supply	✓ No supply risk as it is a common industrial gas
Gas handling	✓ No need for special equipment because of pre-mixing and supply ✓ Can be released into the atmosphere
Life-cycle cost	✓ Reduction of ancillary costs associated with gas management ✓ Capacity of production and initial cost reduction in case of large-lot production by applying module components with SF_6 GIS
Footprint	✓ Dimensions to enable renewal of older existing facilities ✓ Transportation as a complete unit is possible ✓ Existing foundations can be reused
Voltage coverage	✓ Select and apply appropriate technology ✓ Development target up to 500 kV is possible

3.2 Compactness for replacement of GIS

When dry air is used as the insulating medium, its insulating performance drops to about 33% compared with that of SF_6 gas, and the pressure rise is about 3-4 times higher if an internal breakdown were to occur [9]. Therefore, the breakdown voltage value and heat dissipation characteristics are improved by applying an insulation coating to the high-electric-field portions of the inner conductor. Also, the structure of the switchgear and arc quenching method have been improved to reduce the size of the unit. In addition, a pressure release device is applied to protect against a sudden pressure increase in the pressure vessel in the event of an internal arc. The strength design within the fault removal time with protection relay is the same as for SF_6 GIS.

As a result, as shown in Table 3, the installation area is equivalent to that of the existing early-type SF_6 GIS, and the layout enables the replacement of existing facilities including underground substations.

Table 3: Comparison between natural origin GIS and conventional SF_6 GIS at Fuchu substation

	Existing early-type SF_6 GIS	Natural Origin GIS
Overview		
Footprint	100%	100% (Without GIL and with split-type current transformer; 65%)
Weight	100%	96%

3.3 Operation

Synthetic air used in this project is general industrial air consisted of N_2/O_2 (80%/20%), which does not require special gas production equipment and can be purchased premixed.

Therefore, procurement from multiple vendors and gas handling are drastically simplified. In addition, the evacuating equipment required for periodic inspections and replacement of SF_6 GIS is no longer necessary since NOG can be released to the atmosphere, thus reducing the time and ancillary costs associated with SF_6 gas management. Various sensors and diagnostic systems can also be installed to detect signs of abnormality and deterioration at an early stage, thereby enhancing the sophistication and efficiency of inspection and maintenance operations through maintenance based on facility conditions (CBM or condition-based monitoring).

On the other hand, it has been confirmed that nitrogen oxides (NO and NO_2) and ozone (O_3) can be generated at concentrations exceeding safety standards when certain gas discharges occur. Table 4 shows the observed concentrations of decomposition gases during induced current switching in earthing switches and bus-transfer current switching in disconnectors.

Also, Table 4 shows the concentration of decomposition gases per current interruption estimated from the integrated arc energy in case of major failures along with the detection range for commercially available detector tubes, and the concentration limit for safety standards.

Table 4: Estimated decomposition gas density after the current switching or internal accident in natural origin GIS [ppmv]

	Nitrogen monoxide, NO	Nitrogen dioxide, NO_2	Ozone, O_3
Induced current switching; current/recovery voltage (200A/1.5kV) switching	0.35 (0 min.)	0.08 (0 min.)	0.13 (24 hours)
Bus-transfer current switching; current/recovery voltage (2.4kA/200V) switching	0.5 (0 min.)	0.15 (0 min.)	0.2 (30 hours)
Fault removal time by main protection; 31.5kA-150ms	79.5 (1 min.)	36.1 (127 hours)	36.1 (105 hours)
Fault removal time by backup protection; 31.5kA-1850ms	9771.2 (1 min.)	444.1 (248 hours)	444.2 (142 hours)
Detection range with a detector tube	2.5 - 200	2.5 – 200	0.025 - 6.0
TLV-TWA values; allowable concentration	25 - 60	60 - 200	0.1 – 5.0

Note: time to reduce concentration below minimum detector sensitivity for a DS/ES tank(484 liter) is shown in parentheses

If the pressure relief device operates, the arc by-product concentration will decay to below the limit in a very short time due to mixing and diffusion in the atmosphere. However, if the tank is to be opened for internal investigation or equipment replacement, it is necessary to confirm in advance that the by-product concentration is below the limit by measurement using a gas detector tube, as in the case of SF_6 GIS. In the event of decomposed gas emissions in underground and indoor substations, assuming the most severe ventilation conditions based on our substation design standards, we estimate that ventilation for approximately 2 hours will satisfy the safety standard values.

3.4 Effect of reduction of carbon-footprint

Energy is used in all processes from manufacturing to disposal, including the manufacture of materials used in products and power loss during operation, all of which can be equivalently expressed in terms of CO_2e gas emissions.

In this study, Life-Cycle-CO_2e emission (LC-CO_2e) is conducted for a 72/84 kV NOG GIS (synthetic air insulation and vacuum interrupter) and SF_6 GIS, assuming 40 years of lifetime operation from manufacturing to disposal.

Table 5 shows the estimation targets and conditions, and Figure 4 explains the calculation conditions. The equivalent CO_2e gas emissions per unit of materials and activities are estimated using the Japanese database, Inventory Database for Environment Analysis (IDEA); a purely domestic Japanese Life Cycle Inventory (LCI) database jointly developed by the National Institute of Advanced Industrial Science and Technology and the Japan Environmental Management Association for Industry. The statistics of gas leakage and failure rate during operation are based on actual operation in Japan according to the Electric Technology Research Association of Japan [10,11].

Table 5: Calculation conditions for LC-CO_2e

Items \ Gas	（A） SF_6	（B） NOG
Rated voltage	72 kV	72 kV
Rated interruption current	31.5 kA	31.5 kA
Rated current	feeder; 2000 A/ bus; 3000 A	feeder; 2000 A/ bus; 3000 A
Insulation medium	SF_6	Synthetic air
Arc quenching method	SF6 gas blast type interrupter	Vacuum interrupter
Others	✓ One GIS bay with double busbar ✓ Local control cabinet (LCC), Terminal of power cable except power cable, Current transformer (CT) and voltage transformer (VT)	

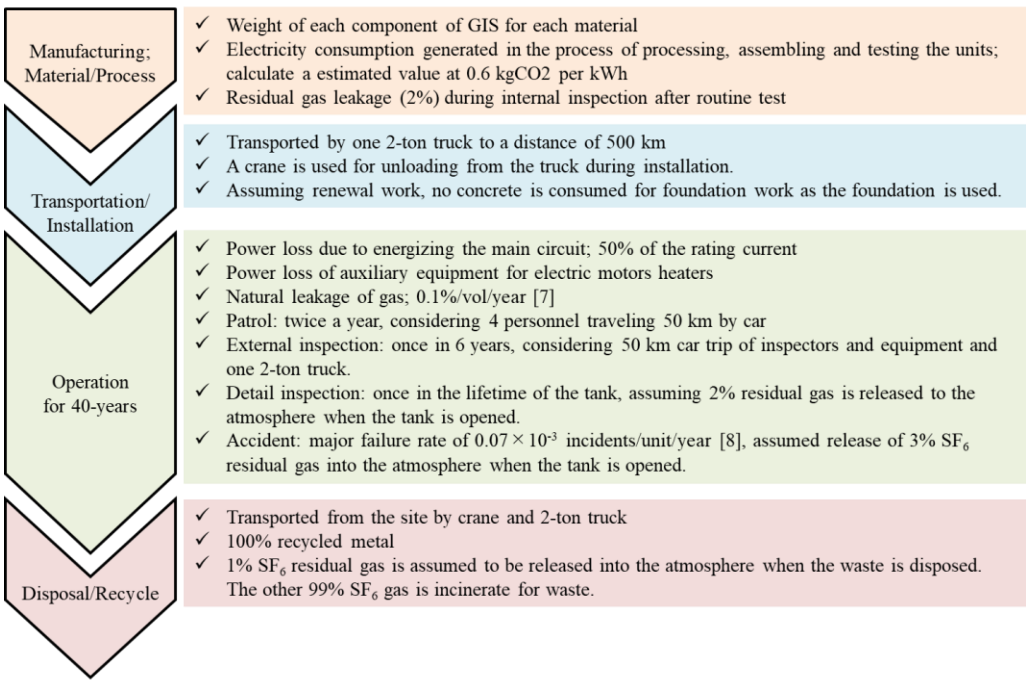


Figure 4: Detail of calculation procedure and conditions

The results of the estimation in a GIS bay are shown in Table 6 and Figure 5. Figure 5 indicates that the total GHG emissions over the 40-year life cycle of the SF_6 GIS is 336 ton-CO_2e and that of the NOG GIS is 89 ton-CO_2e. Therefore, the emission reduction of 247 ton-CO_2e per bay is possible by adopting NOG GIS instead of an SF_6 GIS.

Table 6 indicates the amount of GHG emissions during each life cycle stage. In the case of SF_6 GIS, the major factor accounting for 74% of the total of GHG emissions is gas leakage; composed of residual SF_6 gas during manufacturing, internal inspection, disposal, and slow leakage during operation. The other major factor accounting for 17% of the total is operation; composed of Joule heat loss due to energizing the main circuit and auxiliary equipment such as condensation-preventing heaters. In the case of NOG GIS, although GHG emissions from materials increase due to the increased size of the GIS, this is limited to about 4% of the total emissions, resulting in a 74% reduction in emissions from SF_6 gas emissions, and a 73% overall CO_2e reduction compared to an SF_6 GIS.

Table 6: Result of LC-CO_2e calculation in72/84 kV GIS [kg-CO_2e]

Life-cycle stages		SF_6	NOG
Manufacturing/	Material	27,618	29,551
Manufacturing/ Processing	Electric power	7,152	7,653
	Gas leakage	55,440	0
Transportation	/	406	434
Installation	/	1,624	1,624
Operation	Power loss due to energizing the main circuit	16,707	20,884
	Power loss due to auxiliary equipment	41,768	41,768
	Gas leakage	110,880	0
	Patrol	646	646
	External inspection	108	108
	Detail inspection	55,803	363
	Accident	237	5
Disposal	Transportation	808	819
	Gas leakage	27,720	0
	Crush for waste	2,864	0
	Recycle of materials	-13,794	-14,759
Total		335,986	89,095

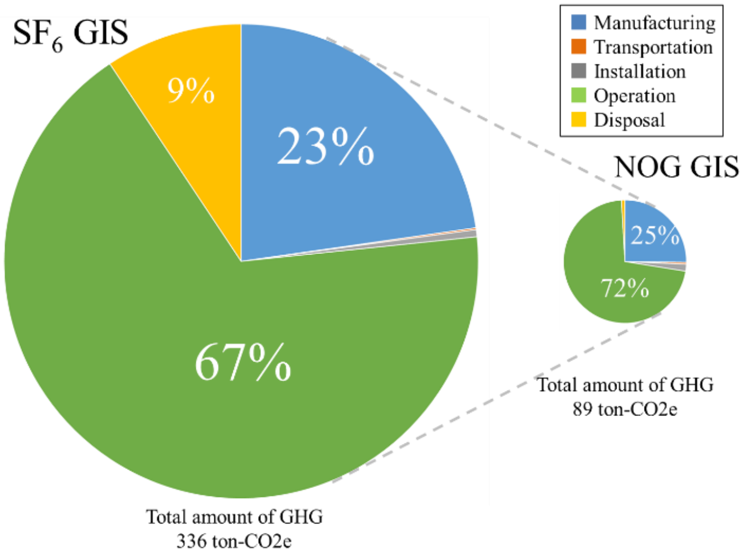


Figure 5: Comparison according to the result of LC-CO_2 calculation in 72/84 kV GIS

4 Conclusions

This paper reports on the process and evaluation results of the application of a GIS without SF_6 gas in the replacement of an early-type 72 kV GIS. The pilot installation at the Fuchu Substation satisfied the seven requirements discussed in Japan, and the equivalent carbon dioxide emissions is estimated to be reduced by 73% compared to the current SF_6 GIS equipment.

In order to further reduce the environmental impact, we will consider reducing the power loss of auxiliary equipment, which accounts for a large proportion of GHG emissions in GIS by reviewing the operational aspects. In addition, we will actively introduce equipment that does not use SF_6 gas in order to achieve 2030-year's target of 46% reduction in GHG emissions compared to the that in 2013 for carbon neutral by 2050.

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