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Mitigating Sulfur Hexafluoride (SF_6) Emission from Electrical Equipment in China

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Abstract: Sulfur hexafluoride (SF_6) is a powerful greenhouse gas with high global warming potential. Future growth in SF_6 use will be driven mainly by increasing demand for electricity and associated infrastructure in developing countries. In relation to electrical equipment, China currently produces the largest proportion of SF_6 emissions. Because of the long lifetimes of electrical equipment, SF_6 emissions are substantially different from its consumption, which has been used as an inaccurate proxy for emission estimations, i.e., the so-called "delayed emission effect." This study established a model to estimate SF_6 emissions by considering the delay through equipment survival, retirement curve, and equipment life cycles. Three scenarios were established to model the potential for mitigation of SF_6 emissions from electrical equipment. The results showed considerable delayed effects in SF_6 emissions associated with electrical equipment. By 2050, the cumulative delayed emission was projected to be 50–249 kt under the different scenarios, which would be 1.2–6.0 $GtCO_2e$. Therefore, replacing emissions with consumption could overestimate actual short-term emissions by 1–2 times. Although electrification in end-use sectors and high penetration of renewables in generation could lower global emissions substantially, SF_6 emissions by 2050 could still increase by 15 kt (i.e., 0.36 $GtCO_2e$) if mitigation measures are not adopted. Thus, a low-carbon electricity roadmap should be complemented by careful management of electrical equipment. The potential for mitigation of SF_6 emissions could be realized through demand-side management to reduce electricity demand and through technological improvements on the supply side to reduce leakage and increase recovery.

Keywords: SF_6 emissions; electrical equipment; China; mitigation

1. Introduction

Sulfur hexafluoride (SF_6) is one of the controlled greenhouse gases identified by the 1997 Kyoto Protocol, because of its high global warming potential (GWP; 23,900). Emissions of SF_6 are derived mainly from four sources: equipment (gas circuit breakers (GCB), gas-insulated switchgear (GIS), and gas-insulated transformers (GIT) as an insulator) used in electricity transmission and distribution (hereafter, electrical equipment), magnesium smelting, semiconductor manufacturing, and SF_6 production [1]. Globally, electrical equipment constitutes the largest source of SF_6 emissions. The excellent insulating and arc-extinguishing characteristics of SF_6 have led to its widespread use in electrical equipment such as gas circuit breakers, gas-insulated switchgear, and gas-insulated transformers. The total amount of SF_6 emissions globally in 2010 was equivalent to 1.25 Gt of CO_2 ($GtCO_2e$), and it subsequently continued to increase at a rate of 10% annually [2,3]. In developed countries [4], SF_6 emissions have been reduced substantially through stabilized electricity consumption, technical developments, and emission reduction measures. Corresponding studies have shown that the recent growth of SF_6 emissions has been mainly attributable to rapidly increasing demand for electricity in non-Annex I countries [1]. According to the International Energy Agency's World Energy Outlook, global electricity demand is projected to grow by 30% during 2015–2040 [5], most of which will be driven by developing countries. Therefore, the emission and control of SF_6 in developing countries such as China will play very important roles in the control of SF_6 emissions globally.

According to the National Emission Inventory of China, the total quantity of SF_6 emissions in 2012 was 1000 t [6], i.e., more than twice the 2005 level (People's Republic of China Second National Communication on Climate Change, SNC) [7], 95% of which was attributed to electrical equipment. To meet environmental requirements, the use of SF_6 gas has been phased out of semiconductor production and, after 2010, the use of SF_6 as a protective gas in magnesium production in China was halted [8,9]. Additionally, given recent improvements in technology and management, leakage during the SF_6 production process can be regarded as negligible. Therefore, electrical equipment remains the primary sector for SF_6 consumption and the main source of future SF_6 emissions.

China is the consumer of the largest quantities of SF_6 in the world. Since 2010, the installed electrical capacity of China has been the largest globally, and most of its new electrical equipment has used SF_6 as the arc-quenching gas. China's annual consumption of SF_6 was 5000–7000 t in 2010, and this has increased at a rate of 20% annually [10–12]. Meanwhile, China has also played an important part in SF_6 emissions, accounting for about one third of the global total, and its rate of increase of SF_6 emissions has been much greater than that of CO_2, CH_4, and N_2O [13–16]. Therefore, control of the consumption and emission of SF_6 in China's power sector is highly important in relation to global SF_6 emission reduction.

Research on the future SF_6 emission scenario in China is limited. A few studies have considered the consumption and emission of SF_6 in relation to electrical equipment in power sector. Other related research has focused mainly on CO_2 emissions from fossil fuel combustion and on the inventory of SF_6 emissions, and only a few studies have investigated future SF_6 emission trajectories [17–19]. Several studies on SF_6 emission inventories have been conducted using methodologies incorporating a Lagrangian model [20–23] and the emission inventory method [1,6,7,24,25]. Some studies have focused on greenhouse gas emissions from the power industry [26–28], but without conducting detailed analyses on SF_6 emissions. Although recent analysis has considered China's SF_6 emissions and emission reduction potential by 2020 [1], there has been no investigation of long-term estimations of SF_6 emissions from China's power sector [29].

Most previous studies of SF_6 scenarios have used SF_6 consumption as a proxy for emissions. However, SF_6 emissions in the power sector are not equivalent to its consumption because of the so-called "delayed emission effect." As a protective gas, SF_6 is usually consumed (i.e., filled and sealed) during the process of equipment production and during its installation. In routine operation, although small amounts of SF_6 can be emitted primarily through leakage, the bulk of SF_6 emission occurs during equipment maintenance and/or retirement [10,25,29]. Therefore, there can be a considerable difference between the consumption and the emission of SF_6 in any given year. The lifetime of electrical equipment in the power sector is usually 30–40 years. Therefore, if the delayed emission effect are not considered, current consumption will be selected as an estimate of annual emissions. Such an assumption would usually overestimate short-term emissions and underestimate long-term emissions, which would have important consequences for assessments of global greenhouse gas concentrations and the effects of global warming.

Another shortcoming of earlier research is the uncertainty associated with electrical equipment. The lack of basic data regarding the consumption and emission of SF_6 associated with China's electrical equipment has resulted in a level of uncertainty in historical emission estimations of about 2–3 times [20–29]. Given the installed capacity of electrical equipment in China has increased rapidly in recent years, the level of uncertainty in estimations of the consumption and emission of SF_6 could be even greater in the future [30,31].

In addition, studies have shown that several alternative gases with low GWP value may replace SF_6 gradually or partially in electrical equipment in power sector. But it is a long-term process and the SF_6 cannot be substituted completely in the short term. In near future, the mixed gas of SF_6/N_2 has the most application prospect to partially replace SF_6. In the long run, lower GWP gas may be used to completely replace SF6 [1,2,4,13]. The projection of SF_6 emissions in China could be further improved in two respects: consideration of delayed emission effects and examination of sensitivity analyses on electrical equipment scenarios. This study complements previous research by focusing on the improvement of the estimation method and on the reduction of estimation uncertainty. For the projection of SF_6 emissions, we constructed a model that considers the delayed emission effect by incorporating factors such as installed capacity, technology choice, and technology improvement and substitution. Furthermore, scenario analyses and sensitivity analyses [32–36] were performed to reduce the uncertainties of related parameters and of the calculated results.

The remainder of this paper is organized as follows. In Section 2, we detail our research method and define some key assumptions, such as the installed capacity of the power sector, lifetime of electrical equipment, emission factor, recovery ratio, and substitution ratio. In Section 3, we discuss the results, including the consumption and emission of SF_6 in the future, its cumulative consumption and emission, sources of consumption and emission, emission reduction potential, as well as the delayed emission effects. In Section 4, we describe the sensitive analysis performed on key parameters of SF_6 consumption and emission. In Section 5, we summarize our research conclusions and key findings regarding the consumption and emission of SF_6 in relation to electrical equipment.

2. Method and Key Parameters

Models used to calculate SF_6 emissions can be divided into two categories [25]. Those in the first category adopt a simplified calculation method that does not consider the difference between consumption and emission due to the delayed emission effect. Thus, consumption of SF_6 can be used as a proxy for emission. Such a simplified methodology is approximately correct for sectors in which SF_6 is used as a cover gas, such as magnesium production. However, for electrical equipment, consumption can no longer be regarded an accurate estimate of emission because of the long lifetime of the equipment and the associated delayed emission effect. Therefore, models of the second category adopt a revised methodology that accounts for the delayed emission effect, which is usually disproportionate to the specific activity or consumption of any given year but closely related to the cumulative activity or consumption of SF_6 stock. As a cumulative variable, the SF_6 stock is closely related to various characteristics of the electrical equipment such as its type, lifetime, survival, and retirement curve. However, the SF_6 stock is also dependent on the filling quantity per unit capacity, leakage rate, and other factors such as technological improvements, management level, substitute products, and recycling technology.

In this study, we use the revised methodology that accounts for the delayed emission effect to calculate SF_6 emissions. In this section we first describe methodology in detail in Section 2.1, then elucidate the future scenario setting in Section 2.2, and finally discuss and estimate the key parameters and assumptions in Section 2.3.

2.1. Methodology

2.1.1. Method of Calculating SF_6 Emissions

A method for calculating the SF_6 emissions of electrical equipment was proposed in 2006 by the Intergovernmental Panel on Climate Change (IPCC), i.e., the IPCC Tier 2 country-specific emission factor method [25]. Based on the equipment life cycle, the SF_6 emissions associated with electrical equipment can be divided among four processes: manufacture, installation, operation and maintenance, and disposal. The emissions associated with the first two processes are mainly related to production quantity and the newly added installed capacity of electrical equipment, whereas the emissions associated with the final two processes are mainly related to the stock of electrical equipment in operation. The emissions associated with the manufacture and installation processes are difficult to distinguish; therefore, they are amalgamated in our analysis.

The emissions from each process are usually equal to the product of the current activity (Activity) or the cumulative activity (Stock) and the emission factor (Emission factor). With consideration of the possibility of recycling during the retirement process, the calculation of SF_6 emissions for electrical equipment in year t can be expressed as

$$E_t = C_{M,t} \times EF_{M,t} + S_{O,t} \times EF_{O,t} + D_{D,t} \times (1 - R_{D,t}) \tag{1}$$

where E_t is the total quantity of SF_6 emissions (t), $C_{M,t}$ is the quantity of SF_6 in the electrical equipment newly manufactured and installed in year t (t), $EF_{M,t}$ is the SF_6 emission factor of the electrical equipment newly manufactured and installed in year t (t/t), $S_{o,t}$ is the current stock of electrical equipment in operation (including the newly added electrical equipment) (t), $EF_{o,t}$ is the SF_6 emission factor of the stock of electrical equipment in operation (including the newly added electrical equipment) (t/t), $D_{D,t}$ is the residual quantity of SF_6 of the electrical equipment retired in year t (t), and $R_{D,t}$ is the recycling coefficient of the residual SF_6 of the electrical equipment retired in year t (%).

2.1.2. Method of Calculating SF6 Consumption

Consumption of SF_6 occurs primarily during the process of filling during manufacture and refilling during routine operation and maintenance [1]. Generally, the quantity of SF_6 emission during the process of operation and maintenance is mainly attributed to natural leakage, which is replenished during the maintenance process. Therefore, the emissions during routine operation and maintenance are approximately equal to the quantity of SF_6 refilled (consumed) during this process. In the process of electrical equipment disposal, SF_6 can be recycled and reused. Therefore, the equation describing the net SF_6 consumption in each part of Equation (1) can be expressed as follows:

$$C_t = C_{M,t} + S_{O,t} \times EF_{O,t} - D_{D,t} \times R_{D,t} \tag{2}$$

where C_t is the total quantity of SF_6 consumed in year t (t), and the other parameters are as described in Equation (1).

The quantity of SF_6 consumed in filling the newly added electrical equipment can be obtained by multiplying the capacity of the new electrical equipment by the SF_6 filling quantity per unit capacity, and then deducting substituted SF_6, as shown in Equation (3).

$$C_{M,t} = N_t \times A_t \times (1 - S_{A,t}) \tag{3}$$

where N_t is the newly added electrical equipment capacity in year t (GW), which equals the net newly installed capacity plus the retired installed capacity; A_t is the filling quantity of SF_6 per unit of added electrical equipment (t/GW); and $S_{A,t}$ is the ratio of SF_6 substituted in the newly added electrical equipment (%).

The SF_6 stock of electrical equipment in operation is equal to the sum of SF_6 in the surviving electrical equipment put into operation in previous years (within the range of equipment lifetime), which is related to factors such the equipment lifetime, service time, survival ratio of electrical equipment, and ratio of substituted SF_6, as shown in Equation (4).

$$S_{o,t} = \sum_{j=1}^{n} N_{t-j+1} \times SR_{t-j+1} \times A_{t-j+1} \times (1 - S_{A,t-j+1}) = \sum_{j=1}^{n} C_{M,t-j+1} \times SR_{t-j+1} \tag{4}$$

where SR_{t-j+1} is the survival ratio of newly added electrical equipment in year $t - j$ (%), n is the equipment lifetime (a), and the other parameters are as explained in Equation (3).

As electrical equipment reaches the end of its life and/or its retirement time, residual SF_6 in the electrical equipment is either emitted directly into the atmosphere or recovered/destroyed. The capacity of retired equipment in year t is equal to the sum of the capacity of the retired equipment that was put into operation in previous years. The residual quantity of SF_6 in the retired equipment ($D_{D,t}$) can be expressed as in Equation (5):

$$D_{D,t} = \sum_{j=1}^{n} N_{t-j} \times DR_{t-j} \times A_{t-j} \times (1 - S_{A,t-j}) \times P_{D,t} = \sum_{j=1}^{n} C_{M,t-j} \times DR_{t-j} \times P_{D,t} \quad (5)$$

where $P_{D,t}$ is the ratio of residual SF_6 in the retired electrical equipment (%) (i.e., fraction of charge remaining at retirement) [25], DR_{t-j} is the retirement ratio of newly added equipment in year $t-j$ (%), and the other parameters are as explained in Equation (3).

2.1.3. Method of Calculating the Survival and Retirement Ratios of Electrical Equipment

To consider the delayed emission effect of SF_6, it is necessary to consider the aging and retirement process of the electrical equipment. The lifetime of electrical equipment is usually 30–40 years, and the retirement curve can be determined as follows. Equipment is retired each year, and the retirement rate is low at the beginning of its operation. However, the retirement rate is increased substantially toward the end of the equipment lifetime [37–39]. To quantify the survival ratio and the retirement curve, a Weibull function with dual parameters is proposed as the survival ratio function. Meanwhile, the retirement rate function is the absolute value of the derivative of the survival ratio function (i.e., the annual retirement ratio), shown as Equations (6) and (7).

$$SR_t = \frac{SP_t}{RP} = \exp^{-\left(\frac{t}{T}\right)^K} \quad (6)$$

$$DR_t = \frac{K}{t} . \left(\frac{t}{T}\right)^K . \exp^{-\left(\frac{t}{T}\right)^K}, \quad (7)$$

where SR_t is the survival ratio of the newly added equipment in year t (%), SP_t is the survival quantity of the newly added equipment in year t (GW), RP is the total quantity of the newly added equipment (GW), DR_t is the retirement ratio of equipment in year t (%), K is the function shape parameter (dimensionless), and T is the average lifetime of the equipment (a).

For this study, the average lifetime of electrical equipment was taken as 30 years, and the function shape parameter was generally one third of the equipment lifetime [39–41] and was chosen as 10. For newly added equipment put into operation, the survival ratio and the retirement ratio for each year are as shown in Figure 1. Once the equipment is put into operation, the equipment survival ratio is high and the retirement ratio is small during the first 20 years. As the age of the equipment reaches 30 years, the retirement ratio reaches its peak. Then, the retirement ratio reduces gradually as the proportion of surviving equipment is reduced. After 40 years, the survival and retirement ratios are close to zero.

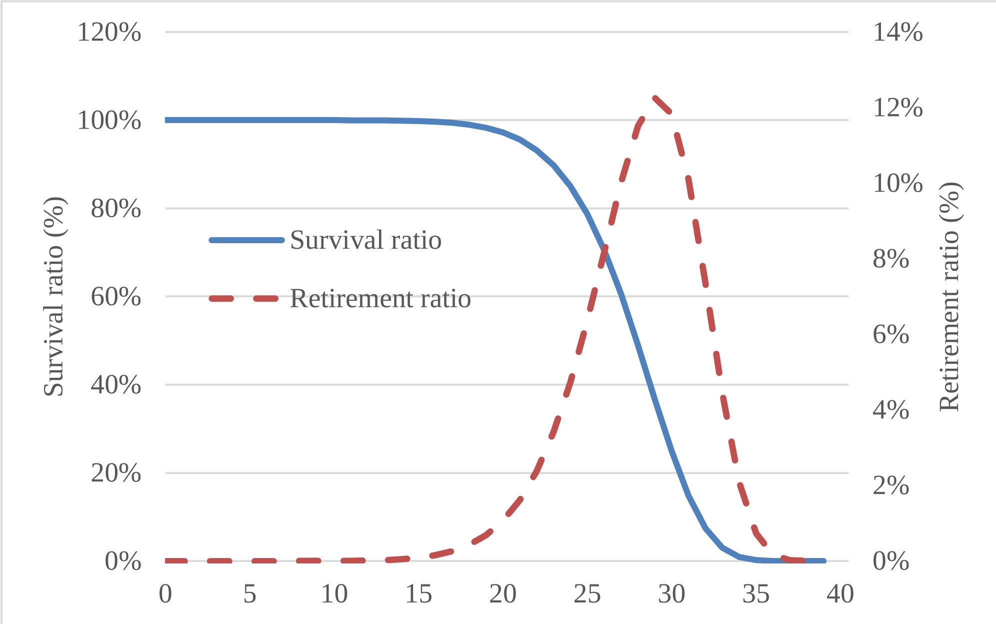


Figure 1. Illustration of the equipment survival and retirement curves.

2.2. Future Scenario Setting

Two different types of factor affect the consumption and emission of SF_6. The first category comprises driving factors, i.e., principally the future installed capacity of electrical equipment, which is determined mainly by population, electricity demand, and the share of renewable energy. The second category is related to factors of SF_6 technology, which include technological improvements, management level, substitution ratio, recovery ratio, and policies for the regulation of SF_6. Considering the uncertainty associated with the future development of these relevant factors, we established three scenarios: a Business As Usual scenario (BAU), Carbon Mitigation Scenario (CMS), and Deep Mitigation Scenario (DMS).

BAU: Business as Usual scenario

In this scenario, per capita electricity demand is high, installed generation capacity increases dramatically, and the proportions of wind and photovoltaic power increase substantially. The SF_6 technology is frozen at current levels, and the consumption and emission rates per unit equipment remain at fixed at current levels. Moreover, only limited substitution of SF_6 is adopted in electrical equipment, and a limited quantity of SF_6 is recycled during the disposal process because of current relaxed policies and regulations concerning SF_6.

CMS: Carbon Mitigation Scenario

In this scenario, per capita electricity demand is moderate, installed generation capacity increases at a modest rate, and the proportions of wind and photovoltaic power increase substantially. Although China has no mandatory legislation/regulation for the control of the consumption and emission of SF_6, reducing or limiting the use of SF_6 is an inevitable trend given technological developments and policy changes in relation to greenhouse gas emissions [1]. The consumption and emission of SF_6 can be reduced through the following measures: (1) reduced filling quantity and minimized leakage rate through improvements in technology and management; (2) an increased recycling ratio prompted by stronger policy incentives; and (3) an increased ratio of substitution of SF_6.

DMS: Deep mitigation scenario

In this scenario, with consideration of the low-carbon development strategy and strict environmental and resource constraints, electricity demand grows slowly and future per capita electricity demand is relatively low in comparison with the other scenarios. Moreover, the developments of wind and photovoltaic power are reasonably slow and the installed generation capacity increases slowly. However, improvements in SF_6 technology and in the substitution and recycling ratios are substantial.

These three scenarios are typical and represented the full range of uncertainty in the SF6 consumption and emission in the future considering different factors uncertainty range. And the information for each parameters setting are detailed in Section 2.3.

2.3. Key Parameters and Assumptions

2.3.1. Population, Per Capita Electricity Demand, and Installed Capacity

The consumption and emission of SF_6 from electrical equipment are proportional to the activity level of the power sector. In this paper, similar to the approach adopted in the SNC [7], the installed capacity is used to represent power sector activity. Thus, the SF_6 consumption and emission of the manufacture and installation processes, operation and maintenance emissions, and disposal emissions are proportional to the newly added installed capacity, stock in operation, and retired capacity, respectively.

Installed capacity is determined by the total electricity demand and the electricity structure, which are closely related to population, per capita electricity demand, and share of renewable energy. The population of China continues to grow at a reasonably slow rate. In 2015, the population of China was 1.38 billion. It is expected to reach a peak of 1.42 billion in 2030, before reducing slowly to 1.40 billion by 2050. In 2015, the installed electricity capacity of China was 1525 GW, and the per capita electricity demand was 4100 kWh, i.e., about half that of OECD countries in 2015 [30]. Various research has shown the installed generation capacity of China could reach 3000–3500 GW by 2050 [17,26]. Considering the uncertainties of per capita electricity demand and future development of renewable energy, this study considered three scenarios for the per capita electricity demand in 2050: 6500, 7500, and 8500 kWh. Meanwhile, the generation shares of wind and photovoltaic power in the three scenarios are projected to increase to 18%, 28%, and 35%. The newly installed capacity is large in the early stage, and it gradually decreases toward the later stage. By 2050, the total installed capacity is considered to reach saturation level. The corresponding installed capacities are shown in Table 1.

Table 1. Installed generation capacity in China (GW) [17,26].

Year	2015	2020	2025	2030	2035	2040	2045	2050
High	1525	2142	2664	3095	3450	3743	3985	4184
Medium	1525	2118	2542	2835	3038	3179	3276	3344
Low	1525	2062	2312	2422	2469	2490	2500	2503

2.3.2. Relationship between Installed Capacity and Transformer Capacity of Electricity in Power Sector

SF_6 is mainly used in gas circuit breakers, gas-insulated switchgear, and gas-insulated transformers as an insulator for the electrical equipment. Generally, these devices are installed in transformer substations and switch stations with various voltage grades ranging from 35 to 1000 kVA, and the transformer substation capacity determines the scale of electricity demand or supply load. Therefore, the consumption and emission of SF_6 are proportional to transformer capacity. For the National Emission Inventory of China in 2012, the national SF_6 emission was estimated using transformer capacity as the driving factor in the sample region [6]. For the SNC in 2005, the installed capacity of the sample region was used as the driving factor to estimate national SF_6 emissions [7]. According to statistics of installed capacity and transformer capacity above 35 kVA in China during 1993–2015, the relationship between transformer capacity and installed capacity is approximately linear with a coefficient of determination (R^2) of 0.9914, as shown in Figure 2. Thus, installed generation capacity can be used as a proxy for transformer capacity to represent the driving factor of SF_6 consumption and emission.

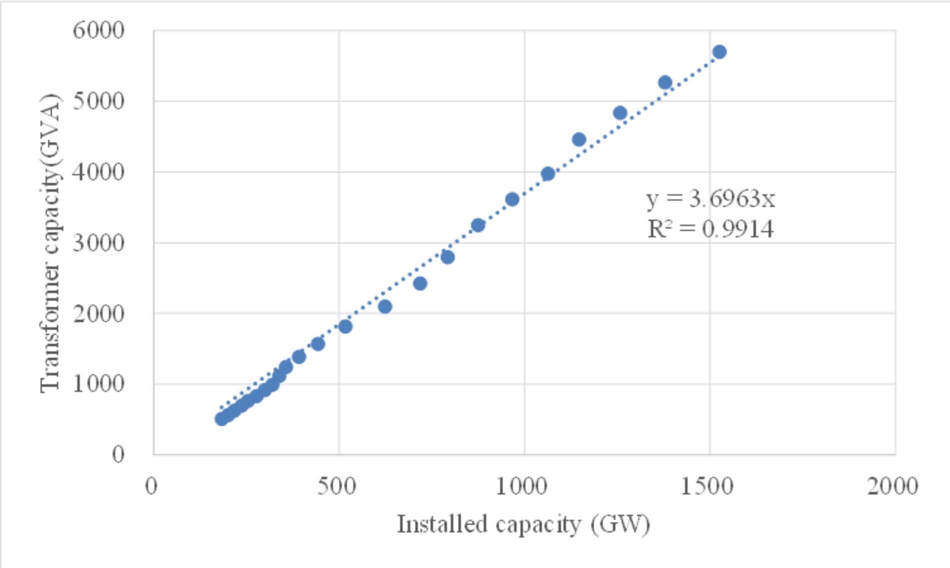


Figure 2. Relationship between transformer capacity and installed capacity in China (1993–2015).

2.3.3. Emission Parameters of SF_6

The parameters related to SF_6 emission include the filling quantity of SF_6 per unit of newly added installed capacity, equipment lifetime, the substitution ratio of SF_6, emission factors of manufacture and installation, emission factor of operation and maintenance, the residual ratio, and the recovery ratio. In this study, 2015 was selected as the base year, and the related parameters were collected from the SNC and other relevant literature. Sensitivity analyses on the key parameters are investigated in the following sections.

As shown in Table 2, the related emission parameters were collected from National Emission Inventory in 2005 [7] or IPCC 2006 [25]. The ranges of parameters are also compared with related literature. For the BAU, the emission parameters were frozen as those of the SNC. For the DMS, the lower bounds of the ranges for the filling and emission factors were selected, as were the upper bounds of the ranges for the substitution and recovery ratios. For the CMS, the averages of the BAU and DMS parameters were adopted. For all scenarios, the parameters for intervening years between the base year and 2050 were obtained via linear interpolation.

Table 2. Parameters of estimation of SF_6 emission from electrical equipment.

Type	Unit	SNC	Range	BAU in 2050	CMS in 2050	DMS in 2050
Initial filling	t/GW	57.78	40–66	57.78	48.89	40
Equipment life	a	30		30	30	30
Substitution ratio of SF_6	%	0	0–100	0	50	100
Emission factor of manufacture and installation	%	8.6	1.71–8.6	8.6	5.155	1.71
Emission factor of operation and maintenance	%	4.7	0.7–4.7	4.7	2.7	0.7
Residual ratio	%	95		95	95	95
Recovery ratio	%	0	0–100	0	50	100

The initial filling quantity per unit of installed generation capacity is the amount of SF_6 consumption per GW of newly installed capacity. Based on historical data of SF_6 consumption and installed capacity during 2001–2010 [4,13], the range of this parameter is 40–66 t/GW, with a median value of 52 t/GW.

The substitution of SF_6 is only considered in newly manufactured and installed equipment because of the technological requirements. Research has shown that SF_6 cannot be substituted completely in the short term. Moreover, the mixed gas of SF_6/N_2 can only partially substitute SF_6. In the long term, a gas with a low GWP might be used to substitute SF_6. Therefore, the substitution of SF_6 to achieve emission reduction is a long-term process. The substitution ratio was generally zero in 2015, and it was assumed that the substitution ratio of new electrical equipment could be increased to 100% by 2050; thus, SF_6 could be substituted completely under the DMS. Therefore, the range of this parameter was selected as 0–100%.

The IPCC default values of emission factors (including natural leakage and emissions of operation, maintenance, and disposal) are 2.6% for the EU, 0.7% for Japan, and 2.0% as a global average. However, there is no default emission factor specified for China [25]. The literature indicates that the operation and maintenance emission factor was 4.38% in 2010, based on the actual SF_6 consumption data of the Guangdong power grid [29]. This is similar to the value of 4.7% of the SNC, which was based on SF_6 consumption data of the North China power grid [3]. Therefore, the operation and maintenance emission factor was set as 0.7–4.7%. In addition, the emission factor of manufacture and installation in the literature and the SNC was 2.18% (1.71–3.25%) [1] and 8.6%, respectively. Therefore, the range of the manufacture and installation emission factor was set as 1.71–8.6%.

Most electrical equipment in China that incorporates SF_6 is not at the retirement stage. In addition, because of technological limitations, the SF_6 recovery ratio remains low [4]. In 2007, the National Power Grid Corp. undertook pilot projects on SF_6 recycling in three provinces: Gansu, Hebei, and Sichuan. By 2014, the National Power Grid Corp. established several processing centers for the recovery of SF_6 in Shanxi, Tianjin, Inner Mongolia, Jiangxi, and other provinces. These centers demonstrated the technical feasibility of the process by achieving a recovery and reutilization rate of SF_6 of 98%. However, the total national scale of SF_6 recovery remains almost negligible. Therefore, assuming appropriate technological development and the introduction of relevant policies, the SF_6 recovery ratio of retired electrical equipment was considered to vary from 0% initially to 100% by 2050 [35–37].

3. Results

3.1. Trend of SF_6 Consumption and Emission

The SF_6 consumption associated with electrical equipment under the three scenarios is shown in Figure 3 as solid lines. It can be seen that the consumption of SF_6 was 12.0 kt in 2015, which is about twice that in 2005. Under the BAU, the consumption of SF_6 is projected to grow to 13.6 kt by 2030 and to 21.3 kt in 2050, i.e., 10% and 80% more than in 2015, respectively. Between 2015 and 2030, growth of SF_6 consumption is expected to be slow, largely because of the slow increases of the newly installed and retired capacities. After 2030, the retirement of installed capacity will increase and the filling quantity of SF_6 will increase in proportion with the total newly installed capacity, which will result in increased growth of SF_6 consumption. Under the CMS and DMS, technological improvements and the increased SF_6 recovery utilization ratio are projected to result in an 80% reduction of SF_6 consumption in comparison with the BAU. Consumption of SF_6 under the CMS and DMS is projected to peak in 2015 and to fall continuously thereafter.

The SF_6 emission associated with electrical equipment under the three scenarios is shown in Figure 3 as dotted lines. Because of the rapid increase of installed capacity, the total SF_6 emission was 3.5 kt in 2015, i.e., about three times that in 2005. By 2030, SF_6 emission is projected to increase to 8.9, 6.0, and 3.6 kt under the BAU, CMS, and DMS, respectively, corresponding to increases of 151%, 70%, and 3% compared with 2015, at annual rates of increase of 6.4%, 3.6%, and 0.2%. By 2050, SF_6 emissions under the BAU, CMS, and DMS are projected to be 18.8, 6.2, and 0.3 kt, respectively, corresponding to increases of 433%, 76%, and −92% compared with 2015, at annual rates of increase of 4.9%, 1.6%, and −6.7%. Compared with the BAU, the SF_6 emissions under the CMS and DMS are expected to be much lower because of the reduction of installed capacity and improvements in SF_6 technology. Under the CMS and DMS, the time of peak emissions is projected to be around 2035–2040, following which the total emissions should gradually decrease. Additionally, the absolute scale of peak emissions could be reduced by more than 60%. By 2050, total emissions under the CMS and DMS could be reduced by more than 80% compared with the BAU.

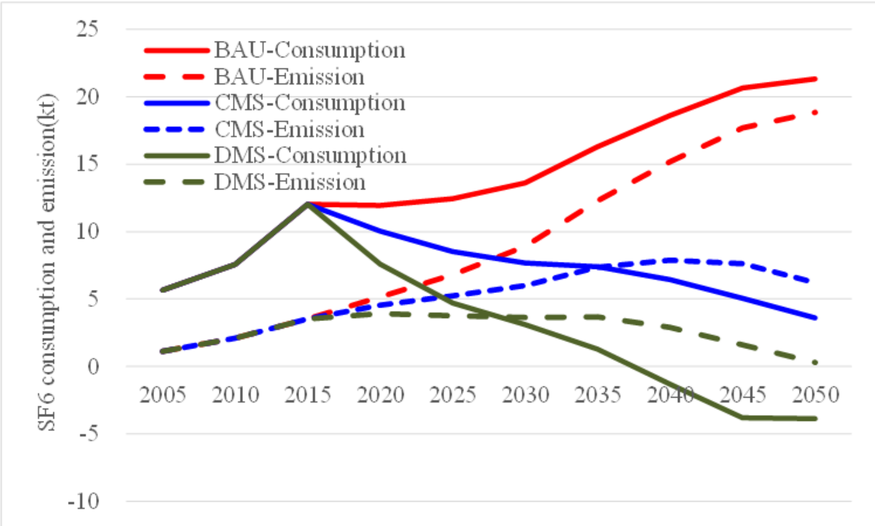


Figure 3. SF_6 consumption (solid lines) and emission (dotted lines) (kt) in China under the three scenarios.

It is evident from Figure 3 that there is considerable difference between the emission and consumption of SF_6. In 2015, SF_6 consumption was about three times that of emission. By 2030, SF_6 consumption is projected to be 1.53, 1.28, and 0.85 times that of emission under the BAU, CMS, and DMS. By 2050, the newly installed and retired capacities should be approximately equal because of the saturation of installed capacity. Under the BAU, SF_6 consumption and emission are projected to converge. Under the CMS and DMS, net consumption of SF_6 is predicted to be even lower than emission because of the increased recovery and substitution ratios.

3.2. Pathway of SF_6 Cumulative Consumption and Emission

The cumulative consumption and emission of SF_6 from electrical equipment in China are projected to increase continuously but with obvious differences. The cumulative consumption was 120 kt in 2015, as shown by the solid line in Figure 4. By 2030, the cumulative consumption under the BAU, CMS, and DMS is predicted to increase to 304, 258, and 214 kt, respectively, corresponding to increases of 164%, 116%, and 78% compared with 2015, at annual rates of increase of 6.4%, 5.3%, and 3.9%. By 2050, the cumulative consumption under the BAU, CMS, and DMS is predicted to be 674, 379, and 188 kt, respectively, corresponding to increases of 463%, 217%, and 57% compared with 2015, at annual rates of increase of 5.1%, 3.3%, and 1.3%. In 2050, the cumulative consumption under the DMS is predicted to be lower than 2035 (peak year) because of improvements in the substitution and recovery ratios.

The cumulative emission of SF_6 in 2015 was 31 kt, which is predicted to increase under all three scenarios, as shown in Figure 4 by the dotted lines. By 2050, the cumulative emission of SF_6 under the BAU, CMS, and DMS is predicted to be 425, 251, and 138 kt, respectively, corresponding to increases of 12.5, 7.0, and 3.3 times compared with 2015, at annual rates of increase of 7.7%, 6.1%, and 4.3%. In 2050, cumulative emissions of SF_6 under the CMS and DMS are predicted to decrease by 40% and

70%, respectively, compared with the BAU. In addition, the relative increase (increase based on 2015) of cumulative emission is higher than the relative increase of cumulative consumption; however, the absolute quantity of cumulative emission is projected to remain below the absolute quantity of cumulative consumption. The ratio of cumulative emission to cumulative consumption was 3.8 in 2015, which is expected to decrease under the BAU, CMS, and DMS to 1.6, 1.5, and 1.4, respectively, by 2050.

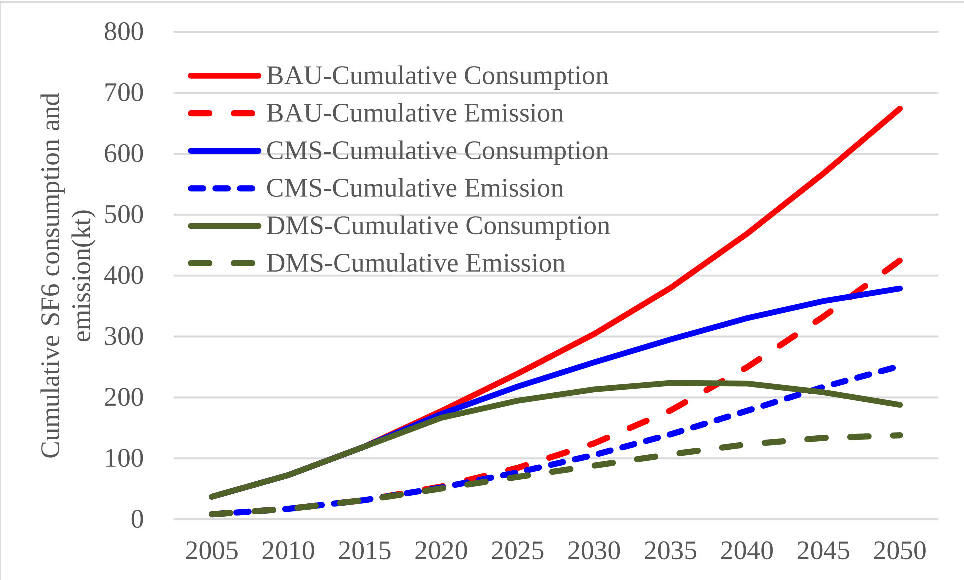
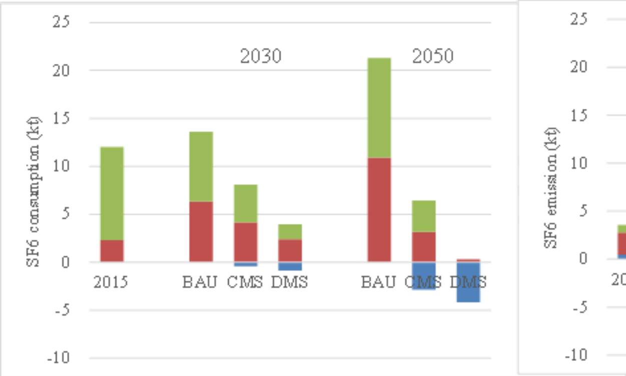


Figure 4. SF_6 cumulative consumption (solid lines) and emission (dotted lines) in China under the three scenarios.

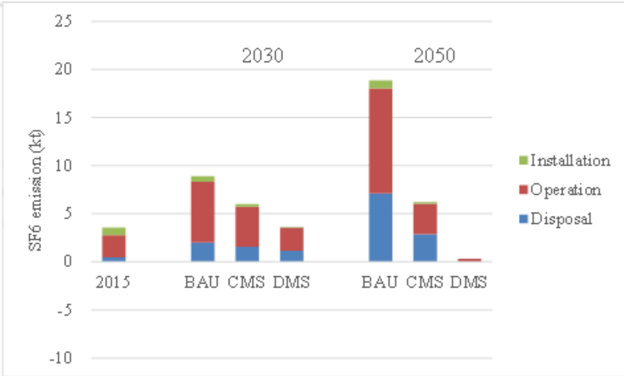
3.3. Sources of SF_6 Consumption and Emission

The sources of SF_6 consumption and emission include newly installed equipment, operational stock, and retired equipment. As shown in the left panel of Figure 5, before 2030, SF_6 consumption can be attributed mainly to SF_6 filling associated with newly installed equipment. It accounted for 80% in 2015 and it is projected to vary from 50 to 55% under the three scenarios by 2030. By 2050, SF_6 filling of newly installed equipment is predicted to still account for 50% of consumption under the BAU. However, it is projected to decrease by about 60% under the CMS and to decrease to almost zero under the DMS. Under the CMS and DMS, SF_6 consumption is associated mainly with the refilling of stock operational electrical equipment during operation and maintenance. Furthermore, the recovery (i.e., negative SF_6 consumption) of SF_6 from retired equipment is greatly enhanced.

As shown in the right panel of Figure 5, the primary source of SF_6 emission before 2030 is mainly leakage from operational stock equipment, which accounts for about two thirds of the total emission. By 2050, under the BAU, SF_6 emission is attributed mainly to leakage from operational stock equipment and to emissions associated with retired equipment. This is because of the considerable reduction predicted for newly installed capacity and the considerable increase projected for retired equipment. Moreover, under the CMS and DMS, substantial enhancements of the SF_6 substitution and recovery ratios are expected because of technological improvements. Therefore, SF_6 emission is expected to derive mainly from leakage of operational stock equipment; thus, the total SF_6 emission is projected to decrease greatly.



(**a**)



(**b**)

Figure 5. Sources of SF_6 (**a**) consumption and (**b**) emission (kt) in China.

3.4. Potential for and Contributions to SF_6 Emission Reduction

The potential for reduction of SF_6 emission from electrical equipment is considerable. To demonstrate the potential for and the contributions to SF_6 emission reduction, the BAU and DMS are shown in Figure 6. By 2050, the SF_6 emissions under the BAU and DMS are projected to be 18.8 and 0.3 kt, respectively, i.e., in comparison with the BAU, the potential for SF_6 emission reduction under the DMS is 18.5 kt (a decrease of 98%).

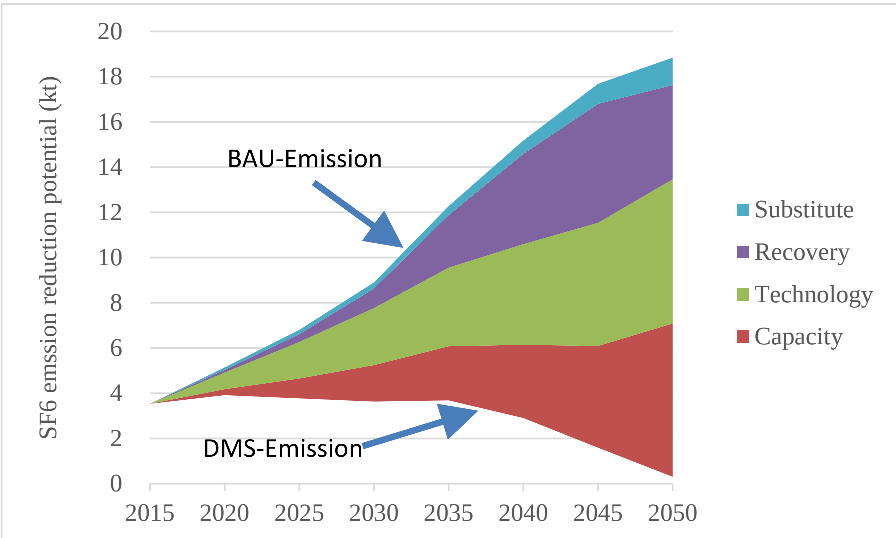


Figure 6. Potential for and contributions to SF_6 emission reduction (kt) in China.

The potential for SF_6 emission reduction in relation to electrical equipment can be assigned to four categories (contributions): reduction of installed capacity, improvement of SF_6 technology (reduction of filling quantity per unit installed capacity and reduction of leakage quantity of operational stock), increase of the SF_6 recovery ratio for retired equipment, and increase of the SF_6 substitution ratio for newly installed capacity. Compared with the BAU scenario, the contribution to emission reduction under the DMS prior to 2030 can be attributed primarily to the reduction of newly installed capacity and the improvement of SF_6 technology. After 2030, the contribution to emission reduction of SF_6 recovery from retired equipment is predicted to increase gradually. By 2050, the contributions of the above four measures to emission reduction potential are projected to be 37%, 34%, 22%, and 7%, respectively.

The greatest potential for emission reduction is the reduction of installed capacity, which implies the electrification in end-use sectors and high penetration of renewables with low capacity factor in generation inevitably increases the installed capacity and SF_6 emissions, although they could lower global emissions substantially. The second and third largest contributions to emission reduction are associated with improvements in SF_6 technology and an increase of the SF_6 recovery ratio. The smallest contribution to emission reduction is attributed to SF_6 substitution by an alternative filling gas, but with limited impact in the early stages on operational stock equipment. In addition, the potentials for and contributions to SF_6 emission reduction under the CMS were found similar to the DMS, but the scale of emission reduction was generally lower.

3.5. SF_6 Delayed Emission Effect

Although SF_6 consumption occurs during the manufacturing process, most of it is emitted in the subsequent processes (operation, maintenance, and retirement). Therefore, the consumption and emission of SF_6 could be markedly different in any given year, i.e., the delayed emission effect. To quantify this, the delayed emission in a specific year is represented by the cumulative consumption minus the cumulative emission (solid bars in Figure 7). The delayed emission effect is quantified as the ratio of delayed emission to cumulative emission (dotted lines in Figure 7). By 2050, the cumulative delayed emissions under the BAU, CMS, and DMS are projected to be 249, 127, and 50 kt, respectively, i.e., equivalent to volumes of greenhouse gases of 5.94, 3.04, and 1.20 $GtCO_2e$ (1.2–6.0 $GtCO_2e$), respectively. The delayed effect ratio (i.e., the ratio of delayed emissions to total emissions) was 280% in 2015 and this is predicted to decrease to 36–60% by 2050.

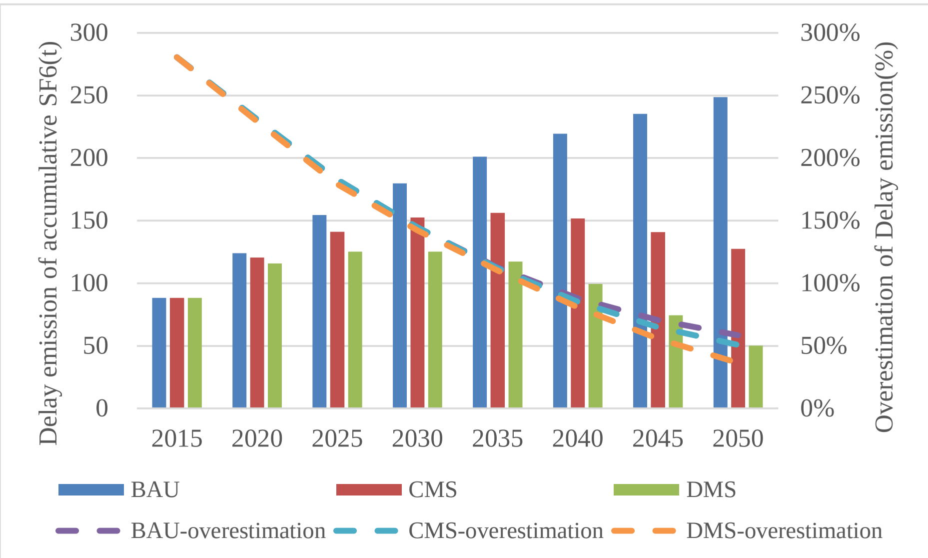


Figure 7. SF_6 delayed emission effect.

Clearly, if the delayed emission effect is not considered and potential consumption is used as a proxy for emissions, there is a possibility that SF_6 emissions in the near future (before 2035) could be overestimated by 1–2 times range. Such a difference between SF_6 consumption and emission is very similar to the current national SF_6 consumption and emission inventories of the U.S.A. and Europe. By 2050, the amplitude of this overestimation should decline gradually, as shown in Figure 7.

4. Sensitivity Analyses

The key parameters affecting SF_6 emission from electrical equipment include the installed capacity, technological improvements (unit filling and emission factor), and substitution and recovery ratios. The relevant parameters were derived mainly from the SNC in 2005 and further crosschecked with available publications and literature. Considering the uncertainties associated with both the key parameters in the current situation and the future improvements in technology, we performed sensitivity analyses.

To quantify the uncertainties associated with the various factors affecting SF_6 consumption and emission, we performed a sensitivity analysis using the CMS as an example. The reason of selecting CMS is that some parameters in BAU and DMS are already of the up limit or low limit and not necessary to make sensitivity analysis. We considered four key parameters: installed capacity, technological improvements, the recovery ratio, and the substitution ratio. It can be seen from Figure 8 that the most influential factor is technological improvement. A 10% increase in technological improvement could reduce SF_6 emission by 9.2% by 2050. The second largest influencing factor is installed capacity, and a 10% increase in installed capacity could increase SF_6 emission by 8.0% by 2050. Then followed in descending order by the recovery ratio and the substitution ratio.

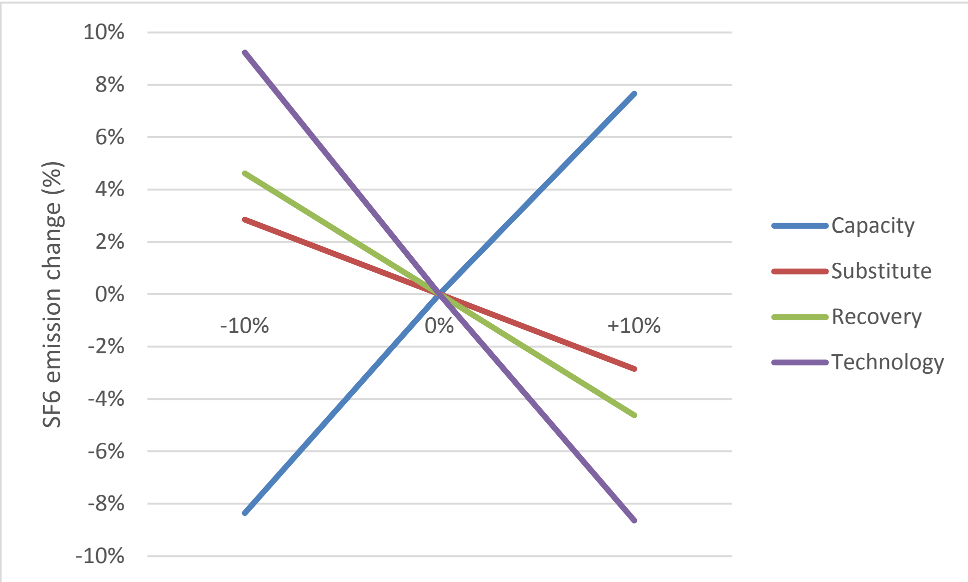


Figure 8. Sensitivity analyses of SF_6 emission change to key factors by 2050.

5. Conclusions

This research explored the future SF_6 consumption and emission pathways associated with electrical equipment in China according to the equipment life cycle. Considering the delayed emission effect, equipment survival, and retirement curves, three scenarios were investigated: BAU, CMS, and DMS. The analysis also examined future SF_6 consumption and emission, cumulative consumption and emission, the sources of consumption and emission, the potential for and contributions to emission reduction, and the delayed emission effect. Moreover, the sensitivity of SF_6 emission to the key factors of installed electricity capacity, technological improvements, and the recovery and substitution ratios was also investigated.

It was found that SF_6 consumption and emission under the BAU could increase substantially to 21.3 and 18.8 kt, respectively, by 2050, i.e., 1.8 and 5.3 times the 2015 levels. Because of the decrease of installed capacity, SF_6 technology improvements, and increases in the recovery and substitution ratios, SF_6 consumption and emission under the CMS and DMS were predicted to be markedly lower than under the BAU (i.e., decreases of over 80%). Correspondingly, the SF_6 cumulative consumption and cumulative emission were projected to increase continuously under the BAU to reach 674 and 425 kt, respectively, by 2050 (i.e., 5.6 and 13.5 times the 2015 levels). Under the CMS and DMS, the same factors were predicted to be about 40% and 70% lower by 2050, respectively, in comparison with the BAU.

It was also found that, before 2030, the source of SF_6 consumption could be attributed mainly to the SF_6 filling quantity of newly added equipment, whereas the source of SF_6 emission could be attributed mainly to leakage from operational stock. By 2050, the source of SF_6 consumption was projected to be associated mainly with the operation, maintenance, and refilling of operational stock. In addition, the recovery and reuse of SF_6 from retired equipment (i.e., negative consumption) were predicted to increase substantially. The source of SF_6 emission was expected to be mainly leakage from operational stock and emissions from retired equipment. By 2050, in comparison with the BAU, the potential for SF_6 emission reduction was projected to be about 18.5 kt under the DMS, and the contributions of the installed electrical capacity, technological improvements, recovery ratio, and substitution ratio to emission reduction were estimated to be 37%, 34%, 22%, and 7%, respectively. The sensitivity analyses indicated that the factors influencing SF_6 consumption and emission in descending order of importance are technological improvements, installed electrical capacity, the recovery ratio, and the substitution ratio.

Finally, we also found that the SF_6 delayed emission effect from electrical equipment was obvious. By 2050, the cumulative delayed emission was projected to be 50–249 kt under the three scenarios, which could be considered equivalent to 1.2–6.0 $GtCO_2e$. Therefore, SF_6 emission before 2035 could be overestimated by a factor of 1–2 times if the delayed emission effect were not considered and consumption were used as an inaccurate proxy for emission.

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