

A Life Cycle Impact Assessment Study on Sulfur Hexafluoride (SF₆) as a Gas Insulator

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Abstract

A lifecycle environmental impact analysis was conducted for SF₆ used as an insulating gas in electrical devices. Eight scenarios with different forms of usage as an insulating gas (pure SF₆ and gaseous mixture of SF₆ with nitrogen) and treatment processes of waste SF₆ (e.g., reproduction after decomposition, reuse after purification) are assumed. Energy consumption and emission of pollutants and toxic materials associated with the treatment processes (only the ones associated with the operations were considered) were estimated for each scenario. Based on the inventory analysis, life-cycle energy consumption, global warming potential, acidification potential, eutrophication potential, generation of photochemical oxidants, and generation of substances having adverse health impacts, were evaluated as the factors denoting environmental impacts. The life-cycle energy consumption can be significantly reduced by the use of the gaseous mixture of SF₆ and nitrogen because the energy consumption required for producing SF₆, a major energy consumption process, can be reduced at the amount of SF₆ replaced by nitrogen compared to that for the scenarios with using pure SF₆. The scenarios reusing the degraded SF₆ after purification can reduce the life cycle energy consumption. On the other hand, emission of the pollutants associated with the transportation process, which will enhance the risks for acidification, eutrophication, generation of photochemical oxidants, will be increased by using the gaseous mixtures, mainly due to the larger burdens.

Introduction

Sulfur hexafluoride (SF₆) is a non-hazardous, inert gas that is used for a variety of applications such as an insulating gas in electrical devices, a melt protection gas in magnesium industry, a cleaning and etching gas in semiconductor industry and liquid crystal production process. The principal usage of SF₆ is as an insulating gas in electrical devices, which accounts for three quarters of the total amount consumed in the year of 2000 in Japan [1]. The insulating gas of SF₆ is advantageous in terms of its excellent insulating performance as well as its chemical stability for a long-term usage. Because of its extremely high global warming potential (GWP = 22200, 100 year base), SF₆ is included as a target gas in Kyoto protocol for emission reduction.

The SF₆ used as an insulating gas will be gradually degraded by the discharge process in the electrical devices, and the degraded SF₆ should be replaced by the fresh gas at the end of life to keep the insulation performance. Although some processes of treating waste SF₆ have been commercialized, no quantitative studies have been found in the literatures on the environmental impact assessments associated with the treatment processes. A number of options could be considered for the treatment of the degraded SF₆ after the use, e.g., reuse after purification or production of new SF₆ after decomposition to raw components. The optimum scenario should be selected by considering the

environmental impacts in addition to the cost and technical feasibilities. This study focuses on the life cycle environmental impact analysis of SF₆ used as an insulating gas in electrical devices. Several scenarios of the treatment processes of the waste SF₆ were assumed, and energy consumption and emissions of pollutants and toxic substances were estimated for each scenario. Based on the analysis, the lifecycle environmental impacts associated with its use and treatment processes were evaluated in terms of the life-cycle energy consumption, risks for global warming, acidification, eutrophication, generation of photochemical oxidants, and generation of toxic substances to the human health. In addition, scenarios with the use of gaseous mixtures of SF₆ with nitrogen as an insulating gas are assumed. Although only pure SF₆ has been used as an insulating gas in practical electrical devices at present, the use of gaseous mixtures of SF₆ with nitrogen or carbon dioxide has been considered as alternatives to replace the use of pure SF₆ [2]. The potential risk of global warming through leakage during the treatment processes can be reduced by the use of such gaseous mixtures. On the other hand, the insulation performance of the gaseous mixture of SF₆ with nitrogen may be reduced compared to that of the pure SF₆. Such a trade-off should be carefully considered upon selection of the appropriate scenarios. This study also discusses the influences of use of the gaseous mixtures of SF₆ and nitrogen on the environmental impacts.

Scenarios treating SF₆

The system boundary considered in this study for the lifecycle analysis covers production of SF₆, use as an insulating gas (either pure or mixed gas with nitrogen) in electrical devices, capturing the degraded gas from the electrical devices, and treatment of the degraded gases (purification and reuse, decomposition and reproduction). The transportation of the SF₆ gas from and to the treatment plants (production, decomposition, purification) is also included in the boundary.

Eight scenarios were assumed in this study, which can be divided into two categories: scenarios with the use of pure SF₆, and scenarios with the use of gaseous mixtures of SF₆ and nitrogen. It is assumed that the insulation performances of gaseous mixtures of SF₆ with nitrogen are equivalent to that of pure SF₆ for simplicity. Thus, the amount of SF₆ used in an electrical device of a given size can be saved at the amount of nitrogen replaced without changing the insulation performance. The scenarios with the use of pure SF₆ are denoted by P-(number) and the scenarios with the use of gaseous mixtures are denoted by M-(number).

Scenarios for pure SF₆ usage and treatment

The following three scenarios (P-1~3) were considered for the use of pure SF₆ gas.

- Scenario **P-1** (reproduction of SF₆ after collection of waste SF₆ and decomposition): Degraded SF₆ gas is collected from the devices without purification, and transported to a large-scale decomposition plant, and decomposed there to the raw components. Then SF₆ is reproduced in an adjacent production plant, and transported to the devices to be used as an insulator.
- Scenario **P-2** (on-site decomposition, reproduction of SF₆ after collection of the raw components): Degraded SF₆ gas in the devices is decomposed on site with portable decomposition equipment to the raw components. The raw components are collected and transported to a large-scale production plant, where pure SF₆ is reproduced. The

produced pure SF₆ will be transported to the devices and used as an insulator.

- Scenario **P-3** (reuse after collection and purification): Degraded SF₆ is collected from the devices without purification, and transported to a large-scale separation plant, where the SF₆ is purified from the waste gas. The purified SF₆ is then transported to the devices to be used as an insulator.

Scenarios for mixed gases of SF₆ and nitrogen

The following five scenarios were considered for the treatment of gaseous mixture of SF₆ and nitrogen.

- Scenario **M-1** (reproduction of SF₆ after collection of waste SF₆ and decomposition): Degraded insulating gas is collected from the devices without purification, and transported to a large-scale decomposition plant, where the waste gas is decomposed to the raw components. The pure SF₆ is reproduced from the components in an adjacent production plant. Then the pure SF₆ is mixed with nitrogen, and transported to the devices and used as an insulator.
- Scenario **M-2** (reproduction of SF₆ after on-site purification, collection and decomposition): The SF₆ in the devices is captured and purified by an on-site separation unit. The recovered SF₆ will be transported to a large-scale decomposition plant and decomposed to the raw components. Then pure SF₆ is reproduced and mixed with nitrogen, and transported to the devices and used as an insulator.
- Scenario **M-3** (reproduction of SF₆ after on-site decomposition and collection of the raw components): The SF₆ in the devices is decomposed on site with portable decomposition equipment. The raw components are transported to a production plant, and pure SF₆ is produced. The SF₆ is mixed with nitrogen, and transported to the devices and used as an insulator.
- Scenario **M-4** (reuse after collection and purification): The degraded insulating gas is collected from the devices without purification, and transported to a large-scale separation plant, where SF₆ is purified. The purified SF₆ is then mixed with nitrogen, and transported to the devices to be used as an insulator.
- Scenario **M-5** (reuse after on-site separation): The SF₆ in the degraded insulating gas is purified by an on-site separation unit. The recovered SF₆ is mixed with nitrogen, and reused in the devices as an insulator.

Operations in the treatment scenarios and power consumptions

Energy consumption and emissions of pollutants associated only with the operating the following processes are considered in this study. In other words, the environmental impacts associated with the plant construction, maintenances were not included.

Production process of SF₆

A commercialized production process of SF₆ is comprised of the following three reaction steps.



Hydrogen fluoride (HF) is produced by the reaction of calcium fluoride (CaF₂,

fluorite) with sulfuric acid in the temperature range of 473 ~ 523 K in reaction (1). Reaction (1) is a highly exothermic reaction with an enthalpy change of $\Delta H = -1105$ kJ/mol at 500 K. The amount of heat required to precede reaction (1) is 99.84 kJ/mol-SF₆ based on the heat required to heating the reactants to the reaction temperature (500 K) from the room temperature (298 K). Since this amount of heat is much smaller than the heat of reaction, no net heat supply is necessary for preceding reaction (1) after attaining a steady state. The hydrofluoric acid produced in reaction (1) should be purified by distillation at 323 K. The energy required for the distillation is 58.0 kJ/mol-SF₆, corresponding to the heat required for heating HF from the room temperature (298 K) to the distillation temperature (323 K).

Reaction (2) is an electrolysis reaction conducted at 373 K. The specific electricity for producing 1 metric ton of fluorine gas is 1410 kAh/t [3]. A commercialized process with a production rate of 3.8 kg/h is operated at the reaction voltage = 10 V. Assuming the efficiency of 97 %, the power consumption for producing 1 mol of F₂ is 1871 kJ/mol. The heat required for heating the reactant HF from room temperature to the reaction temperature is 2.97 kJ/mol. The power consumption for producing 1 mol of SF₆ is, therefore, $3 \times (1871+2.97) = 5,622$ kJ/mol-SF₆.

Reaction (3) is a gas phase reaction of sulfur with fluorine at the temperature of 800 K, slightly above the boiling point of sulfur. The enthalpy change of the reaction at 800 K is $\Delta H = -1095$ kJ/mol, indicating a highly exothermic reaction. The energy required for preceding reaction (3) is equal to the heat required for heating the reactants from the room temperature to the reaction temperature. The heat required is sum of the heat required for heating solid sulfur from the room temperature to the reaction temperature (= 17.1 kJ/mol), and the heat associated with the phase changes (solid →liquid→vapor = 11.3 kJ/mol). However, this much amount of heat could be supplied from the heat of reaction, which is much larger than the sum of the heat required. It can be thus assumed that no additional heat supply is needed to precede reaction (3).

Since the yield of reaction (3) is much lower than 100 %, the crude product should be purified by removing by-products such as S₂F₁₀, SF₄. SF₄ can be easily removed by alkaline washing, while S₂F₁₀ should be first converted to SF₄ by pyrolysis at 673 K for the effective separation.



The energy required for the pyrolysis (4), can estimated by the heat for heating crude SF₆ to the temperature of 673 K from the room temperature: 45.6 kJ/mol-SF₆:

The purified SF₆ is then liquefied by compression from 0.1 MPa to 2.0 MPa at 298 K for storage. Assuming an isothermal compression process at 298 K, the power required for the liquefaction is 7.30 kJ/mol-SF₆.

Totalizing all the energy required for the above-mentioned processes, the energy consumption for producing 1 mole of SF₆ from the raw material to the product in the liquid form is, $58.0 + 5622 + 45.6 + 7.30 = 5,733$ kJ/mol-SF₆.

Transportation of insulating gases

The product SF₆ will be transported to the site where SF₆ (or gaseous mixture with nitrogen) is used as an insulating gas. Pure SF₆ can be transported in the form of liquid after compression. For the liquefaction, the pure SF₆ should be compressed from the atmospheric pressure to 3.72 MPa at 298 K. An isothermal liquefaction process consumes 8.96 kJ/mol-SF₆. Transportation in the form of gas is more appropriate for the gaseous mixture of SF₆ with nitrogen because a considerably high pressure is required for liquefaction.

Assuming transportation at the pressure of 1.0 MPa, the energy consumption for an isothermal compression is 5.78 kJ/mol-SF₆.

The average transportation distance is assumed at 100 km considering the distributions of large-scale electrical transforming stations and production plants of SF₆ in Tokyo metropolitan area. The SF₆ in the form of gas as well as liquid is transported in a steel cylinder with volume of 47 L of the tare weight of 59 kg. The cylinder is mounted and transported in a diesel-powered 4-ton burden truck with the mileage of 3.5 km/L-diesel oil. Assuming energy content in the diesel oil at 38.2 kJ/L-diesel oil, the energy consumption for transporting SF₆ is 77.5 kJ/mol-SF₆.

Similar assumptions were made for the transportation of the recovered waste gas.

Recovery process of SF₆ from electric devices

A vacuum pump is used for recovering SF₆ from the devices. A commercialized recovery process requires a 480-min of operating with a 1.5-kW vacuum pump for recovering all the SF₆ contained in a 500-kV class electric device. Since the amount of SF₆ in a 500 kV class electric device is 1,300 kg (= 8,901 mol), the energy required for the recovering SF₆ is 4.85 kJ/mol-SF₆.

Purification processes

Membrane separation process is assumed for purifying SF₆ [3]. The energy consumption for the separation is heating (373 K) and pressurizing (0.8 MPa) of the feed gas mixture from the atmospheric condition. The amount of energy required for heating and compression are 2.77 and 10.75 kJ/mol-SF₆, respectively. Based on the membrane separation performance reported in the literature, the product rate is 1.1 L/min against the feed rate at 12.8 L/min. The number of the cycle for the membrane separation is, therefore, 12.8/1.1 = 11.6, and hence the energy required for the purification is 13.52×11.6 = 157 kJ/mol-SF₆.

Decomposition processes

A low-temperature plasma decomposition method is assumed for the decomposition process of SF₆ [4]. Based on the laboratory-experimental results [4], the SF₆ flow of 100 mL/min can be completely decomposed with 30-W power plasma equipment, which is equivalent to the energy consumption of 403.2 kJ/mol-SF₆. The evacuation energy for operating at 0.5 Torr is 13.3 kJ/mol-SF₆ assuming 24.2-s operation of 0.55-kW vacuum pump.

Emissions of pollutants

Carbon dioxide (CO₂) emission associated with power generation

The CO₂ emission amount per unit power generation is assumed 393.8 g/kWh, which is the average value of thermal power plants in Japan. This number includes the CO₂ emission associated with construction of plants, transportation and treatment of fuels, and maintenances as well as the one associated with the power generation operations.

Leakage of SF₆ during the recovery process

The leakage of the insulator gas during the recovery process of the waste gas from the electrical devices is assumed at 3 %.

Emissions of pollutant gases during the transportation of SF₆

The emission amounts of CO₂, CH₄, N₂O associated with the transportation by a diesel-powered truck are assumed at 755.4, 0.015, 0.025 g/km, respectively. The emission amounts of CO, hydrocarbons, NO_x, particulate matters (PM) based on the exhaust gas regulation in Japan are 3.46, 1.47, 4.22, 3.55 g/kWh, respectively.

Emissions of pollutant gases during the decomposition of SF₆

The conversion of the decomposition reaction by the plasma treatment is assumed at 98.7 %, and unreacted SF₆ and generated gases will be released to the atmosphere.

Life cycle impact analysis of the scenarios

The following impact indicators were calculated based on the life cycle analysis.

- Energy consumption: total power consumption
- Global warming risk: total emission amount of greenhouse gases unified as the CO₂ equivalent value using Global Warming Potential (GWP) of 100 year base for each component.
- Acidification risk: total emission amount of SO_x and NO_x unified as the SO₂ equivalent value by using Acidification Potential (AP) of each component.
- Eutrophication risk: total emission amount of nitrogen and phosphorous that can cause an overgrowth of phytoplankton, which was unified to the PO₄³⁻ equivalent value by using the Eutrophication Potential (EP) of each component.
- Photochemical oxidant: total emission of carbon oxide and hydrocarbons unified by the C₂H₄ equivalent value transformed by using Photochemical Ozone Creation Potential (POCP).
- Toxicity: total emission amount of toxic substances with adverse health effects, sum of the contribution of each component weighted by using Threshold Limited Value-Time Weighted Average (TLV-TWA). Since TLV-TWA is assigned for SiF₄ and SO₂ only among potentially toxic substances involved in the processes, the toxicity due to these components are considered.

Results for the lifecycle impact assessments

Table 1 shows the results of the lifecycle environmental impact assessments for the scenarios with the use of pure SF₆. Energy consumptions for P-1 and P-2 (scenarios include the decomposition process) are twice as large as that for P-3 (without decomposition). The difference is due to a large power consumption of the reproduction process of SF₆, to which about half of the life cycle energy consumption is attributed in P-1 and P-2. Similar trend is observed for the global warming impact: P-3 showed the lowest among three scenarios. The risks of acidification (AP), eutrophication (EP), and photochemical oxidant generation (POCP), are smallest for P-2. This is because the emissions of these pollutants are mainly associated with the transportation of SF₆, and transport burdens are least for P-2. The risk of emission of toxic substances (TLV-TWA) is smallest for P-3, which is 1/100 times smaller than those for P-1 and P-2. This is because the generation of toxic compounds are mainly attributed to the decomposition process of the waste SF₆, which is not included P-3.

Results of the assessment for the scenarios with the use of gaseous mixtures of SF₆ and nitrogen are shown in Table 2, where only the results of a mixture with a composition of 10:90 (SF₆: N₂) are shown. The energy consumption as well as GWP is significantly reduced by using the gaseous mixtures compared to the scenarios using pure SF₆. This is because

Table 1 Results of the lifecycle impact assessments (scenarios using pure SF₆)

Impact category	Unit	P-1	P-2	P-3
Energy Consumption	MJ/mol	12.1	12.0	5.95
GWP	kg-CO ₂ /mol	141	141	97.9
AP	mg-SO ₂ /mol	129	65.3	128
EP	mg-PO ₄ ³⁻ /mol	23.9	12.1	23.8
POCP	mgC ₂ H ₄ /mol	25.1	12.5	25.1
TLV-TWA	g/TWA/mol	9.98	9.97	0.067

the energy consumption for producing SF₆ can be reduced at the amount of nitrogen replacing SF₆ in the gaseous mixture. Global warming impact caused by the leakage during the treatment processes can also be reduced due to the smaller GWP of the gaseous mixtures. On the other hand, the risks of acidification (AP), eutrophication (EP), and photochemical oxidant production (POCP), which are mainly associated with the transport processes, are much higher than the scenarios using pure SF₆. Since the gaseous mixtures are transported in the form of gas, more cylinders should be necessary to transport a fixed amount of the insulating gas compared to the pure gas, which can be transported in the form of liquid. The risk of emissions of toxic substances (TLV-TWA) can be reduced for the scenarios including the decomposition process (M-1, M-2, M-3), compared with the corresponding scenarios using pure SF₆ (P-1, P-2).

Among five scenarios using the gaseous mixtures, M-5 seems to be the optimum scenario because the energy consumption and pollutant emissions are minimum values, except GWP, which is slightly larger than that for M-1 or M-3. The GWP could be reduced by reducing the leakage during the recovery of the waste insulating gases from the devices. The decomposition and reproduction processes will increase the energy consumption (M-1, 2, 3) as well as AP (M-1) for acidification. Purification in a large size plants after collection will also increase the total energy consumption as well as the emission of the pollutants, such as AP, EP, POCP, (M-4) due to the additional burdens in the transportation process.

Table 2 Results of lifecycle impact assessments (scenarios using 10%-SF₆ + 90%-N₂)

Impact category	Unit	M-1	M-2	M-3	M-4	M-5
Energy Consumption	MJ/mol	3.28	2.21	2.42	2.45	1.60
GWP	kg-CO ₂ /mol	14.2	21.8	14.2	17.5	17.5
AP	g-SO ₂ /mol	1.40	0.707	0.701	1.40	0.707
EP	mg-PO ₄ ³⁻ /mol	260	131	130	260	131
POCP	mg-C ₂ H ₄ /mol	277	140	138	277	140
TLV-TWA	g/TWA/mol	1.07	1.03	1.04	0.078	0.043

Figure 1 shows the influences of the compositions of the gaseous mixtures on the lifecycle impacts for the scenarios using gaseous mixtures. In general, the each lifecycle impact increased with an increase in the concentration of SF₆ of the gaseous mixtures for a

given scenario. The energy consumption and GWP increased more rapidly with an increase in the SF₆ content than other impacts such as AP, EP, and POCP. On the other hand, the risk of toxic substance emission (TLV-TWA) increased dramatically with an increase in the SF₆ content for the scenarios with the decomposition process (M-1, M-2, M-3), while those for the scenarios without the decomposition process (M-4, M-5) were almost negligible.

Conclusions

The lifecycle analysis in this study showed that the life cycle energy consumption, as well as the global warming risk could be significantly reduced by using the mixture of SF₆ with nitrogen as insulating gas compared to pure SF₆. Other environmental impacts, which are associated with the transportation of the waste insulating gas, such as acidification, eutrophication, and photochemical oxidants production, will be increased with the use of gaseous mixtures due to greater burdens of transportations.

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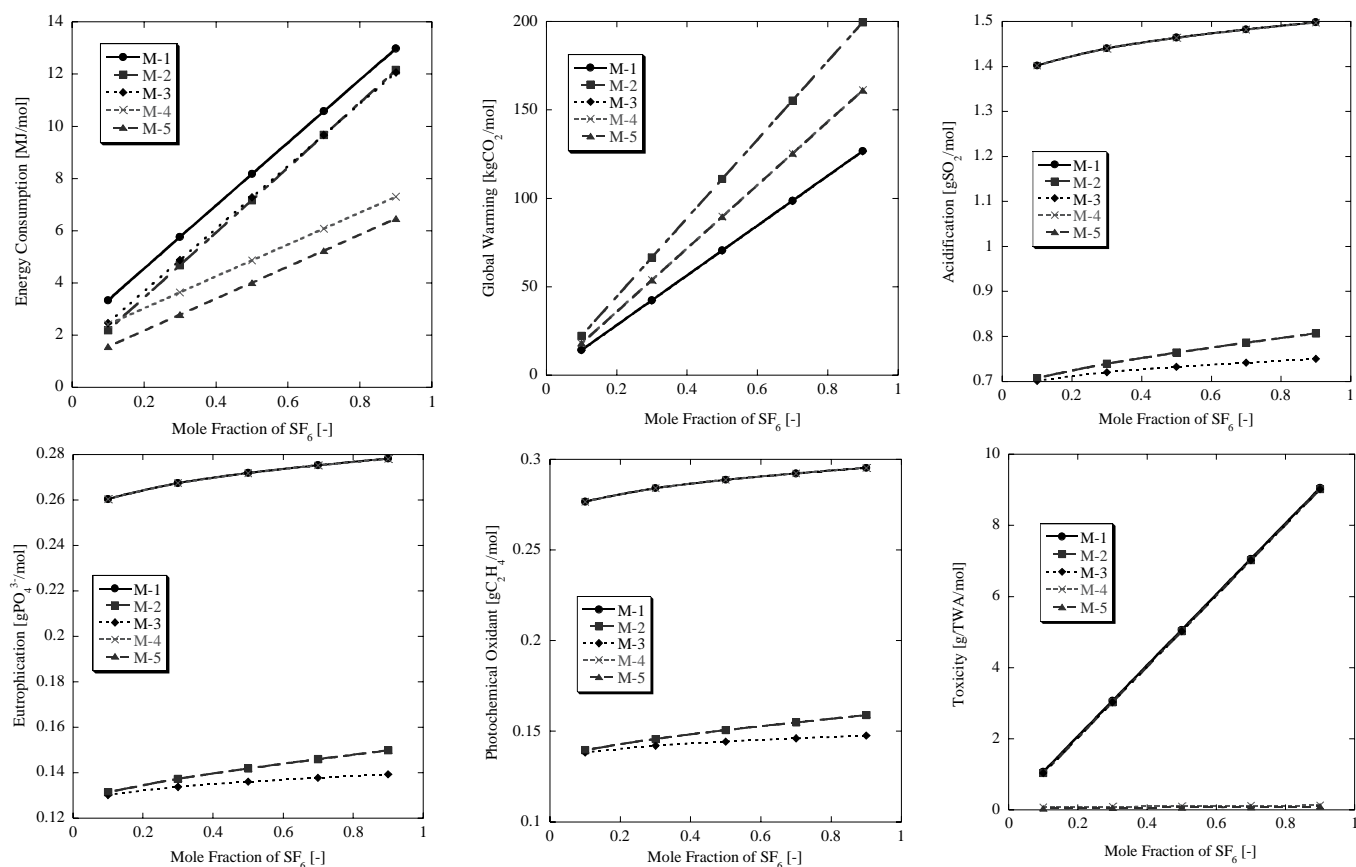


Figure 1 Effects of the composition of the gaseous mixture on the environmental

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