energies

Supplementary Material

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

Pieter Billen [1,*], Ben Maes [2], Macarena Larrain [1,3] and Johan Braet [3]

[1] Faculty of Applied Engineering, Intelligence in Processes, Advanced Catalysts & Solvents (iPRACS), University of Antwerp, 2610 Antwerp, Belgium; ipracs@uantwerpen.be

[2] Faculty of Applied Engineering, Energy and Materials in Infrastructure and Buildings (EMIB), University of Antwerp, 2610 Antwerp, Belgium; ben.maes@uantwerpen.be

[3] Faculty of Business & Economics, Department of Engineering Management, University of Antwerp, 2000 Antwerp, Belgium; johan.braet@uantwerpen.be

* Correspondence: pieter.billen@uantwerpen.be; Tel.: +32 32658801

Received: 17 February 2020; Accepted: 30 March 2020; Published: date

S1. UNFCCC reporting on stock and emissions data

Table S.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 S.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 S.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 S.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.

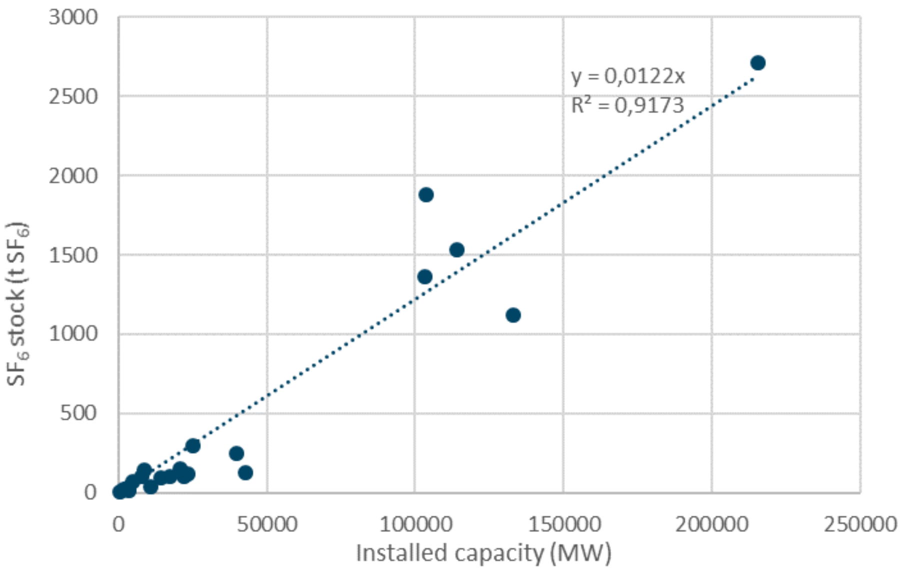


Figure S.1. SF_6 stock of EU28 countries, as reported to UNFCCC, as a function of their installed capacity for 2017 (EU Commission, DG Energy, Unit A4, 2019; UNFCCC 2019).

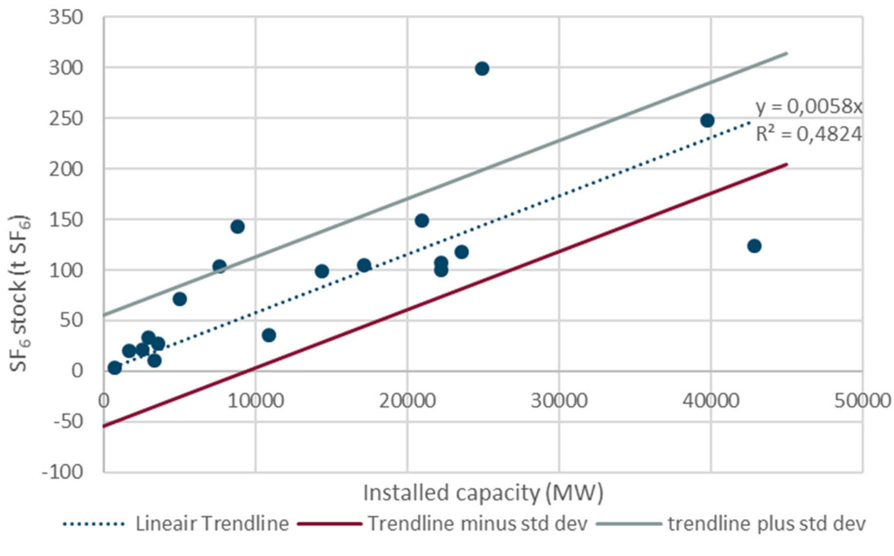


Figure S.2. SF_6 stock of EU28 countries with a low SF_6 stock in function of their installed capacity for 2017 (EU Commission, DG Energy, Unit A4, 2019; UNFCCC 2019).

Table S.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%.

S2. 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 S3-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 S3). 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 S.1 and Table S.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 S.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 S3 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.

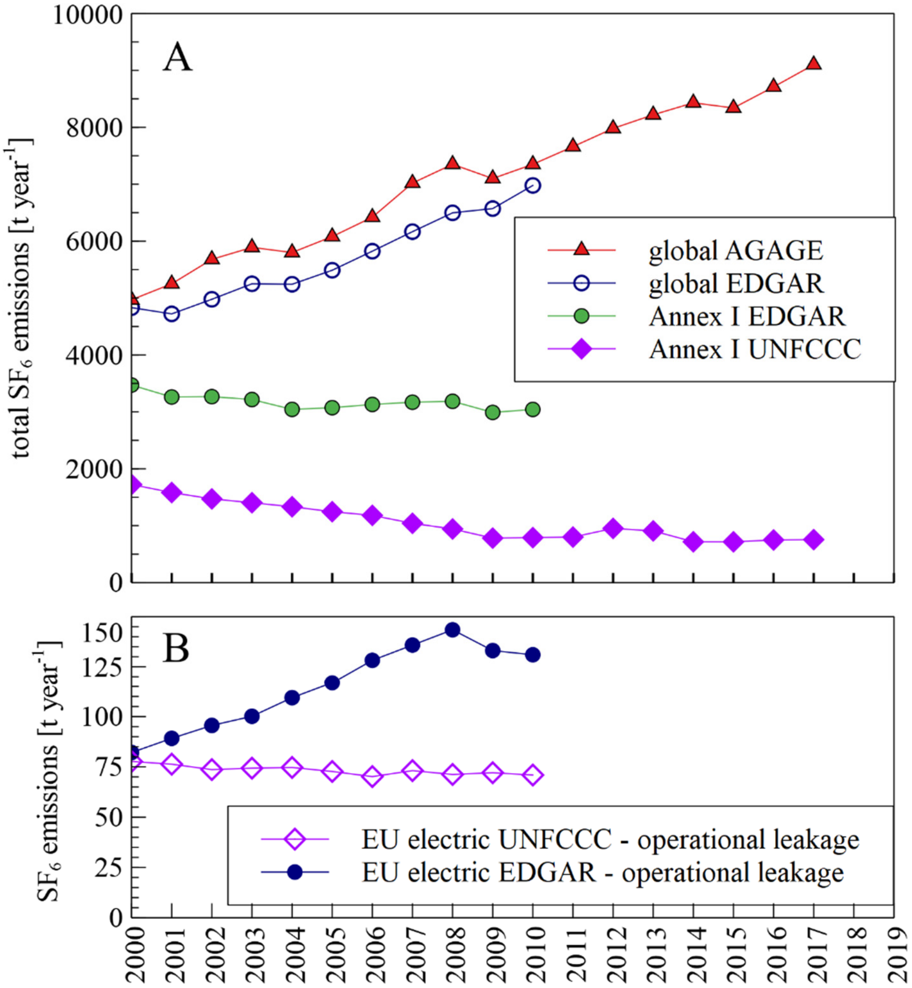


Figure S.3. (A) comparison of reported total global SF6 emissions by EDGAR (2013) to those of the UNFCCC and those from data gained from AGAGE (O'doherty et al. 2018), with global comparison versus Annex I countries only (UNFCCC 2019). Estimated errors are discussed in the original publications, and 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 S.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 S4).

S3. 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.

S4. 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 S.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 S.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 S.3. Contribution HV share of countries to the weighted average HV share for the EU.

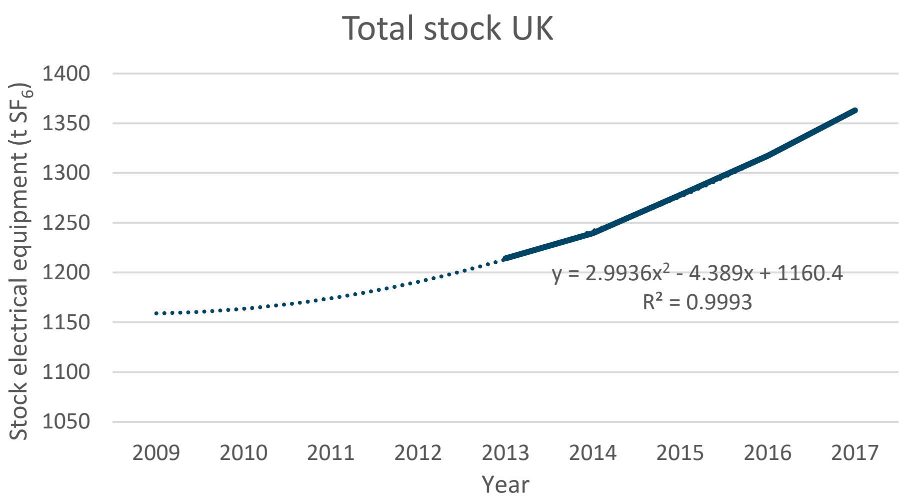
	2009	2010	2011	2012	2013	2014	2015	2016	2017
HV share France (%) (RTE 2007, 2010, 2012, 2014)	47.6	47.6	48.8	48.3	47.5	48.1	48.0	48.0	48.0
Total stock France (t SF_6) (UNFCCC 2019)	1018	1036	1049	1062	1072	1084	1097	1109	1124
HV share Germany (%) (UNFCCC 2019)	55.0	53.5	52.4	51.5	50.5	49.7	50.0	48.8	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 S.3.
- **Italy:** Values were found for all reported years from Table S.3.

- **Spain:** Values were found for all reported years from Table S. 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 S.4). The resulting values can be found in Table S.3.



FigureS. 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 S.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 S.3). A weighted average of 45 % of HV share is found for 2017.

Table S.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 S.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 S.5. Using the average of the two extremes along with the amount of functional units for each type and the info from Table S.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 S.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

S5. Single 145 kV comparison of carbon footprint

Here we show a similar figure to the Figure 2 of the main text, however using a logarithmic scale for comparison between the alternatives, i.e. C5-FK and C4-FN.

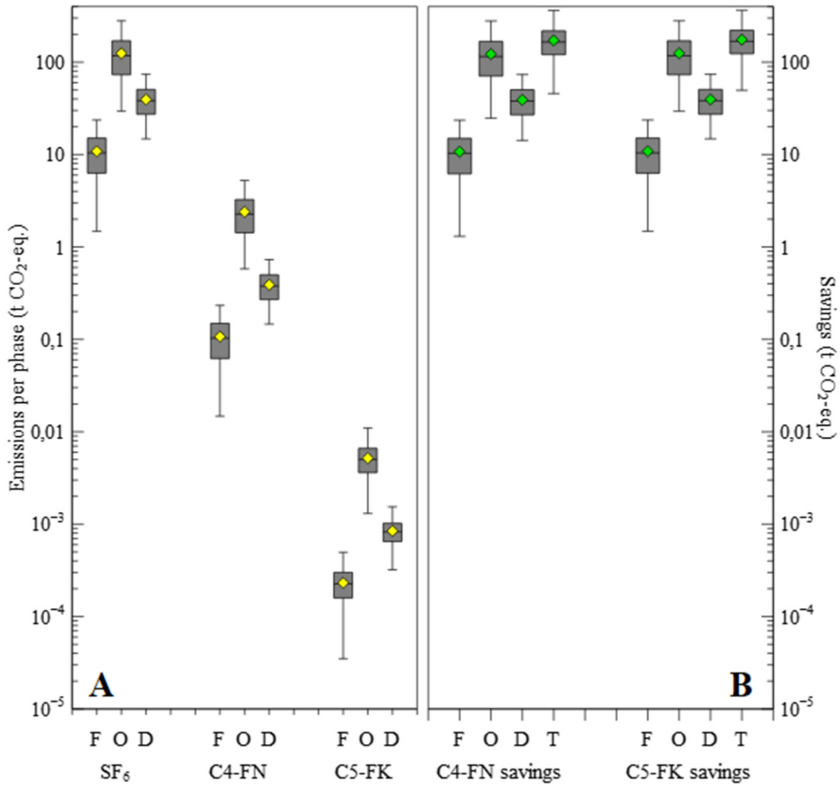


Figure S.5. Comparison (in logarithmic scale) of the carbon footprint, in metric tons of CO_2-eq., per functional unit of a single 145 kV GIS bay over a lifetime of 40 years of operation, for SF_6-based, C4-FN-based and C5-FK-based technology [**A**]. Savings for both alternative technologies with respect 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.

S6. Gas Stock Projections

S6.1. 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.

S6.2. 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 S4.

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 S.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 S.7) with respect to an SF_6 switchgear.

Table S.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 S.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 S.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 $Gas\ Stock_g^{1980} = 0\ \forall\ s \neq SF_6$

S7. 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 S9.

Table S.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 S.10) .

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

Gas	Value (kg Co2eq/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 S.5 below. The emissions were aggregated for clarity in Figure 4 of the main paper.

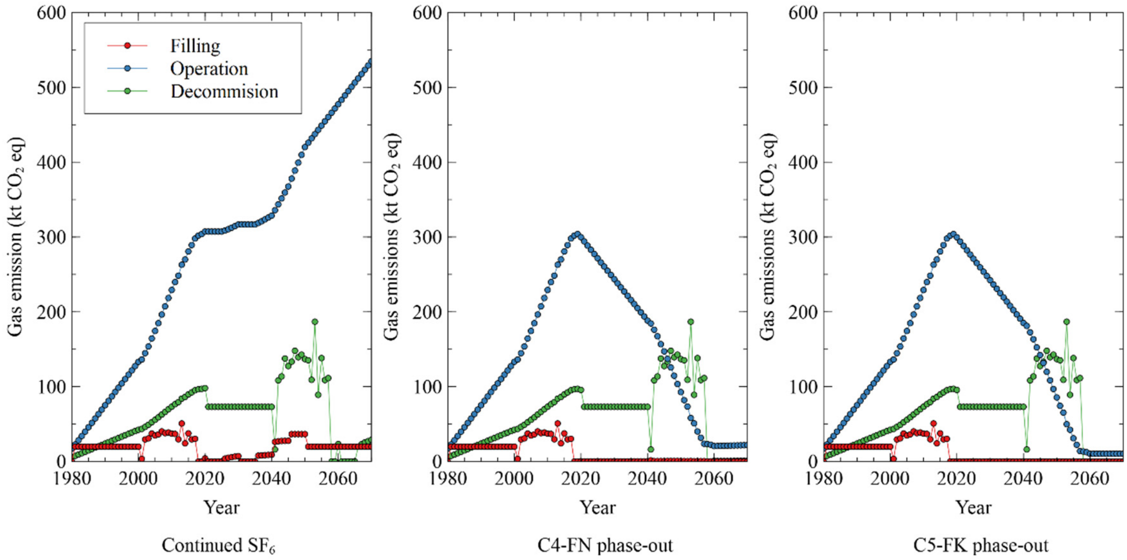


Figure S.6. Disaggregated emissions of three lifecycle phases (filling, operation, decommissioning) as a function of time, for the three scenarios investigated. Left: Continued SF_6 business-as-usual; Center: phase-out of SF_6 towards C4-FN starting in 2020; Right: phase-out of SF_6 towards C5-FK starting 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 S.7, and in the combined graph in Figure S.8 that is analogous to Figure 4 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.

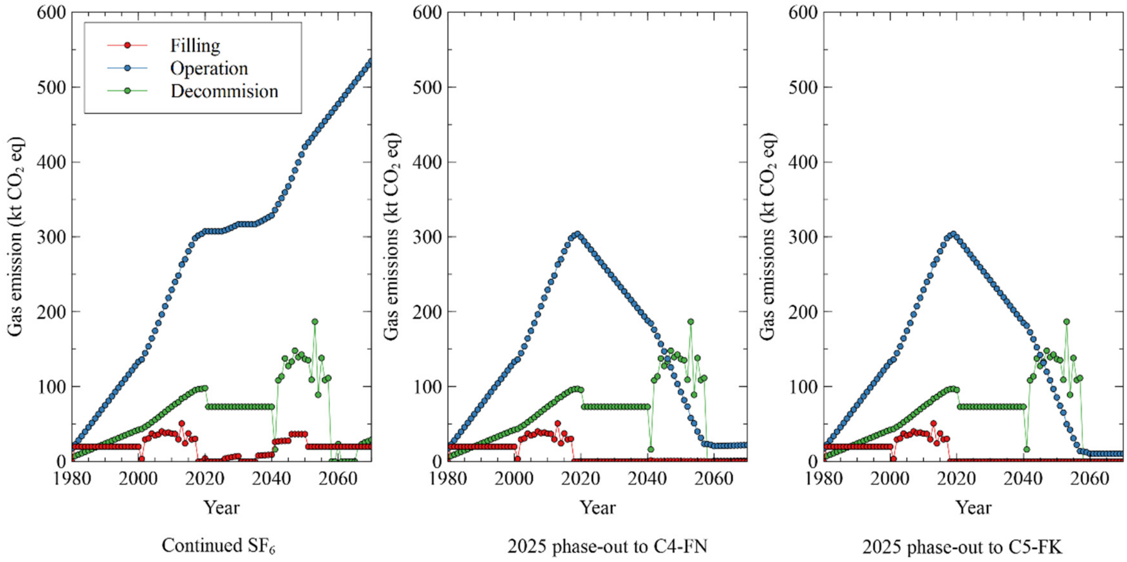


Figure S.7. Disaggregated emissions of three lifecycle phases (filling, operation, decommissioning) as a function of time, for the three scenarios investigated. Left: Continued SF_6 business-as-usual; Center: phase-out of SF_6 towards C4-FN starting in 2025; Right: phase-out of SF_6 towards C5-FK starting in 2025.

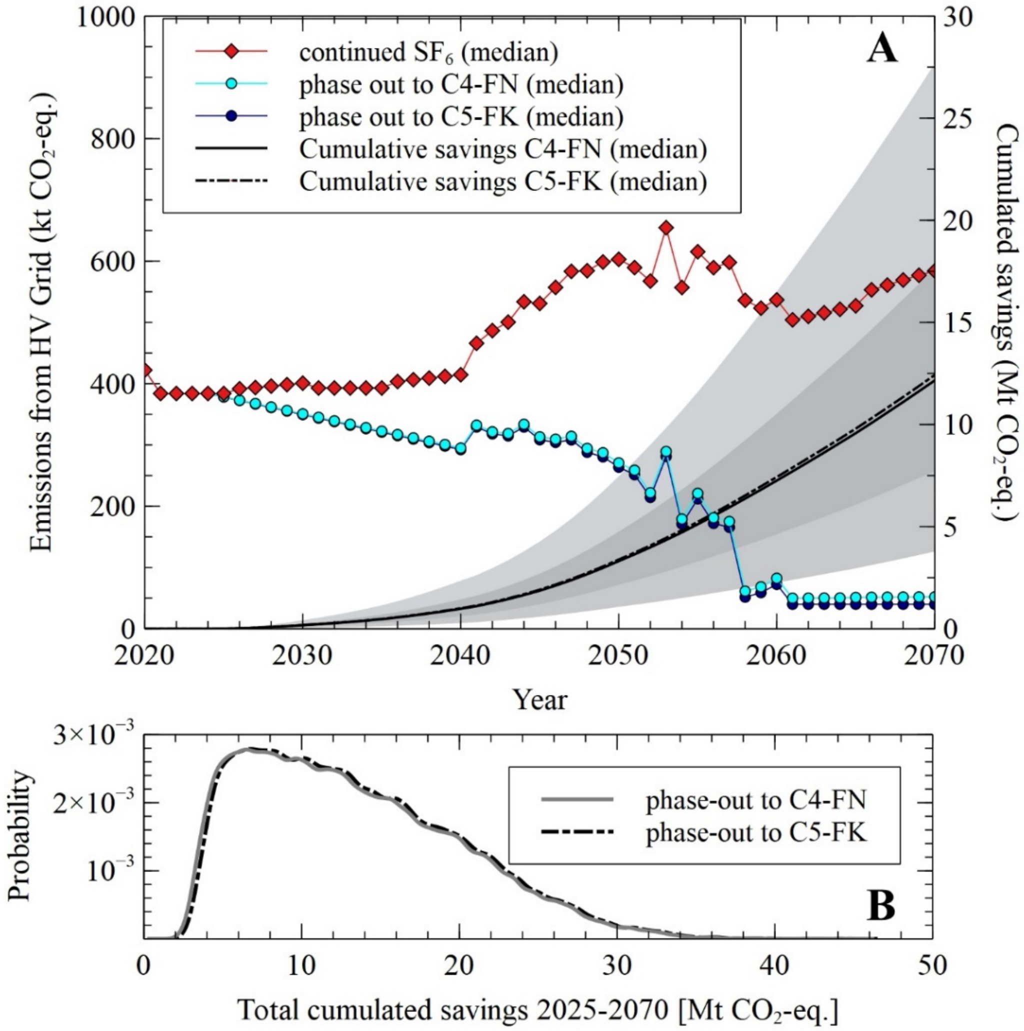


Figure S.8. Annual aggregated emissions from the EU-28 transmission grid (HV GIS bays), in kt of CO_2-eq. in three different scenarios; business as usual, phase-out starting 2025 toward C4-FN technology and phase-out starting 2025 toward C5-FK technology (left axis of [A]), and cumulated savings of both 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. .

References

1. Burgers, K.; Doring, M.; Hussy, C.; Rhiemeier, J.-M.; Franck, C.; Rabie, M. Concept for SF6-Free Transmission and Distribution of Electrical Energy, Ecofys Report 03KE0017, 2018. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/2503/dokumente/final-report-sf6_en.pdf.
2. Carpos, P.; De Vita, A.; Tasios, N.; Siskos, P.; Kannavou, M.; Preopoulos, A. Energy, transport and GHG emissions—Trends to 2050. In *EU Reference Scenario*; Publications Office of the European Union: Rue Mercier, Luxembourg, 2016, doi:10.2833/9127.
3. Eurostat. Electricity and Heat statistics—Statistics Explained. 2019. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_and_heat_statistics#Installed_electrical_capacity (accessed on 11 November 2019).

4. EU Commission, DG Energy, Unit A4. Energy Statistical Datasheets for the EU Countries. 2019. Available online: http://data.europa.eu/euodp/data/dataset/information-on-energy-markets-in-eu-countries-with-national-energy-profiles/resource/24184068-8ec3-470a-ba28-5ca2317c6f6f (accessed on 13 November 2019).
5. IPCC. EFDB—Emission Factor Database. 2006. Available online: https://www.ipcc-nggip.iges.or.jp/EFDB/find_ef.php (accessed on 17 November 2019).
6. Madrigal, M.; Spalding-Fecher, R. *Impacts of Transmission and Distribution Projects on Greenhouse Gas Emissions*; The World Bank: Washington, DC, USA, 2010.
7. MIT. AGAGE: Advanced Global Atmospheric Gases Experiment. 2019. Available online: https://agage.mit.edu/about/ (accessed on 11 November 2019).
8. O'doherty, S.; Stanley, K.; Rigby, M.; Stavert, A. Report to BEIS: Long-Term Atmospheric Measurement and Interpretation (of Radiatively Active Trace Gases); Annual Report (sept 2017–sept 2018); BEIS Contract No. GA0201; Met Office, Exeter, UK, 2018.
9. Ofgem. RIIO-ED1 Electricity Distribution Annual Report 2015-16. 2017. Available online: https://www.ofgem.gov.uk/publications-and-updates/riio-electricity-distribution-annual-report-2015-16 (accessed on 10 November 2019).
10. Ofgem. RIIO-ED1 Electricity Distribution Annual Report 2016-17. 2019. Available online: https://www.ofgem.gov.uk/ publications-and-updates/riio-electricity-distribution-annual-report-2017-18 (accessed on 10 November 2019).
11. Plöger, F.; Schwarz, W.; Thesen, S.; Preisegger, E.; Ajavon, A.-L. N.; Zhou, D. Chapter 8: Other product manufacture and use. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*; Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Eds.; IGES: Kanagawa, Japan, 2006.
12. Prinn, R.G.; Weiss, R.F.; Fraser, P.J.; Simmonds, P.G.; Cunnold, D.M.; Alyea, F.N.; O'Doherty, S.; Salameh, P.; Miller, B.R.; Huang, J.; et al. A history of chemically and radiatively important gases in air deduced from ALE/GAGE/AGAGE. *Journal of Geophysical Research* **2000**, *105*, 17751–17792, doi:10.1029/2000JD900141.
13. Prinn, R.G.; Weiss, R.F.; Arduini, J.; Arnold, T.; Fraser, P.J.; Ganesan, A.L.; Gasore, J.; Harth, C.M.; Hermansen, O.; Kim, J.; Krummel, P. B.; Li, S.; Loh, Z.M.; Lunder, C.R.; Maione, M.; Manning, A.J.; Miller, B.R.; Mitrevski, B.; Mühle, J.; O'Doherty, S.; Park, S.; Reimann, S.; Rigby, M.; Salameh, P.K.; Schmidt, R.; Simmonds, P.G.; Steele, L.P.; Vollmer, M.K.; Wang, R.H.; and Young, D.: The ALE/GAGE/AGAGE Data Base. Available online: http://agage.mit.edu/data (accessed on 20 September 2019).
14. Prinn, R.G.; Weiss, R. F.; Arduini, J.; Arnold, T.; Langley Dewitt, H.; Fraser, P.J.; Ganesan, A.L.; Gasore, J.; Harth, C.M.; Hermansen, O.; et al. History of chemically and radiatively important atmospheric gases from the Advanced Global Atmospheric Gases Experiment (AGAGE). *Earth System Science Data* 2018, *10*, 985–1018, doi:10.5194/essd-10-985-2018.
15. RED Electrica. Corporate Resbonsibility Report 2016. 2016. Available online: https://www.ree.es/sites/default/files/downloadable/ree_corporate_responsibility_report_2016_v2.pdf (accessed on 10 November 2019).
16. RED Electrica. REE Environmental Report 2010. 2010. Available online: https://www.ree.es/sites/default/files/downloadable/ree-memoria-ma-2010-ing.pdf (accessed on 10 November 2019).
17. RED Electrica. EMAS Environmental Statement 2014. 2015. Available online: https://www.ree.es/sites/default/files/downloadable/declaracion_ambiental_emas_2014_eng.pdf (accessed on 10 November 2019).
18. RED Electrica. EMAS Environmental Statement 2018. 2019. Available online: https://www.ree.es/sites/default/files/downloadable/emas_environmental_statement_2018.pdf (accessed on 10 November 2019).
19. RTE. RTE Rapport D'activité 2007. 2007. Available online: http://clients.rte-france.com/htm/fr/mediatheque/telecharge/rapport_2007/RTE_RAnnu_2007.pdf (accessed on 10 November 2019).
20. RTE. RTE Rapport De Développement Durable 2010. (n.d.). 2010. Available online: https://www.rte-france.com/sites/default/files/ra_rte_2010_rdd.pdf (accessed on 10 November 2019).
21. RTE. RTE Activity and Sustainable Development Report 2012. 2012. Available online: https://www.rte-france.com/sites/default/files/ra_rte_2012_ra_uk.pdf (accessed on 10 November 2019).

22. RTE. RTE Activity and Sustainable Development Report 2014. 2014. Available online: https://www.rte-france.com/sites/default/files/rte_rapportannuel2014_gb_bat.pdf (accessed on 10 November 2019).
23. Terna. Terna—Sustainability report 2010. 2010. Available online: http://ternacsr2010.message-asp.com/en.
24. Terna. Terna Sustainability Report 2013. 2013. Available online: http://terna2013csr.rep.message-asp.com/sites/terna2013csr/files/download/en/2013_sustainability_report_en.pdf (accessed on 10 November 2019).
25. Terna. Terna Sustainability Report 2015. 2015. Available online: https://www.terna-reports.it/2016/assets/pdf/Terna_Sustainability_Report_2015.pdf (accessed on 10 November 2019).
26. Terna. Terna Sustainability Report 2018. 2018. Available online: https://download.terna.it/terna/0000/1231/72.PDF (accessed on 10 November 2019).
27. UNFCCC. National Inventory Submissions 2019 UNFCCC. 2019. Available online: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2019 (accessed on 10 November 2019).