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Evaluation of SF_6 Leakage from Gas Insulated Equipment on Electricity Networks in Great Britain

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Abstract: This paper examines the data collected from the power industry over the last six years of actual reported emissions of sulphur hexafluoride (SF_6) and the potential impact. The SF_6 emissions have been collated from the 14 different regions in England, Scotland, and Wales (Great Britain) from the six distribution network operators. The emissions of SF_6 due to the transmission network of Great Britain have also been collated from the three different transmission network operators. By collecting this SF_6 emissions data from the power industry, in both the distribution and transmission networks, an overall view of the scale of SF_6 emissions in Great Britain can be evaluated. Data from the power industry also shows the inventory of SF_6 power equipment in use over the last six years in Great Britain and shows the calculated percentage leakage rate of all of this equipment. In this paper, these figures, as reported by the electrical power industry to the UK government, have been used to estimate the likely inventory of SF_6 equipment in England, Scotland, and Wales by 2050 and the future emissions of SF_6 that could be leaked into the atmosphere by this equipment.

Keywords: sulphur hexafluoride (SF_6); emissions; gas insulated switchgear (GIS); gas insulated line (GIL); transmission; distribution; environment

1. Introduction

This paper examines the reported emissions of sulphur hexafluoride (SF_6) from the power industry in Scotland, Wales, and England. In recent years, it had been concluded that SF_6 is an extremely potent global warming gas and can have a significant impact on global warming if released into the environment. Previously, it was determined that SF_6 has a global warming potential (GWP) of 22,800 times that of carbon dioxide (CO_2) over a 100 year period, as used in EU and UK regulations [1–3]. However, more recent estimates put the GWP of SF_6 at 23,500 times that of CO_2 [4]. SF_6 has an extremely long atmospheric lifetime of 3200 years [4] during which infrared radiation is reflected back towards earth when left in the atmosphere. The use of SF_6 has been banned from applications where a suitable alternative can be provided and is classified as a regulated fluorinated greenhouse gas by both the EU and the UK [2,3]. SF_6 is also listed in the United Nation's Kyoto [5] and Paris agreements [6] as a gas deemed to have a high global warming impact and emissions, an d, therefore, should be reduced.

SF_6 exhibits extremely useful insulation characteristics that allow for its use in distribution and transmission equipment in the power network. It exhibits an insulation capability approximately three times that of air [7] and, therefore, it allows for compact gas-insulated switchgear (GIS) and gas-insulated lines (GIL) to be adopted. These are much smaller in size than air-insulated equipment [7]. SF_6 equipment has a high safety service record when operating under high voltage stresses compared to oil- and air-insulated equipment [8] due to the use of leak detection equipment and its particular use at the medium voltage distribution level and above where the gas can be both indoors or outside. However, due to recent concerns over the environmental impact of SF_6, distribution and transmission network operators have implemented schemes to reduce the impact of SF_6 equipment by reducing the release of SF_6 into the environment [9–14]. Stringent regulations, which require the reporting of leaks whenever they occur, have also been implemented in recent years as a result of the known impact of the global warming potential of SF_6 [2,3,5,6]. Manufacturers of SF_6 equipment play a key role in improving equipment gas seals and providing gas density sensors that allow for the constant monitoring of gas equipment on the power network. In recent years, it has become apparent that a new alternative, environmentally-friendly, gas is needed to replace SF_6 entirely because of its inherent global warming potential. However, this has not been an easy task and, in the market at present, there is no alternative to SF_6 that could directly replace it while fulfilling all its dielectric and interruption properties. Mixtures of SF_6/N_2 have also been proposed for insulation purposes only, however, SF_6 is still a component meaning there is still an environmental impact and this mixture cannot carry out the high voltage interruption performance expected of pure SF_6. Therefore, a large amount of distribution and transmission equipment still exists in the network today with a constant annual leakage rate that varies depending on the age and degradation of the equipment in use. It is of timely importance that how much SF_6 is in use in the distribution and transmission networks, the amount of SF_6 that leaks each year, and the potential impact this gas can contribute to global warming both now and in the future be evaluated.

2. SF_6 Emissions and Calculated Equivalent CO_2 Emissions

The data used in this paper is taken directly from reported emissions from distribution and transmission network operators. SF_6 can be released into the atmosphere by accidental leakage due to faults and/or equipment degradation, which causes loss of gas from seals or sudden decompression [15]. SF_6 leakage may also occur during normal operation due to vibrations and handling operations as equipment is decommissioned or maintenance is undertaken. The data used in this paper is often captured through SF_6 maintenance top-ups which allows the operator to determine how much gas is needed to top-up a piece of equipment to its normal operating pressure and, therefore, how much gas has been lost [16]. Therefore, depending on the amount of maintenance required, the amount of SF_6 emissions may vary.

The equivalent CO_2 emissions in tonnes (tCO_2e) can be directly converted from the SF_6 emissions in kg by using the following equation [3]:

$$tCO_2e = \left(\frac{\text{Mass of } SF_6 \text{ Emissions (kg)}}{1000}\right) \times \text{GWP of } SF_6 \quad (1)$$

This equation uses the quantity of SF_6 in kg divided by 1000 to convert this number to tonnes, multiplied by the global warming potential (GWP) of SF_6. The GWP scale factor used in this paper is 1 kg of SF_6 being equivalent to 22,800 kg of CO_2, as provided by the UK government, Department for Environment, Food and Rural Affairs (DEFRA) [3] and the European Union [2]. Over the reported years 2010–2014, a scale factor of 1 kg of SF_6 to 23,900 kg of CO_2 was previously used. However, this was changed in recent years to 22,800 [1]. The most recent reports suggest this equivalent ratio could actually be 23,500 [4]. In this paper, all data has been re-calculated for the scale factor 22,800 equivalency, even if they were originally reported using a different scale factor. Some reported emissions have discrepancies between source years. In these cases, the most up to date source has been used as some operators have re-calculated these numbers from new data. Some distribution network emissions of SF_6 were given directly as tCO_2e and have been calculated from this figure. All other equivalent CO_2 emissions in this paper have been directly calculated from SF_6 emissions (kg). The regulatory reporting year and the years shown in this paper occur between April and March of the following year rather than a complete calendar year. For example, for the year 2012–2013, the year reported is actually between April 2012 and March 2013.

3. Reported Emissions of SF_6 in Great Britain between 2010 and 2016 by Distribution Network Area

The power distribution network is divided into 14 unique areas in Scotland, England, and Wales. These areas are shown in Figure 1a. The total amount of SF_6 reported as emissions between 2010 and 2016 are shown in Table 1 [15–48]. It is important to note that emissions of SF_6 from the distribution network have fluctuated over the last six years with emissions both rising and falling over the period, as shown in Figure 1b. For the last six years, an average SF_6 emission level of 1149 kg per year can be calculated for England, Scotland, and Wales combined.

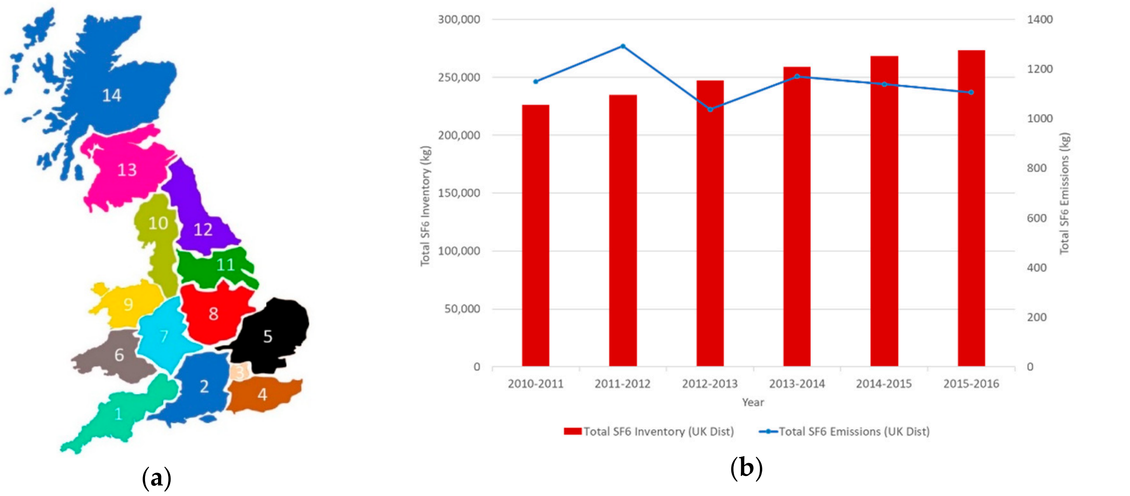


Figure 1. (**a**) Distribution network areas in Great Britain; and (**b**) the total SF_6 inventory (kg) and emissions level (kg) of the electricity distribution network in Great Britain [13–48].

The equivalent amount of CO_2 that would need to be released into the atmosphere to have the same global warming potential as the amount of SF_6 released is shown in Table 2. The equivalent CO_2 emissions, shown in Table 2, have been calculated using a scale factor of 1:22,800. The equivalent average annual CO_2 emissions that equate to 1149 kg of SF_6 is 26,197 tonnes of CO_2.

In Table 3, the inventory of SF_6 equipment used in each distribution network area is collected and classified. Table 3 gives an account of the scale of gas-insulated power equipment that is required to maintain a safe and reliable electricity distribution network in England, Scotland, and Wales. In the future, if an environmentally-friendly alternative insulation medium is found to replace SF_6, the gas inventory shown in Table 3 will need to be replaced with the new alternative gas. From Figure 1b, it can be shown that the amount of SF_6-insulated distribution equipment on the network is still increasing steadily, with an average increase of 9401 kg of SF_6 being introduced into the power distribution network every year. As the amount of SF_6 in the distribution network increases, so too does the potential environmental impact this gas could pose if released.

In Table 4, the annual leak rate on the distribution network for each area is given. The annual leak rate is the calculated percentage of SF_6 emissions in a given area against the total inventory held in that distribution network area. These calculations shows that the actual leakage rate per year of the total inventory held is quite low, with an average annual leak rate of 0.46% of the total SF_6 inventory. This is possibly due to the work already carried out with gas handling procedures and equipment gas seals. However, modern distribution equipment installed in the network should have a leakage rate of 0.1% for a sealed pressure system [49]. Thus, a much higher leakage rate is actually being generated either through older equipment with poor gas seals, accidental gas leaks in gas handling operations, or equipment gas containment failure. It may also be the case that some of the older SF_6 equipment in the distribution networks are of a closed pressure system type, such as those used in single-pressure circuit breakers, which have a much higher leakage threshold of between 0.5% and 1% per year [49].

Table 1. SF_6 emissions (kg) by electricity distribution network area in Great Britain.

Map No.	Distribution Network Area	Yearly SF_6 Emissions (kg)						Data Source
		2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	
7	West Midlands	14.00	130.00	54.00	95.00	62.00	164.00	[17,18]
8	East Midlands	11.00	90.00	42.00	44.00	14.00	45.00	[19,20]
1	South West England	211.00	197.00	141.00	158.00	129.00	100.00	[21–23]
6	South Wales	85.00	85.00	17.00	42.00	141.00	88.00	[24,25]
3	London	43.01	19.00	26.57	10.42	21.60	9.55	[15,16,26–31]
4	South Eastern	17.99	20.00	13.18	16.57	15.87	17.61	[15,16,26–31]
5	Eastern	81.00	71.00	71.00	71.84	67.58	66.89	[15,16,26–31]
14	North Scotland	41.64	43.44	46.00	57.77	66.62	79.00	[32–35]
2	Southern	249.52	267.40	323.02	311.06	303.53	382.00	[32–35]
13	South Scotland	55.09	68.57	61.00	61.70	62.40	0.80	[13,36–39]
9	North Wales	108.46	119.04	121.00	121.80	124.20	29.87	[13,36–39]
12	Northeast	47.00	33.00	36.00	25.00	16.00	24.00	[40–43]
11	Yorkshire	47.00	97.00	36.00	98.00	79.00	84.00	[40–43]
10	North West	137.50	51.50	49.80	57.10	36.10	14.63	[44–48]
	Total	1149.21	1291.95	1037.57	1170.26	1138.90	1105.35	

Table 2. Calculated equivalent electricity distribution network area SF_6 emissions (tCO_2e) (scale factor: 1 kg SF_6 = 22,800 kg CO_2).

Map No.	Distribution Network Area	Yearly Calculated Equivalent CO_2 Emissions/Leakage (Tonnes—tCO_2e)					
		2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016
7	West Midlands	319.20	2964.00	1231.20	2166.00	1413.60	3739.20
8	East Midlands	250.80	2052.00	957.60	1003.20	319.20	1026.00
1	South West England	4810.80	4491.60	3214.80	3602.40	2941.20	2280.00
6	South Wales	1938.00	1938.00	387.60	957.60	3214.80	2006.40
3	London	980.63	433.20	605.80	237.58	492.48	217.74
4	South Eastern	410.17	456.00	300.50	377.80	361.84	401.51
5	Eastern	1846.80	1618.80	1618.80	1637.95	1540.82	1525.09
14	North Scotland	949.39	990.43	1048.80	1317.16	1518.94	1801.20
2	Southern	5689.06	6096.72	7364.86	7092.17	6920.48	8709.60
13	South Scotland	1256.05	1563.40	1390.80	1406.76	1422.72	18.24
9	North Wales	2472.89	2714.11	2758.80	2777.04	2831.76	681.04
12	Northeast	1071.60	752.40	820.80	570.00	364.80	547.20
11	Yorkshire	1071.60	2211.60	820.80	2234.40	1801.20	1915.20
10	North West	3135.00	1174.20	1135.44	1301.88	823.08	333.56
	Total	26,201.99	29,456.46	23,656.6	26,681.93	25,966.92	25,201.98

Table 3. SF_6 Inventory held in each electricity distribution network area (kg) in Great Britain.

Map No.	Distribution Network Area	Yearly SF_6 Inventory (kg)						Data Source
		2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	
7	West Midlands	13,184	13,815	14,658	17,537	19,464	20,866	[17,18]
8	East Midlands	11,690	12,090	13,489	15,684	16,952	18,231	[19,20]
1	South West England	11,992	12,529	11,796	11,327	11,558	11,684	[21–23]
6	South Wales	13,818	14,154	15,333	15,597	16,227	16,632	[24,25]
3	London	42,059	41,567	41,038	-	-	41,825	[15,16,26–31]
4	South Eastern	16,710	17,276	18,670	-	-	19,318	[15,16,26–31]
5	Eastern	26,890	30,482	30,926	-	-	35,825	[15,16,26–31]
14	North Scotland	3864	4094	4430	4887	5232	5511	[32–35]
2	Southern	17,731	18,279	20,278	22,984	21,968	25,702	[32–35]
13	South Scotland	11,017	11,397	11,856	12,564	13,259	12,710	[13,36–39]
9	North Wales	21,691	21,949	21,691	22,193	23,117	16,893	[13,36–39]
12	Northeast	9089	9960	13,832	14,530	15,125	15,259	[40–43]
11	Yorkshire	9089	12,825	16,401	17,281	17,817	18,304	[40–43]
10	North West	17,667	14,410	12,949	13,509	16,852	14,736	[44–48]
	Total	226,491	234,827	247,347	258,727	268,205	273,496	

Table 4. Calculated SF_6 annual leak rate of the electricity distribution network (%) in Great Britain.

Map No.	Distribution Network Area	SF_6 Annual Leak Rate (Percent %)					
		2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016
7	West Midlands	0.11	0.94	0.37	0.54	0.32	0.79
8	East Midlands	0.09	0.74	0.31	0.28	0.08	0.25
1	South West England	1.76	1.57	1.20	1.39	1.12	0.86
6	South Wales	0.62	0.60	0.11	0.27	0.87	0.53
3	London	0.10	0.05	0.06	-	-	0.02
4	South Eastern	0.11	0.12	0.07	-	-	0.09
5	Eastern	0.30	0.23	0.23	-	-	0.19
14	North Scotland	1.08	1.06	1.04	1.18	1.27	1.43
2	Southern	1.41	1.46	1.59	1.35	1.38	1.49
13	South Scotland	0.50	0.60	0.51	0.49	0.47	0.01
9	North Wales	0.50	0.54	0.56	0.55	0.54	0.18
12	Northeast	0.52	0.33	0.26	0.17	0.11	0.16
11	Yorkshire	0.52	0.76	0.22	0.57	0.44	0.46
10	North West	0.78	0.36	0.38	0.42	0.21	0.10
	Total Yearly Average	0.51	0.55	0.42	0.45	0.42	0.40

In Table 5, the average annual SF_6 emissions have been calculated for the years 2010–2016 for all of the distribution network areas. These annual average emissions of SF_6 are shown on a map in Figure 2a with the colour scale representing the level of SF_6 emissions. From the average emissions calculated, it can be shown that southern England and the south west of England have the largest emissions of SF_6 from the gas insulation distribution equipment installed in these areas as the electricity network in these areas is extensive.

Table 5. Calculated annual average SF_6 emissions (kg) (2010–2016) of the distribution network in Great Britain.

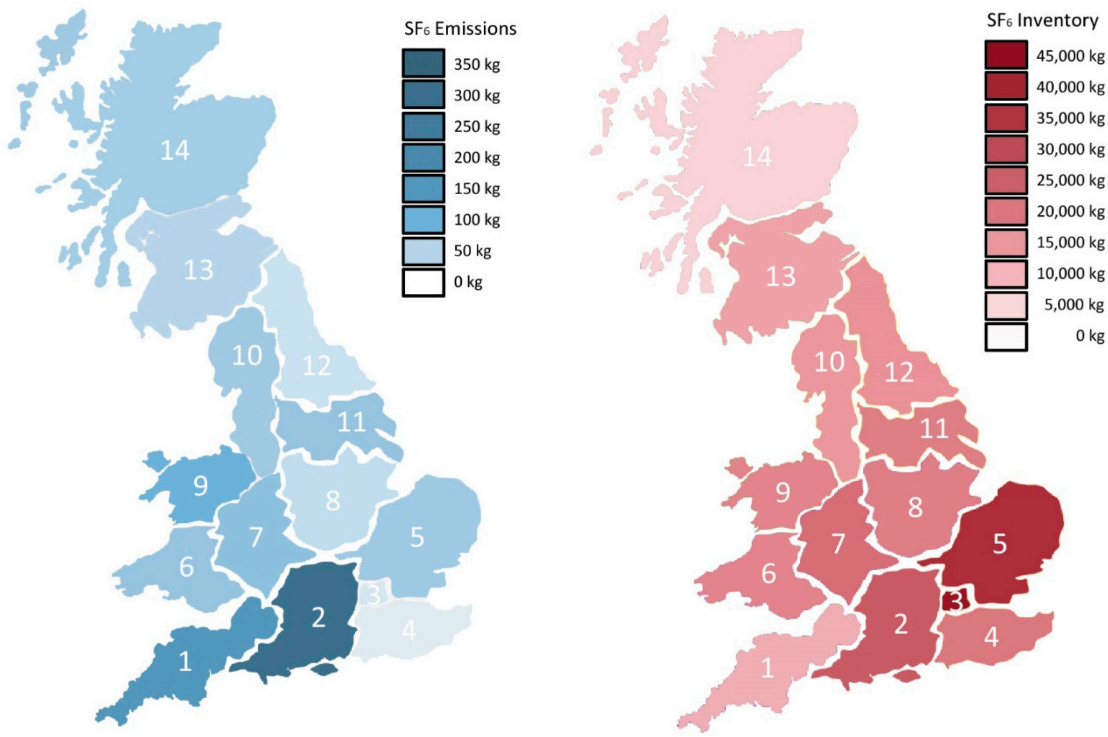
Map No.	Distribution Network Area	Annual Average SF_6 Emissions (kg) (2010–2016)
2	Southern	306.09
1	South West England	156.00
9	North Wales	104.06
7	West Midlands	86.50
6	South Wales	76.33
11	Yorkshire	73.50
5	Eastern	71.55
10	North West	57.77
14	North Scotland	55.75
13	South Scotland	51.59
8	East Midlands	41.00
12	Northeast	30.17
3	London	21.69
4	South Eastern	16.87
	Total Average	1149

In Table 6, the amount of SF_6 inventory on the distribution network is shown for each distribution area for the last reported year (2015–2016). The amount of SF_6 inventory in the distribution network is also shown by location in Figure 2b. It can be noted that the highest inventory of SF_6 equipment is in London and the lowest inventory is in North Scotland for distribution equipment. This is to be expected because SF_6 equipment is often used in dense urban areas where space availability is limited and power requirements are higher. Given that SF_6 equipment is often the most compact solution and has the smallest footprint requirement, its usage is highest in large cities, such as London. However, despite having the most SF_6 insulated distribution equipment, the average SF_6 emissions reported from the London area are small compared to other regions. It could be expected that the larger the amount of SF_6 equipment in one area, the more likely the emissions of SF_6 would be higher. However, the reported data shows that this is not always the case. For some areas, such as Southern

England, the amount of SF_6 inventory is quite high and the emissions are high, but for other areas, like London, the distribution equipment SF_6 inventory is high but the emissions are low. Although it is difficult to determine trends, it is likely that either the SF_6 equipment installed in London is newer than other areas and, therefore, has improved tight gas seals or that the equipment is more likely to be indoors rather than outdoors, like some rural networks. Therefore, the equipment is much less likely to suffer degradation and accidental gas release. It may also be true that the equipment is left for longer periods of time without maintenance so no log of emissions has been taken or, perhaps, maintenance occurs more often and, therefore, accidental emissions of SF_6 are less likely.

Table 6. SF_6 inventory of the distribution network (kg) in Great Britain (2015–2016) [13,16,17,19,21,24,32,40,44].

Map No.	Distribution Network Area	SF_6 Inventory (kg) 2015–2016
3	London	41,825
5	Eastern	35,825
2	Southern	25,702
7	West Midlands	20,866
4	South Eastern	19,318
11	Yorkshire	18,304
8	East Midlands	18,231
9	North Wales	16,893
6	South Wales	16,632
12	Northeast	15,259
10	North West	14,736
13	South Scotland	12,710
1	South West England	11,684
14	North Scotland	5511
	Total Inventory	273,496

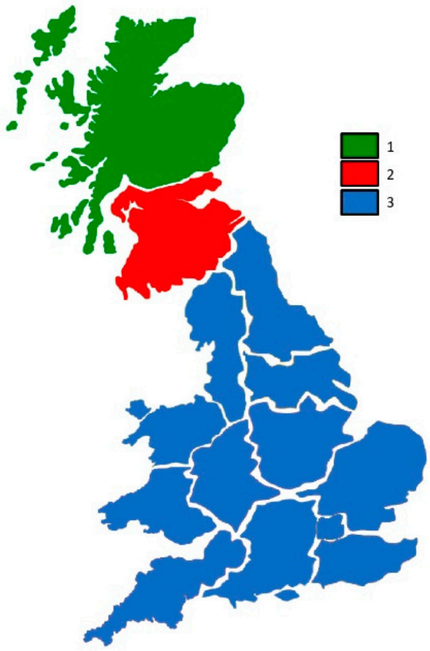


(**a**) (**b**)

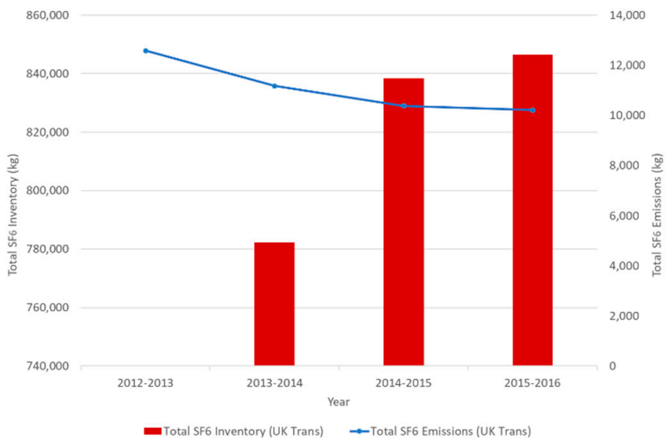
Figure 2. (**a**) Calculated annual average SF_6 emissions (kg) of the distribution network in Great Britain (between 2010 and 2016); and (**b**) SF_6 inventory (kg) of the distribution network in Great Britain (2015–2016).

4. Reported Emissions of SF_6 in Great Britain between 2010 and 2016 by Transmission Network Area

There are three transmission network operators in Scotland, England, and Wales. The network areas covered by each transmission network operator are shown in Figure 3a.



(**a**)



(**b**)

Figure 3. (**a**) Transmission network areas in Great Britain; and (**b**) total SF_6 inventory (kg) and emissions level (kg) of the electricity transmission network in Great Britain.

In Table 7, the emissions of SF_6 reported by transmission network operators are summarised for the three transmission network areas. It can be shown in Figure 3b that, over the last four years, the total emissions of SF_6 has been slowly decreasing, which is likely to be helped by the replacement of the oldest equipment which has the worst leakage rates. New replacement equipment is likely to have improved gas seals that reduce the amount of SF_6 being released into the atmosphere and, therefore, the amount of maintenance top-ups. In some instances, transmission network operators have reported that these figures are distorted by single containment failures which have led to increased amounts of SF_6 being released into the atmosphere. One such event, which occurred in the year 2013–2014, where a rupture disc failure on a newly commissioned circuit breaker led to the release of 113 kg of SF_6 in a single event, this contributed to approximately one-third of the SF_6 released in that year in that area [50].

In Table 7, it can be seen that the amount of SF_6 released into the atmosphere from the transmission network in England, Scotland and Wales was 10,215 kg of SF_6 for the reported year 2015–2016. The calculated equivalent emissions of CO_2 compared to SF_6 emissions with a scale factor of 22,800 gives an equivalent 232,902 tonnes of CO_2 being released into the atmosphere, as shown in Table 8.

The estimated inventory of SF_6 used on the transmission network for England, Scotland, and Wales is shown in Table 9. For the year 2015–2016, the total amount of SF_6 used on the network is estimated using the previous year's figures for map area 1, as no data was available for this year. It can be observed from Figure 3b that the amount of SF_6 used on the transmission network has increased for the last three years. The data in Table 9 indicates that the amount of SF_6 used on the England and Wales transmission network has increased steadily for the last five years, meaning that more equipment insulated with SF_6 must have been installed each year along with innovations in leakage mitigation.

In Table 10, the estimated SF_6 annual leak rate of all equipment on the transmission networks in England, Scotland, and Wales is reported. The leakage rate of each area is calculated using the amount of SF_6 leaked in a particular year as a percentage of the total inventory of SF_6 used on the transmission network. It is important to note from Table 10 that the annual average leakage rate for SF_6 equipment on the transmission network fluctuates from year to year, and this is likely to be caused by accidental leakage from single incidents or the amount of maintenance or new installations undertaken.

Table 7. SF_6 emissions (kg) by transmission network area in Great Britain.

Map No.	Transmission Network Area	Yearly SF_6 Emissions (kg)						References
		2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	
1	Scottish Hydro-Electric Transmission (SHE)	-	-	158.00	335.27	339.20	272.26	[50–56]
2	SP Transmission	727.65	-	520.00	729.50	494.61	441.00	[56–61]
3	National Grid Electricity Transmission	-	12,200.00	11,900.00	10,110.00	9544.00	9502.00	[62–65]
	Total	-	-	12,578.00	11,174.77	10,377.81	10,215.26	

Table 8. Calculated equivalent transmission network area SF_6 emissions (tCO_2e) (scale factor: 1 kg SF_6 = 22,800 kg CO_2).

Map No.	Transmission Network Area	Calculated Yearly Equivalent CO_2 Emissions/Leakage (Tonnes—tCO_2e))					
		2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016
1	Scottish Hydro-Electric Transmission (SHE)	-	-	3602.40	7644.16	7733.76	6207.53
2	SP Transmission	16590.42	-	11,856.00	16,632.60	11,277.11	10,054.80
3	National Grid Electricity Transmission	-	278,160.00	271,320.00	230,508.00	217,603.20	216,645.60
	Total	-	-	286,778.40	254,784.76	236,614.07	232,907.93

Table 9. Estimated SF_6 Inventory on each transmission network area (kg) in Great Britain.

Map No.	Transmission Network Area	Yearly SF_6 Emissions (kg)						References
		2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	
1	Scottish Hydro-Electric Transmission (SHE)	-	-	-	7206	9050	-	[50–56]
2	SP Transmission	-	-	53,806	56,292	58,160	64,814	[56–61]
3	National Grid Electricity Transmission	-	610,000	661,111	718,745	771,189	772,520	[62–65]
	Total				782,243	838,399	846,384	

Table 10. Estimated SF_6 Annual leak rate on the transmission network (percent, %) in Great Britain.

Map No.	Transmission Network Area	SF_6 Annual Leak Rate (Percent, %)					
		2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016
1	Scottish Hydro-Electric Transmission (SHE)	-	-	-	4.65	3.75	-
2	SP Transmission	-	-	0.97	1.30	0.85	0.68
3	National Grid Electricity Transmission	-	2.00	1.80	1.41	1.24	1.23
	Total Average	-	2.00	1.4	2.5	1.9	0.96

5. Conclusions

This paper evaluates the present inventory of SF_6 that is needed to sustain the electrical distribution and transmission networks in England, Scotland, and Wales. It has also shown the present emissions of SF_6 from these networks into the atmosphere, the equivalent CO_2 emissions from this potent global warming gas and the leakage percentage rate at which SF_6 is released from the total inventory.

This paper highlights that, over the last six years, the amount of SF_6 inventory currently held by distribution network operators has increased by an average of 9401 kg per year. In the year 2015–2016, the total inventory of SF_6 on the distribution network was 273,496 kg of SF_6 with a leakage rate of 0.40%. This work has also shown that over the last three years, the average annual increase of SF_6 used on the transmission network has increased by 32,071 kg each year. At current levels, the amount of SF_6 used on the transmission network currently stands at 846,384 kg as of 2015–2016. Over the last three years, the average SF_6 leak rate can be calculated as 1.29% per year.

In the year 2015–2016, the total amount of SF_6 used on the electrical network is approximately 1,119,880 kg in England, Scotland and Wales. The amount of SF_6 released into the atmosphere for the year 2015–2016 was approximately 11,320 kg which is the equivalent of 258,110 tonnes of CO_2 being released into the environment. The environmental impact of this release of SF_6 into the atmosphere from all power utilities around the world, could have serious implications for the future, considering the long atmospheric lifetime that SF_6 has and its ability to contribute towards global warming if nothing is done to reduce its use. This work, therefore, highlights the need to research a new environmentally friendly alternative insulation gas to replace the highly global warming gas SF_6.

At present, research is investigating the use of alternative gases such as CF_3I gas mixtures in simple geometries [66,67], as well as other environmentally-friendly alternatives, such as fluoronitriles, fluoroketones, and HFOs [68], all of which have demonstrated promising results as alternatives. These gases all exhibit a lower global warming potential than SF_6, such as CF_3I, which has a GWP of less than 5 [68,69], compared to the most recent estimation of 23,500 for SF_6 [4]. The environmental impact of these gases in the atmosphere is also decreased with gases, like CF_3I, exhibiting an atmospheric lifetime of less than two days [69] compared to 3200 years for SF_6 [1], however, there are still concerns regarding their toxicity and much research is still needed to evaluate their characteristics in full. Some of these gases are now being trialled as an alternative insulation medium in switchgear [70–72] to replace SF_6. However, at present, the full characteristics of these new insulation gases and their practical feasibility for the long-term are still being investigated, including a 400 kV gas-insulated line (GIL) demonstrator at Cardiff University to trial new alternative environmentally-friendly gases. Industry-led projects are also readily being explored to trial alternative insulation gases to counteract this problem and demonstration sites are being setup by all distribution and transmission network operators in order to find a solution to replace SF_6. Industry-led projects are expected to produce better equipment with improved leakage mitigation to help curb the problem with all network and distribution network operators committed to reducing SF_6 losses [10,12,16,42,45,57,63]. For example, a demonstration site at Sellindge substation in Kent, UK has been commissioned to install a 400 kV substation that is insulated by a new green gas for grid (g^3) as an alternative to SF_6 [73].

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