DEPARTMENT OF ENGINEERING MANAGEMENT

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Replacing SF_6 in electrical gas-insulated switchgear: technological alternatives and potential life cycle greenhouse gas savings in an EU-28 perspective

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Abstract

To date, global atmospheric concentrations of F-gases with alleged high global warming potential are still on the rise. The most potent among the greenhouse gases identified as such by IPCC is sulfur hexafluoride (SF_6), which has been used in various applications because of its chemical stability and inertness, next to its high dielectric strength. In the European Union, its use has to date been banned from several applications, for which technological alternatives exist. An important exception is gas-insulated electrical switchgear (GIS), both for medium voltage and high voltage applications, to which cost-effective and environmentally sound alternatives were unavailable when the F-gas regulation was last revised in 2014. Yet, to date, interest in technological alternatives has grown, and we argue that a next step in the phasing out of SF_6 may spur the accelerated development of alternatives with lower carbon footprint. The installed SF_6 amount in switchgear in the EU-28 is unclear, estimated between 10 800 and 24 700 t (with a mode at 12 700 t) in 2017, resulting in 68 to 140 t of annual emissions from operational leakage only, corresponding to 1.6 to 3.3 Mt of CO_2-eq. The higher emissions value seems more likely, as its underlying model (EDGAR) was earlier corroborated by measurements. In our study, we estimate the potential greenhouse gas savings over the lifecycle of one exemplary 145 kV gas-insulated switchgear bay upon replacing SF_6 by decafluoro-2-methylbutan-3-one (C5-FK) and heptafluoro-2-methylpropanenitrile (C4-FN) mixtures. These single-bay results were projected over estimated future installed high-voltage GIS in the EU-28 consequentially. A phase-out scenario starting from 2020 onwards could reduce the carbon footprint by 4 to 31 Mt, with median at 14 Mt, of CO_2-eq., over a period of 50 years. A phase-out starting in 2025, allowing more time for further technology development, results in 12.5 Mt of CO_2-eq. (median) savings by 2070. Extrapolation to medium voltage is uncertain, given the decentralization of electricity distribution, yet one can assume savings of similar magnitude.

1. Introduction

Sulfur hexafluoride (SF_6) is widely used in electrical switchgear equipment at medium and high voltage, due to its excellent insulation and arc quenching properties, such as its high stability, dielectric strength and heat dissipation and its low boiling point [1,2]. Therefore, gas insulated switchgear (GIS) using SF_6 can be made relatively small in size and can be used both for indoor and outdoor grid stations.

SF_6 is however a gas being cited to have a very high global warming potential (GWP) of approximately 23 500 kg of CO_2 equivalents per kg [3]. Nevertheless, next to electrical switchgear, SF_6 has formerly been used in a wide variety of other products, such as soundproof windows, and some of these applications are still marketed to date in some countries outside of the European Union. Within the latter, in 2006 a first EU F-gas Regulation was adopted (*Regulation (EC) No 842/2006* [4]), aiming at lowering potential climate change effects due to emissions of fluorinated gases. In its original version, the use of fluorinated greenhouse gases was prohibited in various applications, such as domestic windows, footwear, tires, and others. This Regulation was renewed in 2014, introducing further restrictions on the use of fluorinated greenhouse gases *(Regulation (EU) No 517/2014* [5]). The renewed regulation states however that "*Equipment containing fluorinated greenhouse gases should be allowed to be placed on the market if the overall greenhouse gas emissions of that equipment, taking into account realistic leakage and recovery rates, are lower, during its lifecycle, than those that would result from equivalent equipment without fluorinated greenhouse gases*". In our view however, a complete life cycle assessment (LCA) including other impact categories should form the basis of alternatives, rather than greenhouse gases only. Additionally, it is specified that technological alternatives should be available, and not induce disproportionate costs. For these reasons, use of SF_6 in electrical equipment was still allowed, given the lack of realistically viable alternative at the time of the last legislative revision. Nonetheless, the use of SF_6 in GIS should be strictly monitored.

According to National Inventory Submissions 2019 from the United Nations Framework Directive [6] the emissions of SF_6 in the EU-28 in 2017 only was reported by the member states to be 286 t, of which 68 t, or 2 Mt of CO_2-eq., is directly attributed to operational emissions from electrical equipment due to leakage. We stress though that these are indirectly calculated reports, using various methods. 24 of the member states reported their estimated SF_6 stock in operational electrical equipment, as a base for calculating emissions, accounting for a total of about 10 400 t of SF_6 installed. Although monitoring and control measurements are required, few member states seem to have advanced nationwide accounting systems. Hence, this installed base constitutes a risk of over 240 Mt of CO_2-eq., if improperly released.

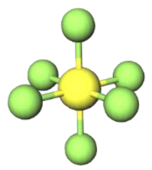
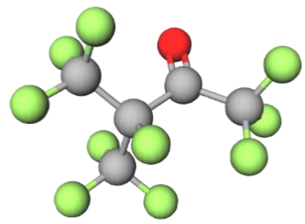
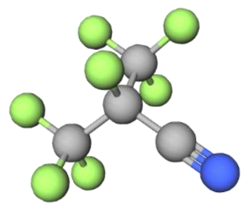
Since the previous revision of the F-gas Regulation (Regulation (EU) No 517/2014) though, various new technological alternatives were developed up to pilot scale and commercial demonstrations. Therefore, the continuous reconsiderations stated in the EU policy imply the need for thorough evaluation of the carbon footprint of technologies alternatives to SF_6 based GIS.

Currently deployed commercial alternatives to SF_6 GIS are both in the medium voltage and in the high voltage range up to 145 kV. For high voltage switchgear, the present-day main alternative to SF_6 is air insulated equipment, yet it was demonstrated that its environmental performance is worse, given the higher areal footprint, preventing it from being installed in dense urban areas and consequently resulting in a suboptimal energy grid [7]. Said equipment's size difference is in part due to the lower dielectric strength of the insulating medium provided in these systems.

Additionally, patent, professional and journal reports show accelerated efforts in the search for innovative and green switchgears. At medium voltage range fluid, solid as well as dry air insulated switchgears using vacuum circuit breakers are being developed [8-13]. Dry air insulated switchgears are being developed for the high voltage range as well [14]. Two types of GIS technology have been developed for deployment both in the medium and in the high voltage range [8, 15-19]. These are based on mixtures of CO_2 and O_2 with two compounds developed by 3M, namely decafluoro-2-methylbutan-3-one (C5-FK) and heptafluoro-2-methylpropanenitrile (C4-FN) (synthesis thereof described in [20,21]). The structures of C4-FN and C5-FK are given in Table 1. These mixtures are demonstrated to have both adequate insulation and arc quenching properties [1,22]. Besides these switchgear mixtures, there is currently research ongoing on the application of 1,3,3,3-Tetrafluoropropene (HFO-1234ze(E)) for both medium and high voltage switchgears [23,24]. A CF_3I mixture was researched as a possible alternative to SF_6 as well, yet it is unlikely to be implemented due its corrosiveness and suspected carcinogenicity [2,25].

Several individual manufacturers, such as General Electric [26], ABB [27] and Siemens [28], have recently announced the expansion of their respective SF_6 free technologies, also to higher voltage ranges, up to 420 kV.

Table 1: Chemical structures of the three investigated technological alternatives for gas insulated switchgear and their typical mixture concentrations.

Sulfur hexafluoride (SF_6)	decafluoro-2-methylbutan-3-one C5-FK	heptafluoro-2-methylpropanenitrile C4-FN
		
Typical concentrations used in gas insulated switchgear		
100%	5.6 mole% C5-FK, 5.6 mole% O_2 & 88.8 mole% CO_2	6 mole% C4-FN & 94 mole% CO_2

The goal of this paper is to project the lifecycle greenhouse gas savings associated with changing GIS systems from SF_6 to technological alternatives. The two major candidates for replacement of SF_6, next to dry air and air insulated switchgear, which were evaluated in another study [7,13,29], are mixtures of C5-FK and C4-FN with CO_2 and O_2, as these are closest to commercialization [26,27,30,31]. Typical mixtures of these two compounds with O_2 and CO_2 (Table 1) are benchmarked in this paper against SF_6 in exemplary high-voltage applications, based on public records only, reflecting the current state-of-knowledge. Next to the comparative ex-ante evaluation of greenhouse gas intensity for a single 145 kV GIS bay, we estimate in this paper the resulting effects of potential phase-out scenarios in terms of greenhouse gas savings for high-voltage applications on an EU-28 scale. Although calculations were done for high voltage switchgear only, given the superior availability of data, the results also give insight in the extrapolation towards medium voltage applications. Potential differences in equipment size are anticipated, as shown in recent reports [32], yet not a subject to the present study due to the lack of available data for a detailed assessment.

2. Methods

2.1 Single high-voltage bay comparative lifecycle carbon footprint assessment

In a first stage of this assessment, a single bay of SF_6 switchgear is compared to a technologically similar bay using C5-FK or C4-FN mixtures, respectively. The functional unit is operation of a single, new (i.e. state-of-the-art technology) 145 kV GIS bay, for 40 years. The amount of pure SF_6 in traditional GIS is obtained from the publicly accessible g^3 calculator of General Electric co. [33], being 63 kg per GIS bay at an operating pressure 7 bar [34].

The amount of C4-FN and CO_2 gas mixture for a 145 kV bay is 30 kg [33] and its density is around half of the density of SF_6 [35]. We assume a mixture of 6 % mole/mole (equivalent to 22 % mass/mass) of C4-FN in CO_2 at 8 bar [34]. The pressure is increased to account for the lower dielectric strength of this specific mixture with respect to SF_6 [34]. This increase in pressure can be adjusted, which would require a higher percentage of C4-FN in the mixture. We accounted for such changes by a sensitivity assessment, investigating the effect of a changing molar ratio on the final results. Given the current state of technology, also the overall mass ratio of alternative gases to SF_6 in GIS will be subject to sensitivity analysis.

A mixture of C5-FK/O_2/CO_2 on 5.6%/5.6%/88.8% molar basis (27%/3%/70% on mass basis) at 7 bar, has a dielectric strength of 77% of SF_6 [36] at 6 bar, so the volume of mixture required for a 145 kV switchgear is about 30% higher than for a SF_6 switchgear. With this, the density of C5-FK at normal condition (10.7 kg/m^3, [37]) and assuming that all gases behave like ideal gases we estimate that for equivalent functionality, a switchgear with 33 kg of C5-FK/O_2/CO_2 mixture at 8 bar will replace a 63 kg SF_6 switchgear at 7 bar.

In both cases, we do not include changes in the construction materials demand for the manufacturing of the GIS equipment itself in the assessment (in other words, we assume the design of the equipment is similar in dimensions and thus materials consumed). To date, data on the exact sizing of the equipment and impact on required building space is scarce, and the few data available are insufficient for a detailed assessment [32].

To build the emissions inventory, we distinguish four different phases; (1) gas mixture manufacturing, (2) filling of the switchgear bay, (3) operation while installed, and (4) decommissioning and recycling of the gas. Publicly accessible knowledge on the manufacturing of all gases is scarce; for SF_6 most studies cite Eco-invent data [38], reporting a manufacturing impact of 122 kg CO_2-eq. kg^{-1}. However, for this value primary sources date back to 1998, and therefore do not likely reflect state-of-the-art technology. For CO_2 and O_2 respectively, reported impacts for the manufacturing stage are 0.7 kg CO_2-eq. kg^{-1} and 0.6 kg CO_2-eq. kg^{-1} [38]. However, to our knowledge, no life cycle assessment of manufacturing and supply of C5-FK or C4-FN were published in literature thus far, as is the case for most fluorochemicals. As both gases are at pilot scale production thus far, and no industrial analogue manufacturing impact is found, combined with the high uncertainty on SF_6 manufacturing impact, this stage was omitted from the study. Intrinsically, in doing this the assumed impact of manufacturing the gases or gas mixtures is equal. Assuming the carbon footprint of SF_6 of 122 kg CO_2-eq. kg^{-1} [38], and the low concentrations of C4-FN and C5-FK in their respective mixtures, this assumption is rather conservative. The low impact of manufacturing CO_2 and O_2 imply that the assumption used (omitted manufacturing stage), retains its conservative validity up to a fivefold as high impact for the fluorochemicals as alternatives for SF_6.

Emissions of the respective gases of gas mixtures during the initial filling and refiling of the GIS equipment with gas (phase 2) were modeled using a modified PERT Probability Density Function (PDF) with a γ-factor (describing the weight to the mode) of 1. The minimum value was considered to be 0.1%, based on a value of 0.4% found during tests, whereby it was alleged about 15 years ago that a lower value would be possible with state of the art equipment [39]. The mode or most likely value is considered to be 0.5%, which is equivalent to the ABB environmental declaration [16] and the maximum was set at 1.6%, which is the maximum value targeted by some authors for 2020 [40]. The filling emissions are not standard operating procedure though, estimated leakages are always accidental. Therefore they are inherently subject to high uncertainty.

Emissions occurring from the leakage during operation of GIS equipment (phase 3) were modeled using a modified PERT (γ=1) PDF for the emission factors as reported on recent equipment by switchgear manufacturers [16,17,39,40,43,44]. For SF_6 the minimum was set at 0.05% (as most manufacturers will aim at a maximum of 0.1%), the mode was set at 0.1%, corresponding to the lower threshold for which SF_6 emissions should be actively monitored according to the revised F-gas regulation [5]. The maximum of the PDF for the leakage emission factor is set at the industrial standard of 0.5% [45]. For the C4-FN/CO_2 and C5-FK/O_2/CO_2 switchgears, that operate under higher pressure, these values were doubled, as a conservative estimate.

Given the regulatory developments of the last decade, research and development initiatives were undertaken for advanced recovery and recycling of SF_6 from GIS [46,47]. We modelled the emission factor for phase 4 with a modified PERT (mode weight equal to 1) distribution. Its mode is at 2%, as stated by Glaubitz & Plöger [40] and as an often reported value in UNFCCC reports for EU-28 countries [6]. The minimum value was assumed from the ABB environmental declaration [16] and the maximum was set at 5%, given that this was the maximum value reported by a country in the UNFCC reports [6]. Nevertheless, we argue that this value still seems rather low, given the vacuum that must be applied to the devices for such deep gas recovery. There is no apparent reason why the recovery and recycling of C5-FK or C4-FN mixtures would be any different to that of SF_6, hence the same PDF for the phase 4 emission factor is assumed.

The carbon footprint was assessed using a combination of deterministic data and probability density functions, as outlined above, by multiplying the direct emissions of the insulation gases or gas mixtures with their assumed global warming potential based on recent reports. The global warming potential of SF_6 as reported by IPCC changed across their latest reports, with the latest value 23 500 kg CO_2-eq. kg^{-1} [3]. The global warming potential of C4-FN is less scrutinized, yet established at 2100 kg CO_2-eq. kg^{-1} by Owens et al. [48]. The global warming potential of C5-FK is shown to be lower than 1 [49,50].

2.2 Estimation of EU-28-wide installed amount of SF_6 gas in gas insulated switchgear equipment

Emissions of SF_6 are estimated from UNFCCC [6], which is an international environmental treaty to report on GHG emissions via a bottom up approach based on IPCC guidelines. In analogy to our single bay assessment, the UNFCCC method distinguishes production, use and decommissioning. Data on the amount of SF_6 in produced, operating and decommissioned switchgears is collected as a first step of the bottom up calculations [51]. Consequently, although not strictly required, many countries do explicitly or at least implicitly mention their estimated amounts of SF_6 in electrical equipment [52]. UNFCCC reports emission data as far back as 1990 and until two years prior to the last publication (hence the 2019 report has data on 2017 emissions). The total reported stock for the EU-28, excluding four countries, in 2017 is 10 428.5 t SF_6, yet extrapolation to the entire EU-28 using the installed net electricity generating capacity [53] leads to an estimate of 10 800 t for 2017.

Nevertheless, comparison of UNFCCC reported data, which are predominantly a result of indirect accounting methods, with the results of the more generic modeling method, the *Emissions Database for Global Atmospheric Research* (EDGAR) shows a large discrepancy. EDGAR modeled from 2000 until 2010 the SF_6 atmospheric emissions (up to version v4.2 FT2010;[54]) based on international annual technological statistics combined with geographical information systems modeling, in a more generic and transversal way than UNFCCC [55]. Similar to earlier accounts [55,56], benchmarking of estimated global and regional emissions to top-down inverse modeling of regional emissions based on atmospheric measurements of the AGAGE project [57-61], as shown in Figure A.3 in the Appendix, demonstrates that the EDGAR calculations are much more in line with empirical data. Multiple reports therefore indicate that UNFCCC emissions data are likely underreported [62-65].

Public data are to date inconclusive though whether the emission factors used in UNFCCC reporting methods are underestimated, or the underlying assumptions about the installed stock of SF_6. We therefore approach the installed stock of SF_6 in electrical equipment as a probability density function (PDF) with minimum and maximum defined by two scenarios; either the installed stock of UNFCCC is correct at 10 800 t (assuming the emission factors are strongly underestimated), or the average emission factor of UNFCCC reportings (0.57 %, more details can be found in the Appendix section A1) is correct, leading to an installed stock of 24 700 t, as EDGAR emission estimates were about twice as high as UNFCCC estimates for the last reported years (2007-2010). In our view, the most likely stock value (mode of the PDF) is 12 700 t (equivalent to almost 300 million t of CO_2-eq., if ever released), which is an extrapolation of the German stock figure on the basis of net electricity generating capacity [66] (see section A3 of the Appendix). The German reporting is since 2011 based on detailed sales data of manufacturers, including imports/exports, constituting a reliable mass balance [6], and its extrapolation seems to us the most likely value for the EU-28.

The resulting probability density function of installed SF_6 stock in electrical equipment is aggregated; the data contains both medium voltage and high voltage equipment. As we firstly investigate exemplary high voltage switchgear in this study, represented by a 145 kV bay functional unit, an apt estimator for the EU-28 wide HV share is required. To this end, we used transmission and distribution grid operator data [67-80] next to direct UNFCCC reports for the five EU countries with the highest SF_6 stock (accounting for about 80 % of the total EU-28 stock), and determined an average share of high voltage SF_6 stock of 45 % of the total. This estimate is also subject to a skewed probability distribution as a result of uncertainty on the distribution grid data quality (see the discussion in the Appendix, section A4).

2.3 Consequential time-series modeling of greenhouse gas savings in phase-out scenarios

A projection of the EU-28 stock of SF_6 gas in HV switchgear was made by regression of the stock changes with the installed net electricity generating capacity (NEGC) for the period 2000 until 2017. Earlier a linear relation was found between the amount of SF_6 installed and the grid capacity in China [81]. In the present study, the regression [stock SF_6/NEGC] was done using data of Eurostat [53] for the grid capacity, and stock of SF_6 directly taken from UNFCCC [6] reports. The resulting regression was applied to the PDFs of the stock; as only linear transformations were applied to the primary data. The expansion of the grid, and hence the growth of SF_6 stock in GIS under unchanged policy, is modeled by applying the SF_6/NEGC regression function to the projection of the electricity installed capacity of the energy reference scenario of the European Commission of 2016 [82]. The latter seems conservative, as no expansion is expected in this scenario for the next decade.

The projected growth of GIS stock over an analysis period of 50 years (2020 until 2070), whereby we develop scenarios for a phase-out of SF_6 initiating in 2020. A phase-out scenario means that all newly installed switchgears should be based on an SF_6-free alternative technology, whereas existing installations are continued to be used and maintained until end-of-life. The lifetime expectancy of each individual HV GIS bay is assumed to be 40 years. We do not assume a refilling of the bays to account for the gas lost by leaking, which is again conservative toward the lower GWP gases. New GIS installations are installed either when current SF_6 bays are at end-of-life and need replacement, or when the electric grid capacity is expanding. The EU reference scenario projects slight decreases of net electricity generating capacity for some periods [82], however upon an expected decrease of the net electricity generating capacity, no decrease of the switchgear capacity is assumed. This is very conservative in our view, given the further developments in the grid, as well as the potential for technology expansions.

2.4 Uncertainty Analysis

Where possible, throughout the study we applied stochastic methods on data, as outlined in the sections above. After performing a sensitivity analysis in which we studied the effects of varying each variable independently in a +10% and -10%, we could detect the ones that had a greater influence in the final result. In case there was sufficient information or informed criteria, these variables were modeled as probabilistic. In other case, a parametric sensitivity analysis was performed.

The propagation of uncertainties (and corresponding PDFs) are carried out using Monte Carlo calculations, taking 30 000 samples with the Latin Median Hypercube method. This technique spreads the sample points more evenly across all possible values than Monte Carlo sampling, by selecting the median values of 30 000 intervals of equal probability instead of generating a random sample of 10 000 points [83]. Calculations were performed using Analytica software. Table 2 gives a summary of the PDFs for the variables used as input to the analysis. Variables that do not figure in the table are considered as deterministic values in the analysis, as for them a reasonable PDF could not be argued. For some of these variables that have an important impact on the result a parametric sensitivity analysis is performed.

Table 2: Description of probabilistic parameters used

Parameter	**Uncertainty background**	**PDF type**	**Description**
EF filling [16,39,40]	Variety across sources	Modified PERT (γ=1)	**SF_6:** 0.1%, 0.5%, 1.6% **Alt(1):** 0.1%, 0.5%, 1.6%
EF operation (leaks) [5,16,41-44]	Variety across sources	Modified PERT (γ=1)	**SF_6:** 0.05%, 0.1%, 0.5% **Alt(1):** 0.1%, 0.2 %, 1%
EF recovery/recycling [6,16,40]	Variety across sources	Modified PERT (γ=1)	**SF_6:** 1%, 2%, 5% **Alt(1):** 1%, 2%, 5%
EU-28 total SF_6 stock in GIS	UNFCCC vs. EDGAR data	PERT negatively skewed	Min= 10800, mode= 12700, max= 24 700
Share of HV SF_6 stock	MV stock uncertainty	Modified PERT (γ=1)	38.5%, 45%, 87.3%
Intercept regression SF_6/IC(2)	Regression	Normal	μ=-6930 σ = 7 %
Parameter coefficient regression SF_6/IC(2)	Regression	Normal	μ= 0.017 σ= 3.2 %

(1) Alt: alternative technology, including either C4-FN or C5-FK mixtures
(2) IC: grid installed capacity, equal to the maximum of historical NEGC

3. Results

3.1 Single 145 kV GIS bay comparative carbon footprint assessment

In replacing the insulation gas of a single 145 kV GIS bay with a lifespan of 40 years, there seems to be a very high potential of emissions savings during the use phase, i.e. as a result of operational leakage, given the lower GWP of the alternative technology compounds (Figure 1). Additionally, since similar dielectric strengths can be accomplished using mixtures of C4-FN and C5-FK with CO_2 (and O_2) at increased pressures, the total amount of fluorinated gases to be produced is significantly lower than the amount of SF_6 for comparable performance. Figure 1 shows the carbon footprint of the three investigated lifecycle phases (filling, operation, decommissioning) of different GIS systems, with gas composition and amounts, as well as emission factors, as outlined above. The projected savings from using C4-FN or C5-FK technology from the direct gas emissions during filling, use and recovery/recycling are completely due to the lower GWP of the respective gas mixtures. The impact of the three calculated lifecycle phases for alternative technologies is negligible compared to SF_6 GIS. This means that even though no publicly available, peer reviewed manufacturing (cradle-to-gate) LCA results for the production phase of most fluorochemicals are available, and therefore the impact of this phase is highly uncertain and not accounted for, the manufacturing impact of the total gas mixture should be about 170 t of CO_2-eq. higher than that of SF_6 to exceed the overall carbon footprint of a current individual GIS bay. Moreover, if we assume a current manufacturing carbon footprint of the 63 kg of SF_6 in one GIS bay, the resulting impact of 8 t of CO_2-eq. (122 kg CO_2-eq. per kg; ecoinvent) is very low with respect to the overall lifecycle carbon footprint. It is thus very unlikely that the manufacturing impact of the alternative technology gas mixtures, containing less than 25 % m/m of the fluorochemicals, has a manufacturing impact of over 20 times that of SF_6. Therefore, it is safe to conclude that the manufacturing stage has no influence on the general trend that SF_6 free technology has a potential to reduce the carbon footprint of HV GIS bays. This is in agreement with Rabie & Franck [55], who state that the impact of manufacturing of the gas becomes irrelevant in comparisons between fluorochemicals involving SF_6, having such high reported GWP.

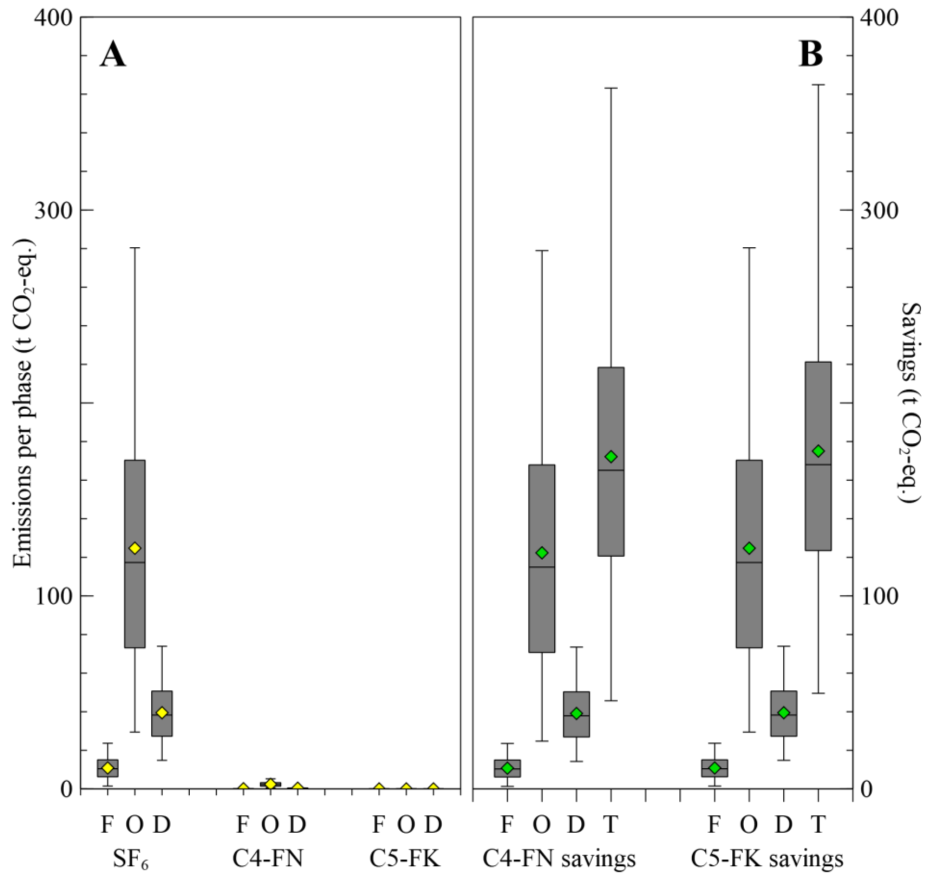


Figure 1: Comparison of the carbon footprint, in metric tons of CO_2-eq., per functional unit of a single 145 kV GIS bay over a lifetime of 40 years of operation, for SF_6-based, C4-FN-based and C5-FK-based technology [A]. Savings for both alternative technologies with respect to SF_6 systems are also shown [B]. Results are disaggregated into filling (F), operation (O) and decommissioning (D), or shown as total savings (T). The boxplots are composed of the median, interquartile range, and minima and maxima, with the diamonds representing the averages.

3.2 Cumulative greenhouse gas savings in the EU-28 (HV) transmission grid in SF_6 phase-out scenarios

The total SF_6 stock in GIS in the EU-28 was projected using the established regression between the installed net generating electricity capacity in the period 2000-2017 on an annual basis, and the UNFCCC reported stock of SF_6 in electrical equipment (Figure 2A). Using this regression, we projected the PDF of the EU-28 SF_6 stock of 2017, toward 2070, using projections of the net electricity generating capacity of the EU [82], as shown in Figure 2B. This projection concerns both the distribution (MV) and transmission (HV) stock of SF_6. The total stock of SF_6 is expected to stagnate between 2020 and 2035, as a result of a projected stagnation of the net electricity generating capacity in this period. Therefore no expansion of the amount of installed GIS bays is expected either. This is rather conservative, as currently grid are becoming more decentralized, electricity consumption is rising and industrial electrification is intensifying. Nonetheless, bays at the end of their 40-years lifespan are replaced by alternative technology in a phase-out scenario. The annual amount of SF_6 replaced in this manner is nevertheless considerable, given the sharp historical SF_6 stock increase in the period 1980 until 2000 (Figure 2B). The uncertainty, predominantly a consequence of the aforementioned limited reliability of UNFCCC [6] reports, is represented by the interquartile range (IQR) and the 95% central range (95CR).

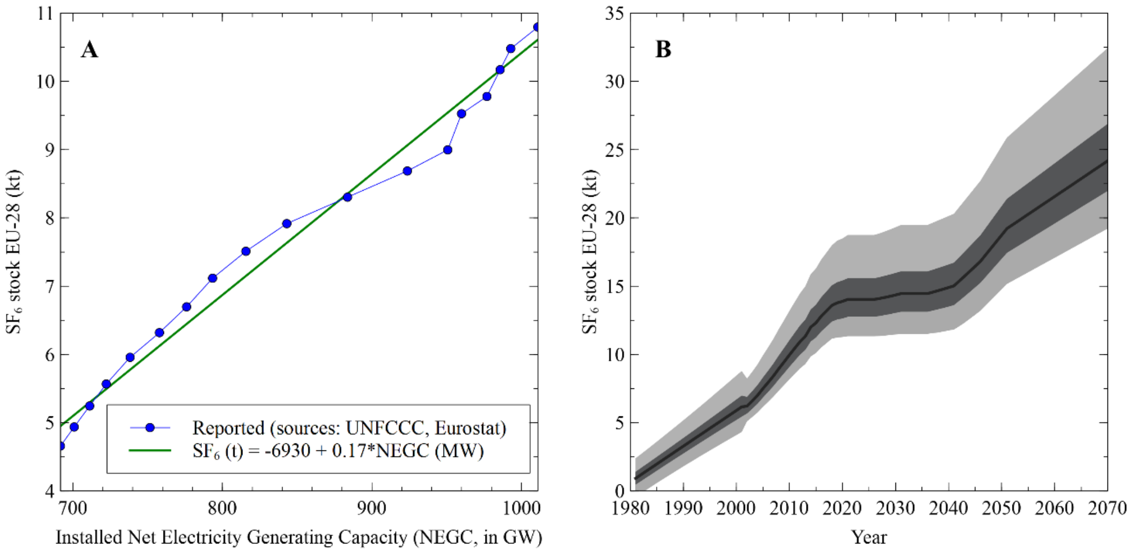


Figure 2: Regression of the increase of SF_6 stock at EU-28 scale resulting from an expansion of the net electricity generating capacity of the grid, based on UNFCCC (2019) and Eurostat (2019) data, with implications for the parameters of the stock probability distribution [A], and projection of this regression on the outlook for the electricity grid until 2070 [B], with the line representing the median, the dark and light shades in B represent the IQR and 95CR, respectively.

The projection of Figure 2B allowed subsequently to estimate the replacement of SF_6 GIS in a phase-out scenario, starting from 2020, for the transmission (HV) grid, constituting about 45 % of the total SF_6 stock. The 145 kV example of the single-bay assessment is taken as representative for the HV grid. Assuming that at end-of-life, thus after 40 years, all SF_6 GIS must be replaced by alternative technology (either C4-FN or C5-FK), and assuming that expansions of the grid, upon an increase of the net electricity generating capacity (Figure 3B), should also be done using SF_6-free technology, the potential consequences of such phase-out scenario become apparent in Figure 3. Herein we show the identified greenhouse gas emissions from either the SF_6 GIS technology scenario (i.e. business-as-usual, continuation of state-of-the-art SF_6 GIS), versus those scenarios in which alternative technologies are introduced, using the single 145 kV bay comparisons of Figure 1. The large year-to-year variations of the emissions are due to the various timings in which SF_6-technology is either introduced (emissions of filling) and/or taken out of the grid (emissions from recovery/recycling), see the Appendix (Figure A.5) for more background. Upon cumulating the differences of the annual emissions, it is clear that the savings may amount to about 14 Mt of CO_2-eq., as median of a PDF between 4 and 31 Mt CO_2-eq. as 95% central range. The potential savings achieved by either of both SF_6-free technologies are nearly overlapping. Postponing the phase-out by five years, starting in 2025, would decrease the cumulated savings in 2070 to a median of 12.5 Mt of CO_2-eq. (Figures A.6 and A.7 in the Appendix). Such scenario is more likely, allowing more time for further technological development and deployment.

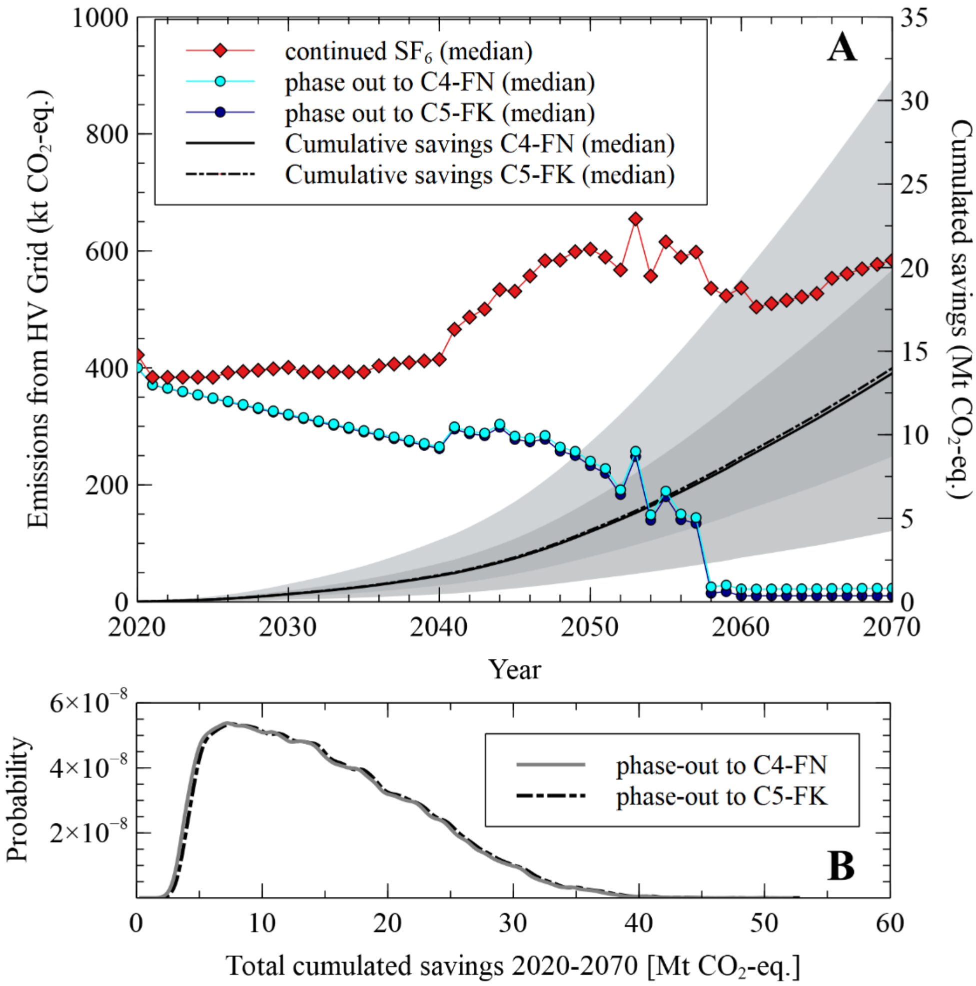


Figure 3: Annual aggregated emissions (not actual emissions, but assuming the grid is state-of-the-art technology) from the EU-28 transmission grid (HV GIS bays), in kt of CO_2-eq. in three different scenarios; business as usual, phase-out starting 2020 toward C4-FN technology and phase-out starting 2020 toward C5-FK technology (left axis of [A]), and cumulated savings of both alternative technologies with respect to continued SF_6 technology in Mt of CO_2-eq. (Right axis of [A]). For clarity, in [A] probability distributions are not given for the annual emissions values, but shown in the cumulative savings as IQR (dark shaded) and 95CR (light grey shaded), only for C4-FN scenario as both phase-out scenario savings nearly overlap, as appearing from their final PDFs [B]. The latter represent the modeled probabilities only for total cumulated carbon footprint.

4. Discussion

As shown in the previous section (e.g. Figure 2B), there is a high uncertainty related to the amount of SF_6 installed, given the past discrepancies between UNFCCC reports and backward modeling from atmospheric concentrations. Additionally, our analysis strongly relies on projections of the electricity grid capacity [82], which is by definition uncertain, as well as on the assumption that the past relation between net electricity generating capacity and installed SF_6 stock can safely be extrapolated. The first of these intrinsic uncertainties is captured in our modeling, whereas the latter two are not, given our limitations to deal with potential market or technological disruptions. Nevertheless, results for the single 145 kV bay, representative for transmission grid GIS, are independent of these uncertainties, and can therefore be considered as robust. The savings per individual SF_6 GIS bay replaced by C4-FN or C5-FN technology range from about 50 to 360 t of CO_2-eq., with median around 170 t of CO_2-eq.

Given the technological uncertainties related to novel technology, in our modeling we doubled the emission factors for operational leakage, adding to the robustness of our findings. The total savings may amount to 14 Mt of CO_2-eq. (median) over a period of 50 years in a phase-out scenario towards either C4-FN or C5-FK as alternative technologies. Although when related to the total impact of electricity at point of consumption the potential savings are rather small, the technology is available for rapid market penetration. We do stress however that other impact categories were not taken into account, and should be further studied.

Recent industrial reports have indicated that the emission factors for state-of-the-art HV GIS technology, relevant for the future projections made, are currently approximating those of MV GIS technology. We did not model the replacement ratio on a molar or mass base though. Yet, although not explicitly modeled in this work, if replacement ratios are not too different from those of HV GIS bays, the similarity of emission factors implies that similar greenhouse gas savings may be expected. More uncertain is though the potential replacement scenario for the distribution grid, yet it can also be assumed that, given its share of about 55% of all currently installed SF_6, the potential cumulated savings on an EU-28 scale are of the same order as those for the transmission grid. Additionally, the current trend toward decentralized electricity generation, causes accelerated expansion of the distribution grid and hence medium voltage switchgear.

5. Conclusions

Although alternatives for SF_6 in gas insulated electrical switchgear, such as those based on fluorochemicals such as decafluoro-2-methylbutan-3-one (C5-FK) and heptafluoro-2-methylpropanenitrile (C4-FN), can be considered as emerging technologies, the significant difference in reported global warming potential of these gases and their mixtures clearly results in a large potential reduction of the overall carbon footprint. An exemplary, conservative analysis on a single 145 kV bay shows savings between 50 and 360 t of CO_2-eq. over its lifespan, when switching to C5-FK or C4-FN instead of state-of-the-art SF_6 technology. Although studied under large uncertainty, given the early technological stage, the results are robust toward either higher emission factors, as well as higher manufacturing impact of the C5-FK and C4-FN technologies. However, the latter should be corroborated by additional research, as should these findings be expanded to other impact categories.

The single bay assessment was projected to the entire transmission grid in the EU-28, using the estimated total amount of SF_6 in electrical equipment, and a growth thereof calculated through a correlation with grid capacity. A potential phase-out scenario for high voltage equipment as from 2020, assuming end-of-life equipment replacements and grid expansions should be done by C5-FK or C4-FN technologies, results in total savings of 4 to 31 Mt, with median at 14 Mt, of CO_2-eq., over a subsequent period of 50 years. A postponed phase-out to 2025, taking into account the current technological readiness, would still result in a median of 12.5 Mt of CO_2-eq. saved over a period until 2070. The broad distribution is caused predominantly by the uncertainty on the installed stock, next to uncertainties on emission factors. Although we did not explicitly model medium voltage equipment, savings of the same order can be assumed for the distribution grid gas insulated switchgear.

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Appendix

Contents

A1. UNFCCC reporting on stock and emissions data

Table A.1. Reported SF_6 stock for electrical equipment for EU-28 countries in 2017 (UNFCCC 2019)

Country	**Austria**	**Belgium**	**Bulgaria**	**Croatia**	**Cyprus**	**Czechia**	**Denmark**
Reported stock (t SF_6)	299.59	100.19	35.41	71.5	/	107.46	99.22
Country	**Estonia**	**Finland**	**France**	**Germany**	**Greece**	**Hungary**	**Ireland**
Reported stock (t SF_6)	21.53	104.18	1124.34	2711.89	/	143.18	/
Country	**Italy**	**Latvia**	**Lithuania**	**Luxembourg**	**Malta**	**Netherlands**	**Poland**
Reported stock (t SF_6)	1530.62	33.6	10.58	19.54	3.82	/	123.97
Country	**Portugal**	**Romania**	**Slovakia**	**Slovenia**	**Spain**	**Sweden**	**UK**
Reported stock (t SF_6)	148.97	118.18	103.57	27.2	1879.16	247.83	1362.99

Reported SF_6 stock (= amount of SF_6 in installed electrical equipment) from countries was taken straight from the UNFCCC CRF (Common Reporting Format) files of the EU-28 countries (Table 2(II).B-Hs2) (UNFCCC 2019). Cyprus, Greece, Ireland and the Netherlands did not report their SF_6 stock. The total reported stock amounts to 10 428.5 t SF_6 for the year 2017.

To estimate the unreported stock, we used a linear correlation between the installed net electricity generating capacity and the SF_6 stock of the different countries. The SF_6 stock from the countries who did not explicitly nor implicitly report it was extrapolated based on their installed net electricity generating capacity. There is a wide difference in the ratio of stock versus installed capacity for countries with a low installed capacity compared to countries with a high installed capacity (see Figure A.1). The correlation was performed with the cluster of countries with a low installed capacity since the countries with the unreported stock all had an installed capacity in that lower range (see Figure A.2). This method provides a roughly estimated value of 378 t SF_6, that corresponds to a 3.6% of the total reported stock. This results in a total stock of 10 800 t SF_6 for the EU-28 countries. The linear regression coefficient is 0.00577 t of SF_6 per MW installed capacity. The trendline has an R^2 of only 0.48 and a standard deviation of 55 t. Even though it is a rough estimate, Figure A.1 does show that a low installed capacity is a good indicator of a country having a low SF_6 stock. The lack of precision on the estimate will have little effect on the precision of the total stock, due to the small amount of the unreported stock with respect to the total stock amount.

The inherent differences between the countries in terms of SF_6 intensity per capacity (leading to the poor correlation) may be due to different electrical grid structures (e.g. centralized vs. decentralized, geography, population density) and/or due to the preference to varying technological switchgear alternatives. Additionally, the accounting method for SF_6 for at least some countries might be flawed. As an example, medium voltage switchgear is not only used by distribution grid operators but also widely installed at private (medium and small) enterprises, making it difficult to account for.

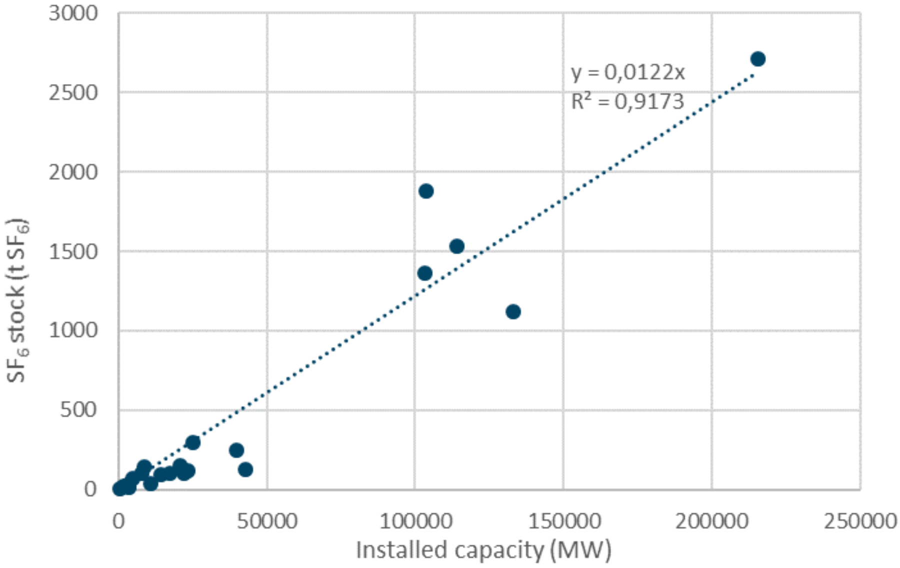

Figure A.1. SF_6 stock of EU28 countries, as reported to UNFCCC, as a function of their installed capacity for 2017 (EU Commission, DG Energy, Unit A4, 2019; UNFCCC 2019)

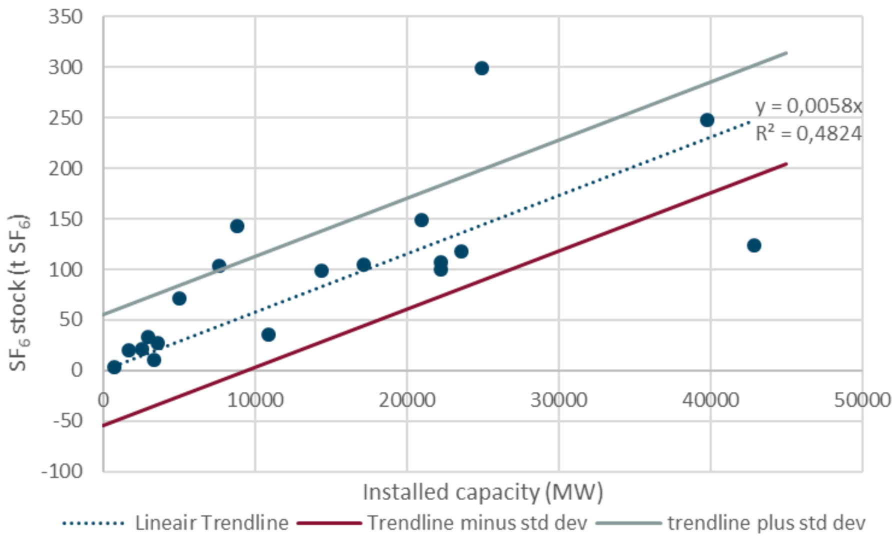

Figure A.2. SF_6 stock of EU28 countries with a low SF_6 stock in function of their installed capacity for 2017 (EU Commission, DG Energy, Unit A4, 2019; UNFCCC 2019)

Table A.2. Countries implied (inversely calculated) overall emission factor for SF_6 in electrical equipment during use (UNFCCC 2019)

Country	Austria	Belgium	Bulgaria	Croatia	Cyprus	Czechia	Denmark
Implied emission factor	0.53	0.38	1.99	0.39	NE	2.63	0.49
Country	**Estonia**	**Finland**	**France**	**Germany**	**Greece**	**Hungary**	**Ireland**
Implied emission factor	0.49	0.5	0.73	0.23	NA	2.6	NA
Country	**Italy**	**Latvia**	**Lithuania**	**Luxembourg**	**Malta**	**Netherlands**	**Poland**
Implied emission factor	0.8	1.31	0.19	0.31	1.03	IE	2
Country	**Portugal**	**Romania**	**Slovakia**	**Slovenia**	**Spain**	**Sweden**	**UK**
Implied emission factor	0.23	1.84	0.29	2.54	0.48	0.5	0.9

Only few countries report the emission factors used for each type of switchgear. For those without explicit data disaggregation, an implied overall emission factor per country is calculated (equals emission during use divided by stock). The used emission factors can be either estimated by the country, and are therefore country specific emission factors. In cases where a country can't estimate their emission factor, IPCC standards asks to use their given default values (IPCC 2006). These default values are quite high compared to those estimated by countries and are in no way a true representation of what the actual emission factor would be for that country. When calculating the weighted average implied emission factor for electrical equipment during use for the EU28, countries using default values where therefore not taken into account. From the 28 countries Czechia, Hungary, Poland and Latvia reporting using default emission values (= tier 1 method (Madrigal & Spalding-Fecher, 2010; Plöger et al., 2006)). the weighted average (weighing factor is SF_6 stock) implied emission factor for the EU-28 is 0.57%.

A2. Insights from the Emissions Database for Global Atmospheric Research (EDGAR)

A comparison of the modeled emissions of EDGAR v4.2 as well as the reported UNFCCC emissions with top-down inverse modeling of regional emissions based on atmospheric measurements of the AGAGE project (O'doherty et al. 2018; MIT 2019; Prinn et al. 2000; Prinn et al. 2018a-b), as shown in Figure A3-A, demonstrates that the EDGAR calculations are much more in line with empirical data. EDGAR (2013) reported SF_6 emission values from electrical equipment during use for several EU countries until 2010. These values where summed and compared with the reported EU-28 value from UNFCCC (2019). From 2006 until the last reported data, 2010, the EDGAR reported SF_6 emissions about 1.85 times higher to those from the UNFCCC (see Figure A3). If we assume that EDGAR estimates are correct and UNFCCC estimates remain to this day about 1.85 times those of EDGAR, then the SF_6 emission from electrical equipment during use in 2017 would be 125 t SF_6 instead of the reported 68 t of SF_6. EDGAR summed values do not account for the entirety of EU-28 countries; it did not report any SF_6 emission from electrical equipment during use for Bulgaria, Croatia, Cyprus, Latvia, Lithuania, Luxembourg, Malta, Slovakia, Romania, Slovenia, Estonia and Czech Republic. These countries contribute together 11.3 % to the UNFCCC reported SF_6 emissions from electrical equipment during use. This means that the difference would not be 1.85, but should be adjusted to a factor of 2.09, resulting in an emission of 140 t of SF_6 emitted from in-use electrical equipment. Given the large uncertainty we rounded this factor to 2. The SF_6 stock is inversely calculated by using the estimated weighted average emission factor (0.57%, from Table A.1 and Table A.2) for the EU-28. This results in an estimated stock of 24 700 t of SF_6, which is twice that of the UNFCCC estimate.

Nonetheless, various reports state that the estimated emissions from the bottom up approach by UNFCCC might be underestimated (Leip et al. 2018; Levin et al. 2010; Weiss et al. 2018; Weiss & Prinn, 2011). Next to UNFCCC reporting, an EU Joint Research Center initiative, Emissions Database for Global

Atmospheric Research (EDGAR) modeled from 2000 until 2010 the SF_6 atmospheric emissions (up to version v4.2 FT2010; EDGAR 2013) based on international annual technological statistics combined with geographical information systems modeling. The method seems more generic and transversal than the variety of methods used for UNFCCC reporting, although detailed methods are not published (Rabie & Franck 2018). Also Rabie & Franck (2018) demonstrate similarly that UNFCCC reported emissions are likely underestimated. For the analyzed time frame 2000-2010, emissions calculated by EDGAR and corroborated by top-down atmospheric data (Rigby et al. 2010), are higher than those reported by the UNFCCC for the EU. EDGAR v4.2 reports the SF_6 emission from electrical equipment during use for many of the EU countries (see Figure A.1B). The SF_6 emission from the unreported countries is calculated by using the relative contributions from the respective countries to the EU-28 SF6 emission from electrical equipment during use from the UNFCCC. For 2007-2010, the SF_6 emission from electrical equipment during use for the EU-28 from EDGAR is on average 2 times higher than those from the UNFCCC. In the further analysis, we extrapolated the average ratio between emissions from EDGAR and UNFCCC of 2 from 2007-2010 to 2017 and further.

With the currently available public information, there seems no scientific basis to judge the correctness of either the installed stock of SF_6 in electrical equipment or the real emission factors for electrical equipment during operation. Assuming that the EDGAR modeled emissions are realistic, applying an average EU-28 emission factor, for electrical equipment during use, as reported by UNFCCC of 0.57 % (calculated from the country specific emission factors, see above), inverse calculations yield an overall stock of SF_6 in electrical equipment of 24 700 t in the EU-28 for 2017. This value is much higher than the UNFCCC estimates, yet reflects the high uncertainty on the latter. Alternatively, considering the aforementioned stock estimate on the basis of UNFCCC reporting of 10 800 t of SF_6, consistency with EDGAR and subsequently AGAGE models would imply an overall emission factor of 1.3 %, which is unrealistically high. It is our appreciation that more likely the UNFCCC data are underestimates of the real amount of SF_6 used in electrical equipment in the EU-28, given the lack of universal accounting method across member states, uncertainties about import/export and large number of operators of medium voltage equipment. For the reasons outlined above, we assume that the actual stock of SF6 throughout Europe can only be represented by a probability distribution between 10 800 t and 24 700 t. The modus of this distribution could be set at 12 700 t (equivalent to almost 300 million t of CO_2-eq., if ever released), which is an extrapolation of the German stock figure on the basis of net electricity generating capacity (EU Commission, DG Energy, Unit A4, 2019, see section A3 below). The German reporting is since 2011 based on detailed sales data of manufacturers, including imports/exports, constituting a reliable mass balance (UNFCCC 2019), and its extrapolation seems to us the most likely value for the EU-28.

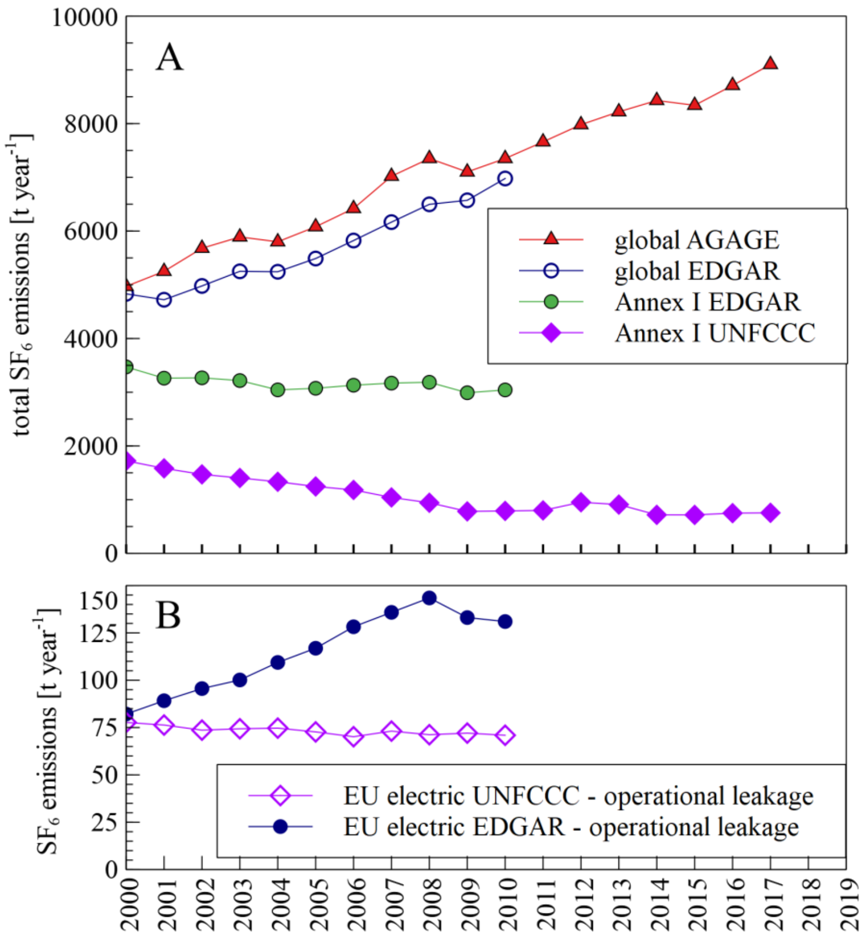

Figure A.3. (A) comparison of reported total global SF6 emissions by EDGAR (2013) to those of the UNFCCC and those from data gained from AGAGE (O'doherty et al. 2018), with global comparison versus Annex I countries only (UNFCCC 2019). Estimated errors are discussed in the original publications, and in Rabie & Franck (2018). (B) EU SF6 emissions from electrical equipment during use (operational leakage) as reported by the UNFCCC compared with EDGAR reported values (contribution SF6 emission from unreported countries not taken into account).

The resulting probability density function of installed SF6 stock in electrical equipment is aggregated; the data contains both medium voltage and high voltage equipment. As the scope of this study restricts to high voltage switchgear only, represented by a 145 kV bay functional unit, an apt estimator for the EU-28 wide HV share is required. For the five EU countries with the highest SF6 stock in electrical equipment according to UNFCCC reports, France, Germany, Italy, Spain and the United Kingdom, data on both MV and HV stock are available for a period between 2009 and 2017. Germany directly reports both MV and HV to UNFCCC (2019), whereas for France, Italy and Spain public data obtained from transmission grid operators were used (RED Electrica 2010, 2015, 2016, 2019; Terna 2010, 2013, 2015, 2018; RTE 2007, 2010, 2012, 2014) and for the United Kingdom data from distribution grid operators were used (Ofgem 2017, 2019). The HV share across these countries, as a weighted average, is quite stable at approximately 45 % (see Table A.3). This value can be extrapolated to the EU-28, since the five aforementioned countries account for about 80 % of the total SF6 stock installed according to UNFCCC (2019) reports, leading to a PDF ranging from 4860 t to 11 100 t of SF6 in HV switchgear, with the modus at 5 700 t, if the aforementioned uncertainty on the total stock is taken into account. Nonetheless, the 45 % estimate itself is also subject to a skewed probability distribution as a result of uncertainty on the distribution grid data quality (see the discussion in the SI, section A4).

A3. Extrapolation of German stock data to EU-28

The reported situation of the SF_6 stock was extrapolated for the entire EU-28, based on the amount of SF_6 stock it has for its installed net electricity generating capacity. The rationale is that the method for the German reporting to UNFCCC is based on direct industrial accounting, including the tracking of imports and exports, seemingly superior to other countries reporting, which is done using rather indirect methods. The installed capacity in Germany is estimated to have been 215.5 GW in 2017 (EU Commission, DG Energy, Unit A4, 2019). The SF_6 stock in 2017 was 2712 t SF_6 (UNFCCC 2019). This gives therefore 12.6 t SF_6 per GW. The installed capacity for the EU was 1011 GW in 2017 (EU Commission, DG Energy, Unit A4, 2019). This results in an estimated 12 700 t SF_6 for the EU-28, which is 17.5% higher than the UNFCCC estimates.

A4. Calculation of the share of HV in SF_6 stock in the EU-28 grid

For the five EU countries with the highest SF_6 stock in electrical equipment according to UNFCCC reports, France, Germany, Italy, Spain and the United Kingdom, data on both MV and HV stock are available for a period between 2009 and 2017. Germany directly reports both MV and HV to UNFCCC (2019), whereas for France, Italy and Spain public data obtained from transmission grid operators were used (RED Electrica 2010, 2015, 2016, 2019; Terna 2010, 2013, 2015, 2018; RTE 2007, 2010, 2012, 2014) and for the United Kingdom data from distribution grid operators were used (Ofgem 2017, 2019). The HV share across these countries, as a weighted average, is quite stable at approximately 45 % (see Table A.3 below). This value can be extrapolated to the EU-28, since the five aforementioned countries account for about 80 % of the total SF_6 stock installed according to UNFCCC (2019) reports (see Table A.1). Nonetheless, the 45 % estimate itself is also subject to a skewed probability distribution as a result of uncertainty on the distribution grid data quality (see below).

The HV share for the EU-28 is estimated by calculating the weighted average HV share of the five aforementioned countries with the largest contribution to the EU-28 SF_6 stock, as data from transmission operators are accessible.

$$Weighted\ average\ HV\ share = \frac{\sum_{i=1}^{n} HV\ share_i * Total\ stock_i}{\sum_{i=1}^{n} Total\ stock_i}$$

Table A.3. Contribution HV share of countries to the weighted average HV share for the EU

	2009	2010	2011	2012	2013	2014	2015	2016	2017
HV share France (%) (RTE 2007, 2010, 2012, 2014)	47.6	47.6	48.8	48.3	47.5	48.1	48.0	48.0	48.0
Total stock France (t SF_6) (UNFCCC 2019)	1018	1036	1049	1062	1072	1084	1097	1109	1124
HV share Germany (%) (UNFCCC 2019)	55.0	53.5	52.4	51.5	50.5	49.7	50.0	48.8	48.0
Total stock Germany (t SF_6) (UNFCCC 2019)	1955	2033	2134	2219	2292	2375	2545	2628	2711
HV share Italy (%) (Terna 2010, 2013, 2015, 2018; RTE 2007, 2010, 2012, 2014))	25.3	26.1	28.1	31.4	33.3	34.5	35.3	36.2	37.0
Total stock Italy (t SF_6) (UNFCCC 2019)	1209	1248	1310	1361	1401	1427	1467	1504	1531
HV share Spain (%) (RED Electrica 2010, 2015, 2016, 2019)	14.2	13.9	15.5	17.1	17.7	18.7	20.9	23.0	23.1
Total stock Spain (t SF_6) (UNFCCC 2019)	1429	1518	1583	1639	1685	1736	1785	1830	1879
HV share UK (%) (Ofgem 2017, 2019)	78.1	78.1	78.1	78.1	78.3	78.0	78.4	77.7	78.0
Total stock UK (t SF_6) (UNFCCC 2019)	1159	1164	1174	1191	1214	1239	1278	1317	1363
Weighted average HV share (%)	43.9	43.2	43.6	44.1	44.1	44.3	45.2	45.3	45.4

The HV share for France Italy and Spain is calculated by dividing the SF_6 stock reported by said countries TSOs (transmission system operators) with their total SF_6 stock reported to the UNFCCC.

The HV share for the UK is calculated by first gaining the MV share by dividing the SF_6 stock reported by UK's DSOs (distribution system operators) with its total SF_6 stock reported to the UNFCCC.

Germany's HV share is obtained by dividing the HV SF_6 stock, reported in the NIR (national inventory report), with the sum of the HV and MV SF_6 stock that is reported in this same report.

Assumptions made:

- **France:** SF_6 stock data from TSOs (transmission system operators) were available from 2005 till 2014. After 2009 the HV share seems to be steady. The average value of the HV share, starting from 2009 till 2014 is 48 %, which is the value withheld as an estimate for subsequent years.
- **Germany:** Germany makes a further distinction in the NIR for electrical equipment by not only reporting MV and HV switchgears, but also other electrical equipment. It's unknown how much of this other electrical equipment is used on the high voltage level. Due to the small share of other electrical equipment to the total SF6 stock, the impact of it on the HV share of Germany will be rather small, even if the HV share of the other electrical equipment would be largely different from that of the switchgear and control gear. Therefore, this data was not taken into account. Values were found for all reported years from Table A.3.
- **Italy:** Values were found for all reported years from Table A.3.
- **Spain:** Values were found for all reported years from Table A.3.
- **UK:** data was available from 2010 till 2017. UNFCCC's reported SF_6 stock data did not initially include two of the three transmission grid operators SF_6 stock. These where eventually taken into account from 2013 onwards. This meant however that HV share of the UK was underestimated for the years before 2013 when using our calculation. Instead, the HV share of the UK for the

years 2009 till 2013 has been estimated as the average HV share of 2013 till 2017, since this value remained steady for the last couple of years. For the weighted average, the total stock of each country was necessary. UK's incomplete stock for the years before 2013 meant however that if we were to use those values, the impact of the UK on the HV share would have been underestimated for those years. Instead we estimated the SF_6 stock based on a trendline, of the data from 2013 onwards, using a quadratic equation (see Figure A.4). The resulting values can be found in Table A.3.

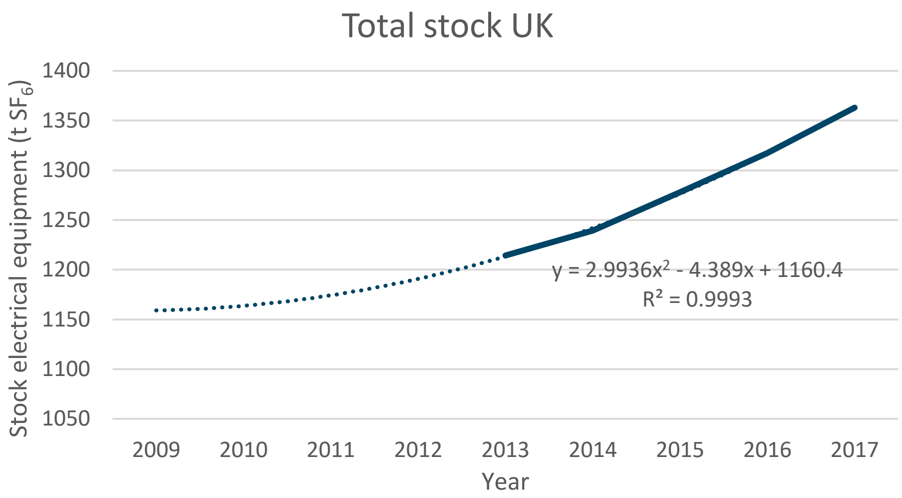

Figure A.4. Estimated SF_6 stock for the UK for the years 2009 until 2012, based on stock from 2013 onwards (UNFCCC 2019).

The weighted average HV share (weighing factor is total stock) is rather constant throughout recent years, only experiencing a slight increase (see Table A.3). However, this does not mean that countries themselves have a steady HV share. E.g., the HV share of Italy and Spain has risen strongly, whereas Germany has experienced a rise in MV share instead (see Table A.3). A weighted average of 45 % of HV share is found for 2017.

Table A.4. Ecofys distribution of switchgears for Germany (Burgers et al., 2018).

Voltage level	Electrical equipment	Estimated percentage of functional units in the area		
		Generation	Public grid	Consumption/ industrial grids and infrastructure
Medium voltage	Switchgear (primary distribution)	10%	45%	45%
	Switchgear (secondary distribution)	5%	65%	30%
	Generator circuit-breakers	100%	-	-
High voltage	Switchgear	1-2%	>90%	5%

An Ecofys report looked at how the switchgears were distributed in terms of operators (Burgers et al., 2018). It was found that for HV switchgears more than 90% is owned by public grid operators (see

Table A.4), making the SF_6 stock reported by TSOs a good estimate for the total HV stock. This is however not the case for MV switchgears, which are largely owned by the industry as well, making DSO reports insufficient to assess the total MV SF_6 stock.

If UK's switchgear distribution is like that of the Germany, this would mean that we underestimated UK's MV stock by the use of DSO reports, resulting in a higher estimated HV share than in reality. To calculate the average distribution for MV switchgears knowledge of the number of operational units (called functional units in the Ecofys report, however this may cause confusion with LCA definitions) for each type and the SF_6 mass for each type of operational unit is required. Ecofys reports that there are around 500 000 primary switchgear functional units, 2 000 000 secondary switchgear functional units and 2000 generator circuit breaker functional units (Burgers et al., 2018). The SF_6 mass for each functional unit can be found in Table A.5. Using the average of the two extremes along with the amount of functional units for each type and the info from Table A.4 we find that about 35 % of MV SF_6 stock comes from the industry and 6.8 % of MV SF_6 stock comes from electricity generation. This would result in an HV share of 67.5 % for the UK in 2017, along with an estimated stock of 1580 t SF_6 and would result in an HV share of 44 % for the EU, which is quite similar to the value calculated without taking Ecofys report into account.

Table A.5. Average SF_6 volumes per installation at each voltage level (Burgers et al., 2018).

Electrical equipment and components	Switchgear and components	SF_6 volume in kg per installation (average)
Medium-voltage electrical equipment	Switchgear for primary distribution (per functional unit)	2.5–3.5kg
	Switchgear for secondary distribution (per functional unit)	0.7–2.5kg[11]
	Generator circuit-breaker installations (per functional unit)	4–6kg
High- and extra-high voltage electrical equipment	High-voltage switchgear (per functional unit)	90–170kg
	Extra-high voltage switchgear (per functional unit)	~ 380kg
High-voltage switchgear components	Circuit-breakers (per phase)	Dead-tank: 25–40kg Live-tank: 7–9kg
	Instrument transformers (per phase)	(72.5kV) 5kg (245kV–550kV): 35-50kg

A5. Gas Stock Projections

A5.1. Grid installed capacity time series

The generation installed capacity for years 2000 to 2017 is obtained from Eurostat (2019) and the projections from 2018 to from the EU Commission Reference Scenario of Carpos et al. (2016).

The grid installed capacity is considered to be equivalent to the generation installed capacity when this one remains constant or increases. It is assumed that switchgears are not removed in case the generation installed capacity decreases from one year to another. Therefore, if the EU commission projects a decline in generation installed capacity the grid installed capacity remains constant.

The EU Commission Reference Scenario 2016 (Carpos et al., 2016) shows values every 5 years, thus for the unreported years the values are linearly interpolated. On the other hand, for the period before 2000 and after 2050 the values found in the period between 2000 and 2050 are linearly extrapolated.

A5.2. SF_6 Stock time series

The projection of the SF_6 stock business as usual scenario, where all future switchgears installed are SF_6 based, is calculated considering that the observed relationship between the grid installed capacity and the SF_6 stock remains constant.

The least square regression uses the grid installed capacity statistics of the EU (Eurostat 2019) as the main driver of the calculated SF_6 stock (UNFCCC 2019) between 2000 and 2017. The results show that that the SF_6 stock (tonnes) is highly correlated with the installed capacity (MW) with an adjusted R^2 of 0.98. Additionally, the Anova test indicates that installed capacity can explain the SF_6 stock (tonnes) with a 99.99% of significance.

Accordingly, the base value for the SF_6 stock from 2018 to 2050 was calculated with Equation 1 , where IC represents the grid installed capacity.

$$StockSF_6^t = 0.017 * IC^t - 6930$$

Equation 1: SF6 stock projection

Since the UNFCCC calculated stock might be underestimated, for the uncertainty analysis, the stock is assumed to have a PERT distribution where the minimum value corresponds to de aforementioned projection (Equation 1). The mode is assumed to be a 17% higher than the min value (based on the stock calculated with the German emission factors) and the maximum value is assumed to be a 128% higher than the minimum value (based on the EDGAR calculations).

The high voltage stock share (HV) of the total grid SF_6 stock is assumed to remain constant for the future. Its most likely value (45%) is calculated as the weighted average of the 5 largest countries of the EU-28. Additionally, for the uncertainty analysis this value is modeled with a triangular distribution with a min of 38.5% and a maximum of 87.3%, according to what is mentioned in the previous section A4.

As a next step, the gas stock growth is calculated for the different phase-out scenarios. We calculate the business as usual SF_6 stock growth as the first difference of the stock time series. Then, the growth of the gas stock in the alternative gases scenarios (C4-FN/CO_2 or C5-KF/O_2/CO_2) is estimated considering that all new switchgears from 2020 onwards are made from these mixtures. This is reflected by a phase out dummy variable that takes the value of 1 when there are new switchgears installed with that specific gas, and 0 when not (Table A.6). The amount of gas required to replace 1 ton of SF_6 is a proportion of the amount of gas required for a C4-FN switchgear (Table A.7) with respect to an SF_6 switchgear.

Table A.6. Phase out variable values for each switchgear type scenario s

Time/scenario	t ≥ 2020	t < 2020
Continued SF_6	0	1
Phase-out to C4-FN	1	0
Phase-out to C5-FK	1	0

Table A.7. Replacement factor for different gases and switchgear types

Scenario/Gas	SF_6	C4-FN	C5-FK	CO_2	O_2
Continued SF_6	1.00	0	0	0	0
Phase-out to C4-FN	0	0.10	0	0.37	0
Phase-out to C5-FK	0	0	0.13	0.37	0.02

To calculate the stock growth of gas *g* in each scenario *s* we first assume an hypothetical scenario were the installation of switchgear with fluorinated gases is only due to an increased in installed capacity and that decompiled SF_6 switchgears are replaced by switchgears of the same type of gas. Even though this intermediate variable is not representative of the stock growth in a phase-out scenario, it will allow us to calculate the real stock growth without entering a circular relationship between the stock growth and the decompiled gases.
Considering the high voltage share (HV), the SF_6 projected stock, the phase out variable (PhO) and the replacement factors (RF) we can calculate the hypothetical stock growth of gas *g* in each scenario *s* (Equation 2).

$$HSG_{g,s}^{t} = HV * (StockSF_6^{t} - StockSF_6^{t-1}) * RF_{g,s} * PhO_s^{t}$$

Equation 2: Hypothetical stock growth for gas g on year t in scenario s

Under this same hypothetical scenario, were retired switchgears are replaced by the same gas switchgears, we calculate the annually decompiled gas. This corresponds to the total amount of gas that is retired from the switchgears and that will later be recycled, disposed or emitted to the air (decommissioned gas). Since the switchgears that are retired are the ones that were installed LS years ago, this variable depends on the expected lifetime of the switchgear (LS). the. Specifically, the decompiled gas is equivalent to the gas stock growth LS years before. Equation 3 shows how the hypothetical decompiled gas for year t and gas g is calculated. As a base case we assume that the lifespan of the switchgear is 40 year, for all types of switchgears.

$$HD_{g,s}^{t} = \begin{cases} HSG_{g,s}^{t-LS} & if\ t > 1980 + LS \\ \dfrac{StockSF_6^{t}}{LS} & if\ t \leq 1980 + LS\ and\ s = Continued\ SF_6 \\ 0 & if\ t \leq 1980 + LS\ and\ \ s \neq Continued\ SF_6 \end{cases}$$

Equation 3: Decompiled gas for gas g on year t

With these two intermediate variables ($HSG_{g,s}^{t}$ and $HD_{g,s}^{t}$) we calculate the final gas stock growth ($Stock\ Growth_{g,s}^{t}$) considering that in the phase out scenarios the decompiled switchgears are replaced by novel gas switchgears.

Table A.8. Stock growth for gas g in scenario s and year t

Scenario/Gas	**SF_6**	**C4-FN**	**C5-FK**	**CO_2**	**O_2**
Continued SF_6	$HSG_{g,s}^{t}$	**0**			
C4-FN phase-out	$HSG_{g,s}^{t} - HD'^{t}_{g,s} * PhO_s^{t}$	$HSG'^{t}_{g,s} + HD_{SF_6,s}^{t} * RF_{g,s} * PhO_s^{t}$			
C5-FK phase out					

With this it is possible to calculate the total stock or accumulated stock in the different scenarios (Equation 4).

$$Stock_{g,s}^{t} = Stock_s^{1980} + \sum_{i=1981}^{t} Stock\ Growth_{g,s}^{i}$$

Equation 4. Estimated stock for gas g on year t in scenario s

Where $Gas\ Stock_g^{1980} = 0\ \forall\ s \neq SF_6$

A6. Projection of carbon footprint to EU-28 over 50-year timeframe

For the carbon footprint, three sources of emissions are considered: the leakages during the filling and refiling, the operation and the decommissioning of the switchgears. Since the exact emission factors are unknown, they are considered to have a modified PERT distribution with a weighting factor to the mode equivalent to one. Parameters for the emission factors for all phases are shown in Table A.9.

Table A.9. Emission factors for the different phases

Stage	Distribution	Mode	Min	Max
Filling and refiling	Modified Pert (γ=1)	0.5%	0.1%	1.6%
Operation SF_6 switchgear	Modified Pert (γ=1)	0.1%	0.05%	0.5%
Operation C4-PFN/CO_2 switchgear	Modified Pert (γ=1)	0.2%	0.1%	1%
Decommission	Modified Pert (γ=1)	1%	2%	5%

The emissions produced due to the leakage during the operation are calculated with the current gas stock and the respective emission factor (Equation 5).

$$Operation_{g,s}^{t} = EF_{operation,g} * Stock_{g,s}^{t}$$

Equation 5: Emissions during the operation of the switchgear

As explained above, we assume that switchgears that are retired are the ones that were installed LS years ago and the decompiled gas is equivalent to the gas stock growth of that year (Equation 6). As a base case we assume that the lifespan of the switchgear is 40 year, for all types of switchgears.

$$Decompiled_{g,s}^{t} = \begin{cases} \max(Stock\ Growth_{g,s}^{t-LS}, 0) & if\ t > 1980 + LS \\ \dfrac{Stock\ _{g,s}^{t}}{LS} & if\ t \leq 1980 + LS \end{cases}$$

Equation 6: Decompiled gas for gas g on year t

With this the emissions due to the decommission are calculated as:

$$Decommision_{g,s}^{t} = EF_{decommision} * Decompiled_{g,s}^{t}$$

Equation 7: Decommissioning emissions

During the filling and refilling of the switchgears leakages also occur. The emissions that occurred during such process can be calculated as:

$$Filling_{g,s}^{t} = \ EF_{filling} * \ Stock\ Growth_{g,s}^{t-LS}$$

Equation 8: Emissions during the manufacturing and filling of the switchgears

The carbon footprint in each scenario, by multiplying the emissions of the filling and refilling (Equation 8), operation (Equation 5) and decommissioning (Equation 7) by the alleged global warming potential of each gas (Table A.10).

Table A.10. Alleged global warming potential of the different gases.

Gas	Value (kg Co_2eq/kg gas)
SF_6	23500
C4-PFN	2100
CO_2	1

$$Carbon\ Footprint_s^t = \sum_G GWP_g * \left(Operation_g^t + Filling_g^t + Decommision_g^t\right)$$

Equation 9: Carbon footprint for each switchgear scenario

With this is possible to calculate the yearly savings and accumulated saving in each scenario, where all the new switchgears installed are SF_6 free.

$$Acumulated\ savings_s^t = \sum_{i=1980}^{t} Carbon\ Footprint_{SF_6}^t - Carbon\ Footprint_s^t$$

Equation 4: Accumulated carbon emission saving due to the installation of switchgears with alternative gases

Therefore, the total saving for the 50-year period correspond to the accumulated saving on the year 2070. The disaggregated emissions for the three investigated lifecycle stages (filling, operation, decommissioning) are given for the three investigated scenarios – continued SF_6 use as business-as-usual, phase-out towards C4-FN and phase-out towards C5-FK, are shown as a function of time in Figure A.5 below. The emissions were aggregated for clarity in Figure 3 of the main paper.

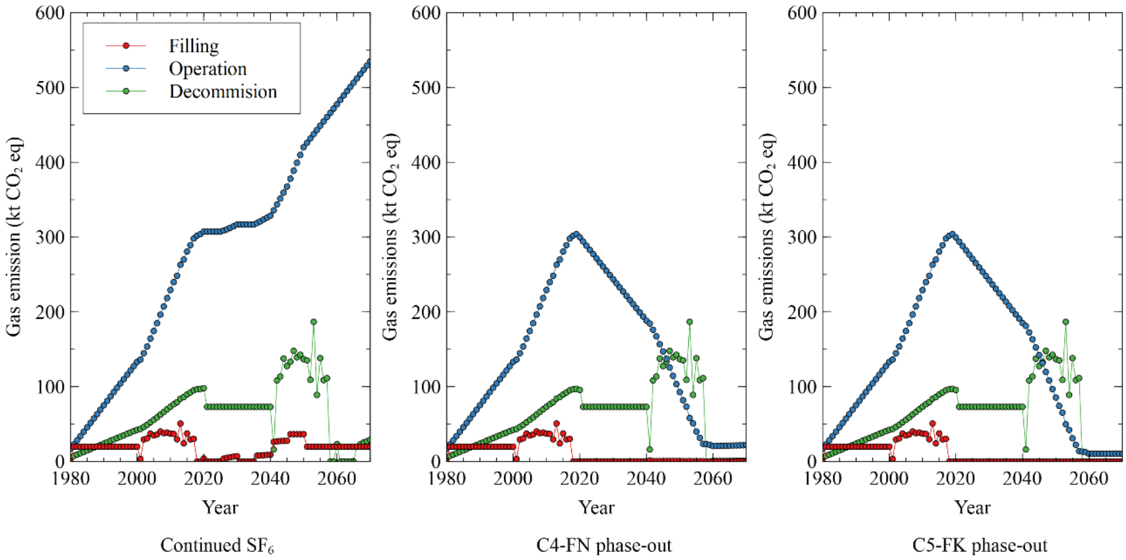

Figure A.5. Disaggregated emissions of three lifecycle phases (filling, operation, decommissioning) as a function of time, for the three scenarios investigated. Left: Continued SF_6 business-as-usual; Center: phase-out of SF_6 towards C4-FN starting in 2020; Right: phase-out of SF_6 towards C5-FK starting in 2020.

A phase-out scenario starting in 2025, rather than 2020, was modeled analogously to the former, with only minor adaptations in the years. This results in the disaggregated emissions of the three lifecycle phases for the three scenarios investigated shown in Figure A.6, and in the combined graph in Figure A.7 that is analogous to Figure 3 of the main paper. The overall cumulated savings over a timeframe of 45 years, to 2070, decreases slightly to a median of 12.5 million tonnes of CO_2-eq., compared to the median of 14 million tonnes of the phase-out in 2020.

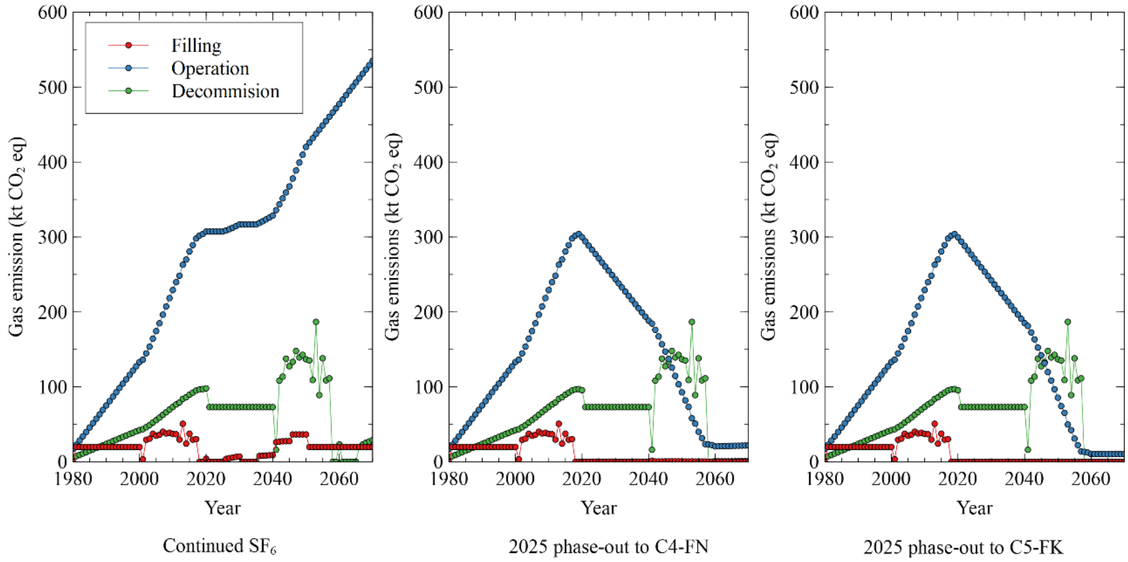

Figure A.6. Disaggregated emissions of three lifecycle phases (filling, operation, decommissioning) as a function of time, for the three scenarios investigated. Left: Continued SF_6 business-as-usual; Center: phase-out of SF_6 towards C4-FN starting in 2025; Right: phase-out of SF_6 towards C5-FK starting in 2025.

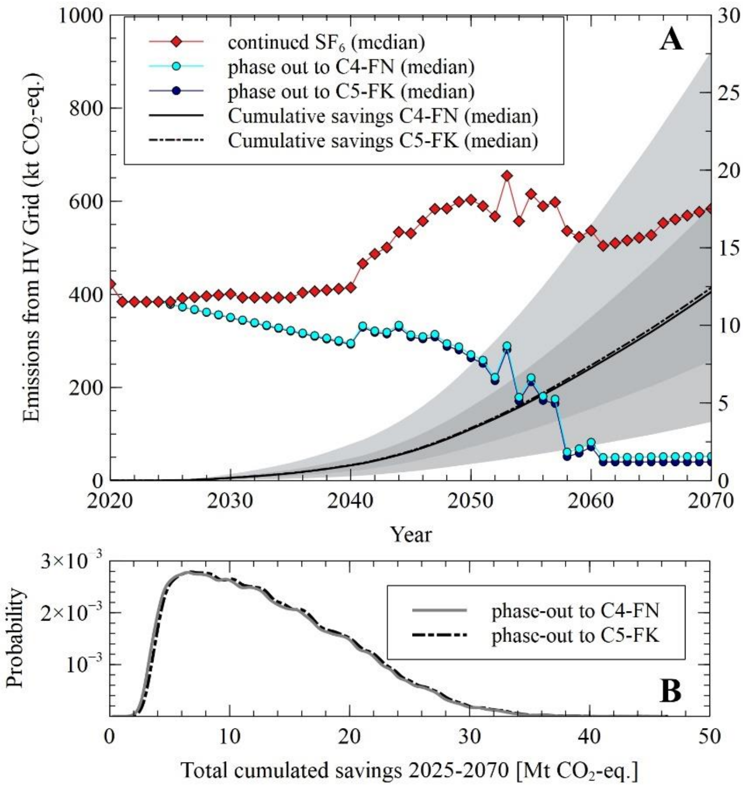

Figure A.7. Annual aggregated emissions from the EU-28 transmission grid (HV GIS bays), in kt of CO_2-eq. in three different scenarios; business as usual, phase-out starting 2025 toward C4-FN technology and phase-out starting 2025 toward C5-FK technology (left axis of [A]), and cumulated savings of both alternative technologies with respect to continued SF_6 technology in million tonnes (Mt) of CO_2-eq. (Right axis of [A]). For clarity, in [A] probability distributions are not given for the annual emissions values, but shown in the cumulative savings as IQR (dark shaded) and 95CR (light grey shaded), only for C4-FN scenario as both phase-out scenario savings nearly overlap, as appearing from their final PDFs [B]. The latter represent the modeled probabilities only for total cumulated carbon footprint.

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