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Sulfur Hexafluoride (SF_6) Emission Estimates for China: An Inventory for 1990−2010 and a Projection to 2020

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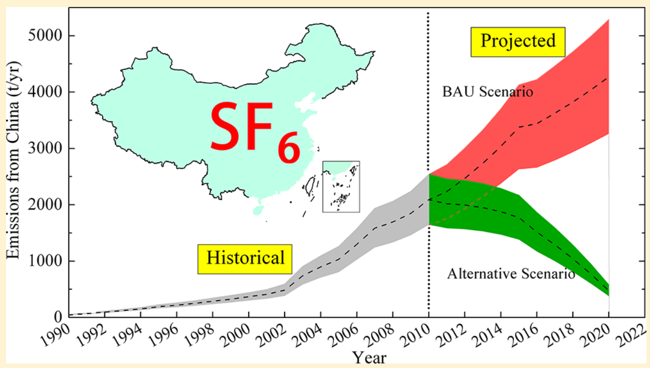
Supporting Information

ABSTRACT: Sulfur hexafluoride (SF_6) is the most potent greenhouse gas regulated under the Kyoto Protocol, with a high global warming potential. In this study, SF_6 emissions from China were inventoried for 1990−2010 and projected to 2020. Results reveal that the highest SF_6 emission contribution originates from the electrical equipment sector (about 70%), followed by the magnesium production sector, the semiconductor manufacture sector and the SF_6 production sector (each about 10%). Both agreements and discrepancies were found in comparisons of our estimates with previously published data. An accelerated growth rate was found for Chinese SF_6 emissions during 1990−2010. Because the relative growth rate of SF_6 emissions is estimated to be much higher than those of CO_2, CH_4, and N_2O, SF_6 will play an increasing role in greenhouse gas emissions in China. Global contributions from China increased rapidly from 0.9 ± 0.3% in 1990 to 22.8 ± 6.3% in 2008, making China one of the crucial contributors to the recent growth in global emissions. Under the examined Business-as-usual (BAU) Scenario, projected emissions will reach 4270 ± 1020 t in 2020, but a reduction of about 90% of the projected BAU emissions would be obtained under the Alternative Scenario.



1. INTRODUCTION

Sulfur hexafluoride (SF_6) is a greenhouse gas (GHG) regulated under the Kyoto Protocol with a global warming potential (GWP) of 23 900 over a 100 year time horizon.[1] The electrical equipment sector is the major emission source of SF_6 (through leakage, maintenance, and retiring), but semiconductor manufacturing, magnesium production, and other minor sources make additional contributions.[2] Compared to anthropogenic sources, natural sources of SF_6 are negligible.[3] Although the atmospheric concentration of SF_6 is relatively low, contributing 0.1% of the total anthropogenic radiative forcing, the concentration is growing continuously[4,5] because of the compound's long lifetime of ∼3200 years.[6]

Close analyses of long-term atmospheric concentrations revealed that the concentration growth rate decreased slightly after 1995, but increased again after approximately 2000, reaching 0.29 ± 0.02 ppt/yr in 2008.[5] This decrease was most likely due to SF_6 emission reductions in industrialized countries that are required to submit National Inventory Reports (NIRs) to the United Nations Framework Convention on Climate Change (UNFCCC: the "Annex I" countries), while the increase after 2000 was probably driven by non-Annex I countries.[4,5] Improved quantification of SF_6 emissions from non-Annex I countries such as China is crucial to better understand the global budget of SF_6.

Recently, some studies have estimated SF_6 emissions for China. Emissions of halogenated compounds (including SF_6) from North China were investigated using gas chromatography-electron-capture detector measurements at the Shangdianzi station (117.12°E, 40.65°N) and with a Lagrangian model FLEXPART.[7] The results were upscaled from the inversion domain to national totals proportional to the population distribution. Using high-frequency in situ measurements taken at Gosan station (126.17°E, 33.28°N), Korea, SF_6 emissions from China were estimated by a tracer ratio method[8,9] and using combined Eulerian and Lagrangian chemical transport models.[10] However, discrepancies were found in the results from these top-down estimates, 0.8 (0.53−1.10) kt for 2007,[7] 1.3 (0.93−1.7) kt for 2008,[8] and 2.4 (1.9−2.9) kt for the 2007−2009 average.[10]

Inventory of SF_6 emissions from China is of great interest to both academia and policy makers, but official documents or

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research publications with concrete information about SF_6 consumption and emissions are lacking. This study will help to remedy this situation. Historical emissions for the period 1990−2010 were inventoried by estimating SF_6 consumption and emission factors in four major SF_6-related sectors. The estimated emissions with assessed uncertainties were then compared to top-down estimates as well as bottom-up estimates, for example, the Emission Database for Global Atmospheric Research (EDGAR).[11] Finally, emissions for the period 2011−2020 were projected under two scenarios to examine the potential for emission reduction in China.

2. ESTIMATION OF CONSUMPTION AND PRODUCTION

In China, SF_6 is widely used in three sectors: the magnesium production sector, the semiconductor manufacture sector, and the electrical equipment sector. Moreover, because SF_6 is produced in large quantities in China, estimating emissions from the production sector is also very important.

2.1. Magnesium Production Sector. The production and casting of magnesium metal may involve SF_6.[12] Previous studies have reported on annual Chinese magnesium exports and domestic consumption,[13−15] as shown in the Supporting Information (SI) Figure S1. These studies revealed that exports account for the majority (about 60%) of China's total magnesium production. Today, China is the world's largest magnesium producer and exporter.[13]

When magnesium is melted for die casting, SF_6 is commonly used as the cover gas, leading to SF_6 emissions. Part of the total magnesium produced is used for die casting. The proportions of magnesium casting to exports or domestic consumption are also plotted in SI Figure S1. Since 2000, the proportions of magnesium casting to exports and domestic consumption have increased gradually and stabilized at levels of 25% and 35% during 2005−2010, respectively. The missing proportion data for the period 1990−1999 are assumed to be constant backward in time from 1999.

China-specific information is not readily available for determining the consumption factor (kg SF_6/t Mg). Available information regarding consumption factors is summarized in SI Figure S2, including consumption factors for the U.S.,[16] Japan,[17,18] EU,[17] and the default value (1.0 kg SF_6/t Mg) suggested by the Intergovernmental Panel on Climate Change (IPCC; [12]). Consumption factors with uncertainties were estimated to be 1.65 (0.69−3.16) kg SF_6/t Mg. This range of values is more rigorous than the single value used in IPCC (2006), and can be applied to estimates in this study as follows:

$$C_1 = P_1 \times T_1 \times CF + P_2 \times T_2 \times CF \tag{1}$$

where C_1 is the annual SF_6 consumption in the magnesium production sector (t), P_1 is the proportion of magnesium castings in exports, T_1 is annual total magnesium exports (kt), CF is the SF_6 consumption factor (kg SF_6/t Mg), P_2 is the proportion of magnesium castings in domestic consumption, and T_2 is annual total domestic consumption of magnesium (kt).

2.2. Electrical Equipment Sector. SF_6 is used widely in China in the electrical equipment sector, such as for gas circuit breakers (GCB), gas-insulated switchgear (GIS), and gas-insulated transformers (GIT).[19] The annual consumption of SF_6 by Chinese electrical equipment manufacturing has been estimated using detailed statistics of the newly installed capacities of the electric power supply in China for the period of 2001−2010.[20] The results show a rapid development of electric system installation throughout these 10 years with a leap during 2004−2006, in accordance with SF_6 consumption in this sector.[20] The demand for SF_6 was only 820 t in 2001, but it increased to 5000 t in 2010, with the largest growth increase from 930 to 3500 t occurring during 2002−2005.[20] Assuming that SF_6 consumption is linearly correlated with electricity consumption, the consumption of SF_6 in 1990 was determined by multiplying the SF_6 consumption in 2001 by the ratio of electricity consumption in 1990 to that in 2001.[21] During the period 1990−2001, we assumed a linear growth of SF_6 consumption in this sector.

2.3. Semiconductor Manufacture Sector. There are several manufacturing subsectors, which are collectively termed the "semiconductor manufacture sector" and include semiconductor, flat panel display (FPD), and photovoltaic (PV) manufacturing.[12] This sector has expanded rapidly in China.[22] Owing to commercial confidentiality and a lack of statistical information (e.g., areas of substrate) for each of these subsectors in China data are difficult to access, therefore it is not possible to calculate consumption by multiplying the substrate areas by consumption factors (e.g., the default value kg/m^2 suggested by the IPCC [12]) at the subsector level. Fortunately, the total consumption in this sector, 150 t in 2005[23] and 400 t in 2010,[24] was estimated in previous studies; these were used as estimates in this study. SF_6 consumption in 1990 was assumed to be zero and annual consumption was assumed to increase linearly during 1990−2005 and 2005−2010.

2.4. SF_6 Production Sector. Emissions also occur during the production of SF_6. The quantities emitted depend on the magnitude of production. Total production was determined by the sum of total domestic consumption plus exports minus imports (eq 2). Chinese exports of SF_6 began in 2003 and exports in 2006 and 2007 were estimated to be 1000 t/yr,[24] which were extrapolated linearly back in time to obtain an estimate of 500 t/yr for 2004 and 2005. The production capacity of highly purified SF_6 (purity >99.999%, mainly for the semiconductor manufacture sector) in China is small; therefore, most high-purity SF_6 is imported from abroad.[20] With an adequate supply of low-purity SF_6 from domestic production, this study assumed that the level of high-purity SF_6 imports was equal to the SF_6 consumed in the semiconductor manufacture sector.

$$P = C_1 + C_2 + C_3 + E - I \tag{2}$$

Here P is the annual total SF_6 production (t), C_1 is the annual SF_6 consumption in the magnesium production sector (t), C_2 is the annual SF_6 consumption in the electrical equipment sector (t), C_3 is the annual SF_6 consumption in the semiconductor manufacture sector (t), E is annual export (t), and I is annual import (t), respectively.

2.5. Total Consumption and Production. The estimated annual consumption in each sector and the total production in China are presented in Table 1 and SI Figure S3. During 1990−2000, the annual consumption was no larger than 1000 t; during 2001−2006, the annual consumption increased 5-fold to more than 5000 t in 2006. Since 2006, the total annual consumption stabilized owing to small changes in consumption in each sector. Among these sectors, the electrical equipment sector, which has accounted for more than 80% of the total domestic consumption since 2006, plays a dominant role in the consumption pattern, which is consistent with the finding that

Table 1. Estimated Annual SF_6 Consumption and Emissions from China with 95% Confidence Intervals (Indicated by ± Values)[a]

year	consumption (t)	emissions (t)
1990	350 ± 70 (100/0/0)	45 ± 10 (81/0/2/17)
1991	403 ± 78 (97/2/0)	70 ± 13 (78/6/2/13)
1992	457 ± 87 (95/4/0)	95 ± 18 (77/9/2/11)
1993	510 ± 96 (94/6/0)	122 ± 23 (77/11/2/10)
1994	565 ± 104 (92/7/1)	152 ± 29 (76/12/3/9)
1995	630 ± 114 (89/8/3)	192 ± 36 (71/12/9/8)
1996	679 ± 122 (89/9/2)	218 ± 42 (74/12/6/8)
1997	736 ± 131 (88/10/2)	252 ± 49 (73/13/7/7)
1998	794 ± 140 (87/10/3)	288 ± 57 (73/12/8/7)
1999	854 ± 150 (86/11/3)	326 ± 65 (72/12/9/7)
2000	916 ± 160 (85/11/4)	369 ± 74 (71/12/10/6)
2001	978 ± 170 (84/11/5)	412 ± 85 (70/12/12/6)
2002	1130 ± 199 (82/11/7)	486 ± 108 (66/11/16/6)
2003	2560 ± 474 (90/5/5)	743 ± 164 (66/8/18/8)
2004	3090 ± 575 (90/5/5)	899 ± 196 (65/7/17/10)
2005	3850 ± 716 (91/4/5)	1030 ± 234 (65/7/19/9)
2006	4930 ± 915 (91/4/5)	1300 ± 279 (66/7/18/10)
2007	5070 ± 927 (89/5/6)	1590 ± 351 (65/7/20/8)
2008	5360 ± 979 (90/6/5)	1700 ± 368 (69/8/15/8)
2009	5750 ± 1050 (90/6/3)	1850 ± 391 (73/9/11/8)
2010	5670 ± 1020 (88/7/5)	2090 ± 451 (72/9/13/7)

[a]Percentages (%) of the consumption and emissions are shown in parentheses for the electrical equipment sector, the semiconductor manufacture sector, the magnesium production sector and the SF_6 production sector, respectively. For example, the percentages of emissions were 81%, 0%, 2%, and 17% for those four sectors in 1990. There is no consumption in the SF_6 production sector, and therefore, only three sectors are listed in parentheses for consumption.

about 80% of the SF_6 is consumed in the electrical equipment sector in China.[25]

Total production almost equaled total consumption in the 1990s, but it surpassed the consumption to supply the overseas SF_6 market occurred after 2003, according to Chinese statistics. A previous Chinese study estimated the total production in China to be about 7000 t in 2009,[25] which was 9.4% higher than estimates in this study.

3. METHODOLOGY FOR ESTIMATING EMISSIONS

The subsequent section describes different methods for estimating SF_6 emissions from each sector. These methods were selected with reference to the decision trees for method choice in the 2006 IPCC guidelines.[12] Detailed descriptions of the methods used to assess uncertainties in emissions from each sector and total emissions are provided in SI Text Section 1.

3.1. Magnesium Production Sector. To calculate emissions from the magnesium production sector, eq 3 was selected, because company-specific SF_6 consumption data were not available and a direct measurement approach was not possible. The annual consumption of SF_6 (C_1) is estimated in Section 2.1. For magnesium foundries, 100% was used as the emission factor (EF_1), because more precise decomposition-level data, allowing a more precise estimate, were not available. This value has previously been adopted by many UNFCCC NIRs (e.g., for Japan[26] and Germany[27]).

$$E_1 = EF_1 \times C_1 \qquad (3)$$

Here E_1 is annual SF_6 emission (t) in the magnesium production sector, EF_1 is the emission factor, and C_1 is annual SF_6 consumption in the magnesium production sector (t).

3.2. Electrical Equipment Sector. Emissions of SF_6 occur at each phase of the electrical equipment lifecycle (manufacturing, installation, use, maintenance, and disposal), as shown in eq 4. This study incorporates emissions from manufacturing into those from installation and combines emissions from maintenance and those from disposal. A combined emission factor is then applied for the combined stages.

Based on practical data from the Guangdong provincial power grid in southern China, Xu et al.[20] found that electrical equipment in 500 kv, 220 kv, and 110 kv networks shared 3.6%, 26.1%, and 70.3% of the SF_6 quantity, respectively.[19] They reported annual natural leakage emission factors of 0.05%, 0.07%, and 0.09% and annual maintenance/disposal emission factors of 2.3%, 3.5%, and 4.7% for equipment in the 500 kv, 220 kv, and 110 kv networks, respectively. Accordingly, the combined annual natural leakage emission factor and the maintenance/disposal emission factor for electrical equipment in Guangdong province were calculated to be 0.08% and 4.3%, respectively. These values could be extrapolated to national annual natural leakage and maintenance/disposal emission factors, because electrical equipment is similar across China. These China-specific emission factors were different from the default values suggested by the IPCC.[12] For example, the recommended use emission factors (including leakage, major failures/arc faults, and maintenance losses) for high voltage switchgear are 2.6% and 0.7% for Europe and Japan, respectively. Because no China-specific manufacturing/installation emission factors have been reported, we adopted emission factors from the assembly fugitive rates in the National Greenhouse Gas Inventory Report of Japan.[26] At present, there is almost no recovery of SF_6 in China,[28] and therefore the recovery factor in eq 4 was set to zero.

$$E_2 = EF_{2i} \times C_2 + EF_{2j} \times T + EF_{2k} \times T \times (1 - R) \qquad (4)$$

Here E_2 is annual emission in the electrical equipment sector (t), EF_{2i} is the annual manufacturing/installation emission factor, C_2 is total SF_6 consumption by equipment manufacturers (t), EF_{2j} is the annual natural leakage emission factor, T is the total amount of SF_6 in all installed equipment, R is the recovery factor, and EF_{2k} is the annual maintenance/disposal emission factor.

3.3. Semiconductor Manufacture Sector. Equation 5 was used for this sector. It is important to note that the use of SF_6 for semiconductor manufacturing requires some of the SF_6 to be destroyed in the process (the F created from this destruction of SF_6 is what is actually consumed in the process and the term "use rate" is applied). Referring to the IPCC guidelines[12] and the NIR of Japan,[26] the use rate of SF_6 is 50%. Moreover, abatement technologies could be applied to the waste stream containing SF_6 to reduce emissions, for example two Clean Development Mechanism (CDM) projects are currently operated by Samsung[29] and LG[30] in the Republic of Korea. However, no projects have yet been initiated in China, thus the abatement rate (a × d) equals zero. The fraction of SF_6 remaining in shipping containers after use is set at 10% by the NIR of Japan.[26]

$$E_3 = (1 - h) \times C_3 \times (1 - U) \times (1 - a \times d) \qquad (5)$$

Here E_3 is annual emission in the semiconductor sector (t), h is the fraction of SF_6 remaining in the shipping container after use, C_3 is the SF_6 consumption in this sector (t), U is the use rate of SF_6 (fraction destroyed or transformed in the process), a is the fraction of SF_6 used in processes operating with emission control technologies, and d is the fraction of SF_6 destroyed in the process by the emission control technologies, respectively.

3.4. SF_6 Production Sector. For fugitive emissions from the SF_6 production sector, a production-related emission factor was used to link production and emission (eq 6). Unfortunately, China-specific emission factors have not been reported. The IPCC reported two default values (8% and 0.2%) for different types of SF_6 supply.[12] However, these factors are single values, rather than a range, and were adopted from publications in 1999, which are likely to be outdated due to operational changes in recent years. The latest information regarding emission factors is summarized in SI Table 1, suggesting emission factors of 2.18% (1.71−3.25%), which were applied in this study.

$$E_4 = EF_4 \times P \tag{6}$$

Here E_4 is annual emission in the SF_6 production sector (t), EF_4 is the production-related emission factor, and P is total SF_6 production (t).

4. HISTORICAL EMISSIONS: 1990−2010

4.1. Annual Emissions and Emission Pattern. The total annual emissions of SF_6 in China (95% confidence interval unless specified otherwise) were estimated by aggregating emissions in each sector from 1990 to 2010 (Table 1). The results show that within the period of 1990−2010, SF_6 emissions increased continuously from 45 ± 10 t in 1990 to 2090 ± 451 t in 2010. Note that an accelerated growth rate was found. For the period 1990−2000, the growth rate was estimated to be 32.4 ± 7.5 t/yr. After 2000, the growth rate increased by about five times to 172.0 ± 45.7 t/yr, which is consistent with the fact that activity data in these four sectors grew rapidly after the year 2000.

Emissions patterns of SF_6 are different from consumption patterns. Although consumption of SF_6 in the electrical equipment sector accounts for more than 80% of total domestic consumption, emissions from this sector are about 70% of total emissions (SI Figure S4). The nature of banking in the electrical equipment leads to delayed SF_6 emissions in this sector. The SF_6 production sector contributed to total emissions, resulting in a lower contribution from the electrical equipment sector to the emission pattern than the consumption pattern. The emission contribution from the magnesium production sector increased from the early 1990s and peaked in 2007 when the production of magnesium reached its highest point. Contributions from the semiconductor manufacture sector decreased slightly from 13% to 9% during this time period, because the growth rate of emissions from semiconductor manufacture (about 14.9%/yr during 1995−2010) was lower than the national emissions growth rate (about 17.2%/yr during 1995−2010). Emissions from the SF_6 production sector constitute about 10% of the total. Because the development of each sector will vary in the future, these emission patterns may also change.

4.2. Comparisons with Published Estimates. Comparisons of our estimates with published ones using either top-down or bottom-up methods are provided in Figure 1. The emissions from China estimated in this study agree with the

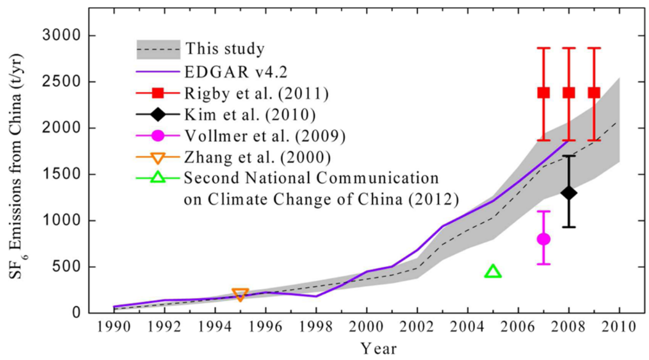

Figure 1. Comparison with other published estimates of SF_6 emissions from China, including estimates for 1995,[31] for 2005,[32] for 2007,[7] for 2008,[8] for the 2007−2009 average,[10] and for 1990−2008.[11].

bottom-up estimates from EDGAR v4.2[11] and Zhang et al.[31] It should be noted that the emission pattern provided by EDGAR differs from our estimates (see SI Figure S4). For example, according to EDGAR v4.2, emissions from the SF_6 production sector accounted for 12−30% of total emissions, about two times larger than our estimates (around 10%), because an emission factor of 8%, which is four times higher than our emission factor of 2.18%, was adopted by EDGAR.[11] Therefore, the activity data (SF_6 production) in EDGAR would be much smaller than our estimated production values. Another large discrepancy was identified between these two estimates for emissions from the semiconductor manufacture sector. The contribution was less than 1% of the national total in EDGAR v4.2, suggesting that emissions are only in the magnitude of several tons, which is considerably less compared to the results of several publications that report hundreds of tons of SF_6 consumed in this sector (Section 2.3). Our estimates are about two times higher than the emission level of 436.7 t for 2005 reported in the Second National Communication on Climate Change of China.[32]

When compared to estimates using top-down approaches, our estimated emissions were higher than those estimated by Vollmer et al. for 2007,[7] slightly higher than those estimated by Kim et al. for 2008[8] and were lower than those estimated by Rigby et al.[10] Vollmer et al.[7] only used measurement data from the Shangdianzi station with 1° × 1° meteorological data. A later study had difficulty in explaining the large variability observed at this station; emission estimates using Shangdianzi-only data were very different from more robust estimates based on data from four Asian stations.[33] Kim et al.[8] and Rigby et al.[10] estimated SF_6 emissions from China based on observation data at the Gosan station. The majority of air transport events from China occur in the winter with winds from the north−northwest to the Gosan station,[8] which allows this station to capture emission signals mostly from northern part of China. Hence, if one station's data are used to estimate SF_6 emissions for all of China, it may lead to biases. Inverse modeling studies using SF_6 measurement data from several stations in East Asia are now in progress with the aim of better constraining emissions from across all of China, then a better comparison between bottom-up and top-down estimates would be possible.

4.3. Proportions of Chinese GHG Emissions. In terms of 100-year GWP,[1] SF_6 emissions from China increased from 1 ± 0 Mt CO_2-eq to 50 ± 11 Mt CO_2-eq during 1990−2010. The direct emissions of CO_2, CH_4, and N_2O in China for 2007, respectively, have been estimated to be 6390 Mt, 831 Mt, and

235 Mt in terms of GWP.[34] The emissions of HFCs and PFCs were calculated from Kim et al.[8] to be 167 Mt and 20 Mt CO_2-eq for 2008, respectively (because results for 2007 were not available, emissions for 2008 were used as an approximation). All of these emissions were derived using the commonly referred GWPs.[1] Thus, the GWP-weighted emissions of SF_6 for 2007 constituted about 0.5 ± 0.1% of the total emissions of six GHGs. The potential emissions of SF_6 in 2007 are 121 ± 22 Mt CO_2-eq (assuming that emissions equal consumption, ignoring the emission delay), and the potential proportion of SF_6 emissions to total GHG emissions (almost no emission delay for CO_2, CH_4, and N_2O, and ignoring emission delay for HFCs and PFCs) is 1.6 ± 0.3%, revealing the importance of SF_6 emissions in China.

Notably, the relative growth rate of SF_6 emissions for the recent period of 2005−2010 was estimated to be about 15.5 ± 8.0%/yr, which is much higher than the relative growth rates of other GHG emissions in China, for example, the relative growth rates of emissions for three major GHGs were estimated to be about 7.9%/yr for CO_2 emissions increasing from 5510 Mt in 2005 to 8050 Mt in 2010,[35] 6.0%/yr for CH_4 emissions and 3.2%/yr for N_2O emissions during 2003−2008 as calculated from EDGAR v4.2 (data are currently only available for the years before 2008).[11] Consequently, SF_6 emissions with a steep relative growth rate cannot be ignored in the Chinese GHG emission system.

4.4. Global Perspective. The contributions of Chinese SF_6 emissions to the global totals are plotted in Figure 2. Annual

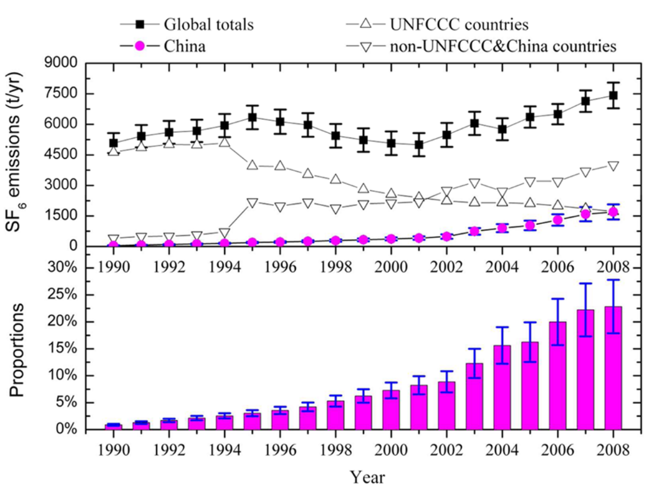

Figure 2. Emission time series for the entire globe, UNFCCC countries, China and non-UNFCCC & China countries (top panel) and the contribution of Chinese SF_6 emissions to global totals during 1990−2008 with 95% confidence intervals (bottom panel). "UNFCCC countries" are Annex I countries that are obligated to report annul emissions to UNFCCC.[36] Global total emissions are shown as ±1-σ uncertainties derived from Rigby et al.[5] Emissions for "non-UNFCCC & China countries" were calculated by subtracting the sum of emissions from China and UNFCCC countries from the global top-down estimates of Rigby et al.[5].

Chinese emissions of SF_6 increased by about 40 times during 1990−2008, while global emissions of SF_6 remained within the 5000−7500 t range. This relatively stable level for the global total was attributed to a combination of emission reductions in some countries (mostly Annex I) and emission increases in other countries.[5] The calculated proportion of global emissions attributed to China displayed a sustained increase during 1990−2008 and peaked in 2008 at 22.8 ± 6.3%. Note that the contribution from China would continue to rise, reaching 23.5 ± 5.8% in 2009 and 25.3 ± 6.7% in 2010, even though global emissions are predicted to increase to 7870 and 8280 t in 2009 and 2010, respectively, following a linear extrapolation of 2004−2008 data.

Around 2000, the overall decreasing trend of global SF_6 emissions stopped and global emissions began to increase again.[4,5] This increase is suspected to be driven by emissions from non-Annex I countries, especially developing Asian countries.[5] According to the top-down global estimates,[5] reported emissions for Annex I countries[36] and Chinese emissions from our study, the emissions from non-Annex I countries (excluding China) were estimated to increase by 1870 t during 2000−2008. Emissions from China increased by 1330 ± 355 t during this period as estimated by our study, which suggests a contribution of 40.7 ± 7.3% to the total emission increases from non-Annex I countries. Considering the rapid increases in both national emissions and their global contributions, SF_6 emissions from China are definitely important for the global totals.

5. PROJECTED EMISSIONS: 2011−2020

5.1. Scenarios for the Projection. Considering the rapid economic and technical developments in the related sectors in China, the consumption and emissions of SF_6 are expected to change accordingly.

The Business-as-usual (BAU) Scenario assumes continuing SF_6 usage and the use of similar technology in these sectors for the period 2011−2020. In the magnesium production sector, according to *China's 12th Five-Year* (2011−2015) *Development Plan of Nonferrous Metals Industry*,[37] the expected annual growth rate of domestic consumption of magnesium is 26.7%, which is much higher than growth rates for other metals. The annual growth rate of domestic consumption of magnesium for 2016−2020 is assumed to be 10%. The averages of exports during 2006−2010 were used to represent the annual export of magnesium during 2010−2020. In the electrical equipment sector, the correlation between the annual electricity consumption increase[21] and SF_6 consumption during 2001−2007 was found to be statistically significant at the 0.01 level. The annual growth rate of electricity consumption is estimated to be 8.8% during 2011−2015 and 5.6% during 2016−2020.[38] Therefore, the estimated annual electricity consumption increase is used for estimating annual SF_6 consumption in this sector. In the semiconductor manufacture sector, production has rapidly increased. For example, the production of FPDs in China has experienced very rapid growth in recent years, and the Chinese government has recently upped tariffs for liquid crystal displays import in to China for assembly, which is likely to lead to many companies opening factories in China.[39] Therefore, SF_6 consumption in 2020 is assumed to be three-times the corresponding value in 2010 with linear growth during 2011−2020. We also cautiously assumed that the annual export/import of SF_6 during 2011−2020 will remain the same as the average of amounts during 2006−2010.

Although no firm regulations regarding SF_6 consumption or emissions are currently enforced in China, annual SF_6 consumption may change because of policy and technology advances (Alternative Scenario). In the magnesium production sector, some species or mixtures of gases can substitute for SF_6.[40,41] The substituting processes were assumed to experience a linear increase from 0% in 2010 to 90% of SF_6

consumption in 2020. In the electrical equipment sector, technologies for detecting and recycling the SF_6 emitted from maintenance and retiring are advancing in China,[42] and several retrieval and purification process centers have been established.[43] A linear increase from 0% in 2010 to 90% in 2020 is assumed for the recovery factor. Substitutes for SF_6 in new equipment are also being developed.[44] Mixtures of gases (e.g., 80% N_2/20% SF_6) may be applied in this sector and a linear increase from 0% in 2010 to 90% in 2020 is assumed. In the semiconductor manufacture sector, locating alternative compounds for etching has been reported to be extremely difficult,[45] while developments in abatement technologies may be more realistic. For example, several CDM projects are currently being operated by Samsung[29] and LG[30] in South Korea. The Alternative Scenario assumes the proportion of SF_6 exhaust systems fitted with abatement technologies will increase from 0% in 2010 to 90% in 2020. Because consumption in these sectors will decrease under the Alternative Scenario, domestic production will also diminish. Emission factors for the production sector are assumed to decrease linearly from the current level to 0.38−0.43%, which was achieved when Japanese facilities were equipped with recovery/destruction units in 2009 and 2010 according to the NIR of Japan.[26]

The methodology for calculating projected SF_6 emissions in these four sectors is the same as that used for calculating historical emissions.

5.2. Projected Emission and Reduction. The projected emissions for 2011−2020 under the BAU Scenario and the Alternative Scenario are shown in Figure 3. Emissions in 2020

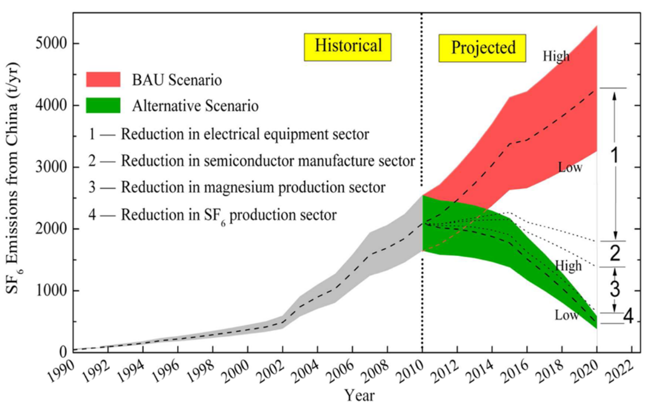

Figure 3. Projected SF_6 emissions from China with 95% confidence intervals for 2011−2020 under the BAU Scenario and the Alternative Scenario. The labels 1, 2, 3, and 4 refer to the respective contributions arising from four sectors to the total emission reductions between the BAU Scenario and Alternative Scenario.

under the BAU Scenario are estimated to be 4270 ± 1020 t (102 ± 24 Mt in terms of GWP) with a growth rate of 7.4 ± 3.7%/yr during 2011−2020. Under the Alternative Scenario, the estimated emissions in 2020 are 476 ± 104 t (11 ± 2 Mt in terms of GWP), only one-ninth of the corresponding value under the BAU Scenario. Furthermore, the estimated emissions in 2020 under the Alternative Scenario reveal a reduction of 74.8 ± 7.7% of the emissions in 2010, which means that emissions in 2020 under the Alternative Scenario are approximately equal to those in 2002. These suggest that if actions are taken such as those under the Alternative Scenario, a large emission reduction would be realized, although rapid developments occur in each sector in China.

Figure 3 also shows the contributions of each sector to the reduction between the two scenarios. In the situation where mitigations occur only in the electrical equipment sector, total emissions will be 1800 ± 701 t in 2020, more than 2400 t lower than the estimated emissions under the BAU Scenario. The contributions from magnesium production sector, electrical equipment sector, semiconductor manufacture sector, and SF_6 production sector are estimated to be 19.3%, 65.2%, 10.8%, and 4.7%, respectively, of the total potential reduction, indicating that in China the electrical equipment sector will be the biggest potential source of SF_6 emission reductions.

In China, efforts are continuously being made to minimize usage, reduce leakage, and enhance recovery efficiency. For example, the CDM Project of the SF_6 recycling project of North China Grid has been underway since 2010.[46] Several retrieval and purification process centers have been, or will be, established in China.[43,47] It should be noted that actual annual emissions in China for the period 2011−2020 may be between these two scenarios, depending greatly on what policies and technologies will be implemented in the next decade. In the United States, voluntary programs between the U.S. Environmental Protection Agency and industry (e.g., International Magnesium Association, Electric Power Systems) have achieved significant emission reductions.[16] In the European Union, Regulation (EC) 842/2006 on certain fluorinated greenhouse gases (the F-Gas Regulation) entered into force on 4 July 2007 and introduced many restrictions. For example, the use of SF_6 is prohibited from 1 January 2008 for magnesium die-casting which consumes more than 850 kg annually.[48] These policy options, either voluntary or regulatory, offer good opportunities for China to reduce SF_6 emissions.

■ ASSOCIATED CONTENT

Supporting Information

A detailed description of the method used to assess uncertainties in emissions is provided in Text Section S1. Production-related emission factors for SF_6 are shown in Table S1. Chinese export and domestic consumption of magnesium and proportions of magnesium casting are presented in Figure S1. Consumption factors (kg SF_6/t Mg) in the magnesium production sector are provided in Figure S2. Estimated annual consumption in each sector and annual total production are shown in Figure S3. Consumption and emission patterns of SF_6 in China are presented in Figure S4. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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