SF_6 Investment Plan
Asset Group Strategy
4 September 2020

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Executive Summary

This document proposes funding required for us to meet our Science Based Target for SF_6 emission abatement and to reverse the rising trend of SF_6 emissions from network assets. The SBT is extremely challenging, requiring us to achieve an average leakage rate across our asset base of ~0.9% by 2026 compared to the present rate of ~1.4%. Based upon our forecasting this equates to a total abatement of 68932kg of emissions during RIIO-2.

To achieve our SBT we propose the following combination of funding:

- Defined interventions at 18 named sites to abate present and future leakage of ageing assets at a cost of [redacted]. Section 5.2 refers.
- Application of pre-emptive, palliative coatings to assets within the first 20 years of service to abate future leak evolution at a cost of [redacted] Section 5.4 refers.
- A flexible funding element to deliver the remaining interventions required to achieve our SBT. By definition the costs of this element are uncertain and we propose an upper bound of [redacted] as described in section 5.3.

Taken together these elements result in a proposed upper funding limit of:

[redacted] = £612.58m

Table 4 (Page 30) presents further detail of the defined value proposals in terms of costs and abatements.

Finally, we recognise the long-term importance of SF_6 inventory reduction; removing the source of the emissions rather than managing them. We propose a funding mechanism to promote and facilitate the early adoption of SF_6-free retro-fill options within existing assets as these solutions become available. This should be based on the NTCC and we propose that the allowed investment per kg of substituted SF_6 inventory should be:

$$(NTCC/1000) \times (GWP_{SF6} - GWP_{Alternative}) \times (\text{leak rate}) \times (\text{effective duration of substitution})$$

No specific funding provision is included due to considerable uncertainty over the scope and effectiveness of such solutions during RIIO-2 however delivery of such options within this cost envelope should be prioritised. An example is presented in section 3.5 resulting is an indicative allowance of [redacted]/kg of SF_6 substituted.

1. Introduction

In line with the UK government's net zero carbon target, it is our strategy to reduce our SF_6 emissions year-on-year progressing towards a net zero position by 2050. As part of this trajectory, we have set a verified science-based target (SBT) of 50% emission reduction from a 2018/19 benchmark by 2030. Assuming a linear reduction trajectory, this equates to a 33% reduction in SF_6 emissions by 2026 (i.e. the end of RIIO-T2) and amounts to a fixed target of no more than 8,180kg of emissions in 2026. Assuming no significant change of inventory this equates to an aggregate leak rate across our asset fleet of ~ 0.9%; a very challenging target.

This paper sets out the basis for our funding proposal to undertake interventions to achieve our SF_6 emission abatement targets, covering only interventions additional to our December 2019 Load & Non-Load plans. We present a clear view of the single funding mechanism for each relevant intervention.

We are currently refining forecasting capabilities to ensure we have a deliverable plan in place to achieve our target as well as to track progress during delivery. Our latest forecasting indicates that, without intervention, our SF_6 emissions could be ~24,000kg per year by 2026 compared to the SBT level of 8,180kg per year in the same year. The difference between these values defines the forecast abatement of actual & forecast leakage that we need to achieve by 2026, i.e. we must plan to have abated ~16,000 kg per year of actual and forecast leakage by 2026 to meet our long-term target.

This paper proposes funding for:

- Defined investments across 18 specific sites to deliver a significant proportion of the required abatement; the fixed element.
- A flexible mechanism for efficiently delivering the balance of required interventions; the flexible element.
- The application of pre-emptive, palliative leak-prevention techniques to assets within the first 20 years of service life to prevent future leakage.
- A mechanism to facilitate the adoption of SF_6-free retro-fill option within existing hardware when these options become available within RIIO-2.

Importantly we propose to deliver the volume of interventions *actually* required to achieve the 2026 SBT, rather than the volumes we currently *forecast* to be required, meaning that during RIIO-2 we will true up the volumes to meet the objective. Over-delivery will only be justified where there is a clear commercial benefit based upon the prevailing NTCC.

For the fixed element of the SF_6 price control deliverable (PCD), Ofgem have confirmed that they will provide us with an ex-ante allowance based on well-justified engineering documentation for ‘no regrets’ named sites identified for intervention. In the event that any of these sites are not delivered within the period, the allowances for the specific site will be returned to consumers. For the flexible element, we propose unit costs allowances (UCA) per asset type and intervention type in section 5.1. These costs will be agreed with Ofgem ahead of the RIIO-2 period and will act as an automatic revenue adjustment mechanism for specific unit outputs associated with these allowances. Revenues will only be adjusted as and when outputs have been delivered and therefore there is no risk of under/over delivery against an allowance.

Besides the quantity of interventions, our strategy also considers the quality and efficiency of interventions. To achieve the SBT, we need to move progressively from repairing leaks that have already occurred, to a combined programme of leak repair and leak prevention, and ultimately to a leak prevention programme. This investment proposal establishes and delivers the first phase of this evolution towards a net zero SF_6 position by 2050 in a way that minimises the risks, and maximises the benefits, to current and future consumers.

2. Business plan context

2.1. Our strategy is informed by stakeholder priorities

During our RIIO-T2 engagement, we spoke to our stakeholders to understand their views about our impact on the environment, including carbon emissions and local impacts, and the improvements we could make. Our stakeholders, especially consumers, told us they want us to take ambitious action on climate change, and potentially use carbon offsetting to make relevant activities carbon neutral as well as maximising responsible use of assets. We should reduce the overall volumes of SF_6 leakage and continue efforts to find alternative insulating gases.

In 2019, our consumer survey also indicated that reducing emissions is almost as important as safety and reliability. With no associated costs indicated at the time of testing, 60% of consumers want us to be a “net zero business” by 2030 or 2040, with younger citizens and women being the most supportive. Some consumers said they would also prefer our efficiency savings to be channelled into environmental investments.

Our stakeholders also wanted us to make investment decisions based on the whole-life cost of each option, including the cost of carbon emissions, and use this approach to help minimise our overall carbon emissions. Our SF_6 investment plan has been designed to take these stakeholder requirements into account.

2.2. Scientific Basis

SF_6 is a particularly potent greenhouse gas. It has a global warming potential (GWP) 23,500 times stronger (according to the latest IPCC data) than CO_2. SF_6 is the largest controllable element of our direct emissions at ~280,500tCO2e in 2018/19, and therefore the primary candidate for us to reduce our emissions footprint.

The RIIO-2 business plan guidance mandates a SBT, which externally verifies targets to limit global warming by 1.5 degrees Celsius. As Figure 1 below shows, the SBT Institute has confirmed that, for National Grid Electricity Transmission (NGET), this equates to a 50% abatement by 2030, from a 2018/19 baseline. Our interim target for 2026 is calculated as 34% abatement assuming a linear pathway. To confirm achievement of the SBT milestone, the emissions target must be reached by scope 1 (Fleet + SF_6) and scope 2 (energy in buildings) independently, with no trading between the two categories. SF_6 is within scope 1 and fleet accounts for only 1.6% of scope 1 so therefore SF_6 alone must be reduced by at least 33%.

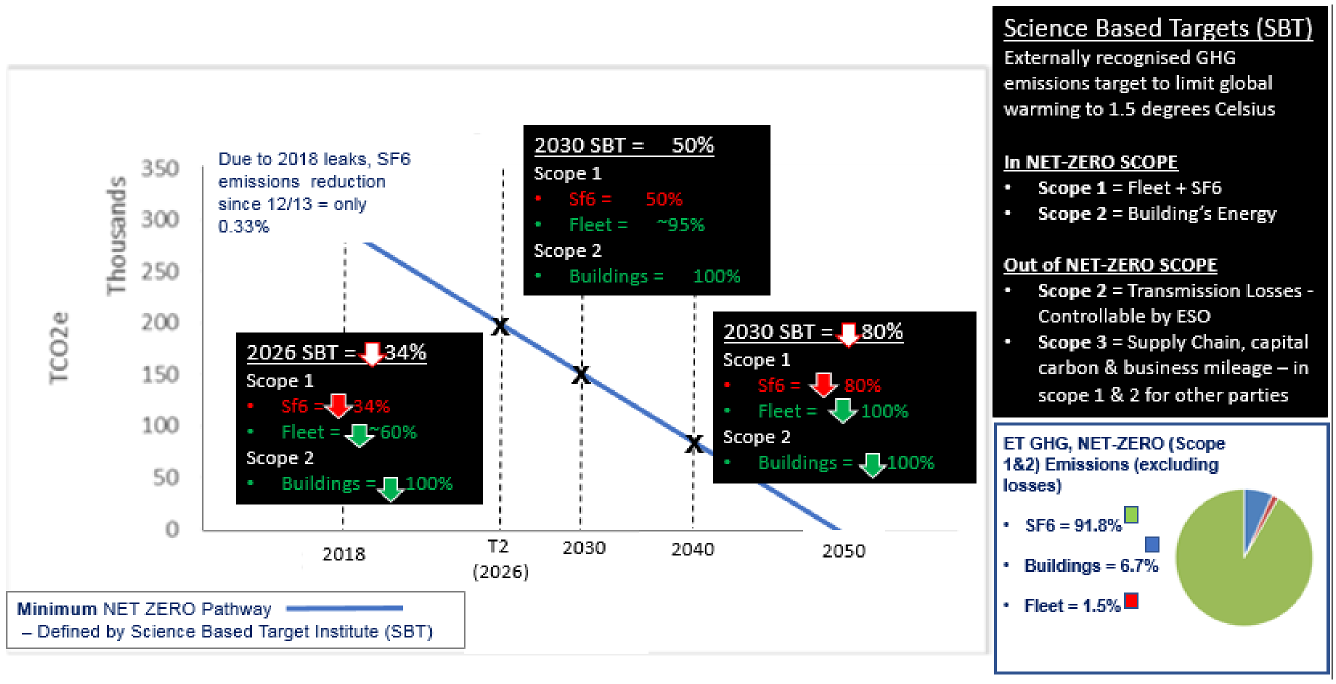


Figure 1 - Details of the emissions included in the SBT Net Zero pathway milestones

2.3. T1 Asset Condition and Performance

Our SBT is based on 2018/19 actual leakage giving a benchmark value of 12,268 kg. This value differs from the value reported for the same period in Business Plan Data Table A6.5 (11,588 kg), which requires reporting of leakage from only those assets commissioned on the NGET system at the time of the completion of that Table. Assets which may have leaked but have been removed from the system within the reporting period are excluded from the A6.5 values, as required by Ofgem. All future/forecast analysis in this proposal is based upon actual emission data to be consistent with our SBT. As requested by Ofgem, all historic emission reporting presented in this paper is based upon A6.5 data. At the network level the difference between real emission and A6.5 emissions is approximately 5.5%. However, for the specific sites mentioned in this proposal, where no significant inventory changes have taken place, real and A6.5 emissions do not differ. As such the use of real or A6.5 emission data has no material impact upon these proposals.

Figure 2 shows NGET SF_6 emissions over the T1 period in the context of inventory growth, non-load replacement of leaking assets, and a programme of repair interventions. Following a fall from 2013 to 2014 there has been a consistent upwards trend from 2014 to-date. From this data, we conclude that perpetuating the existing status-quo approach will not deliver the considerable year-on-year reductions that are required to achieve our SBT. We predict that if we maintain a T1 status-quo approach to SF_6 emission abatement (i.e. perpetuate the focus primarily on fixing leaking assets) emissions will increase significantly in future years (see forecasting section below).

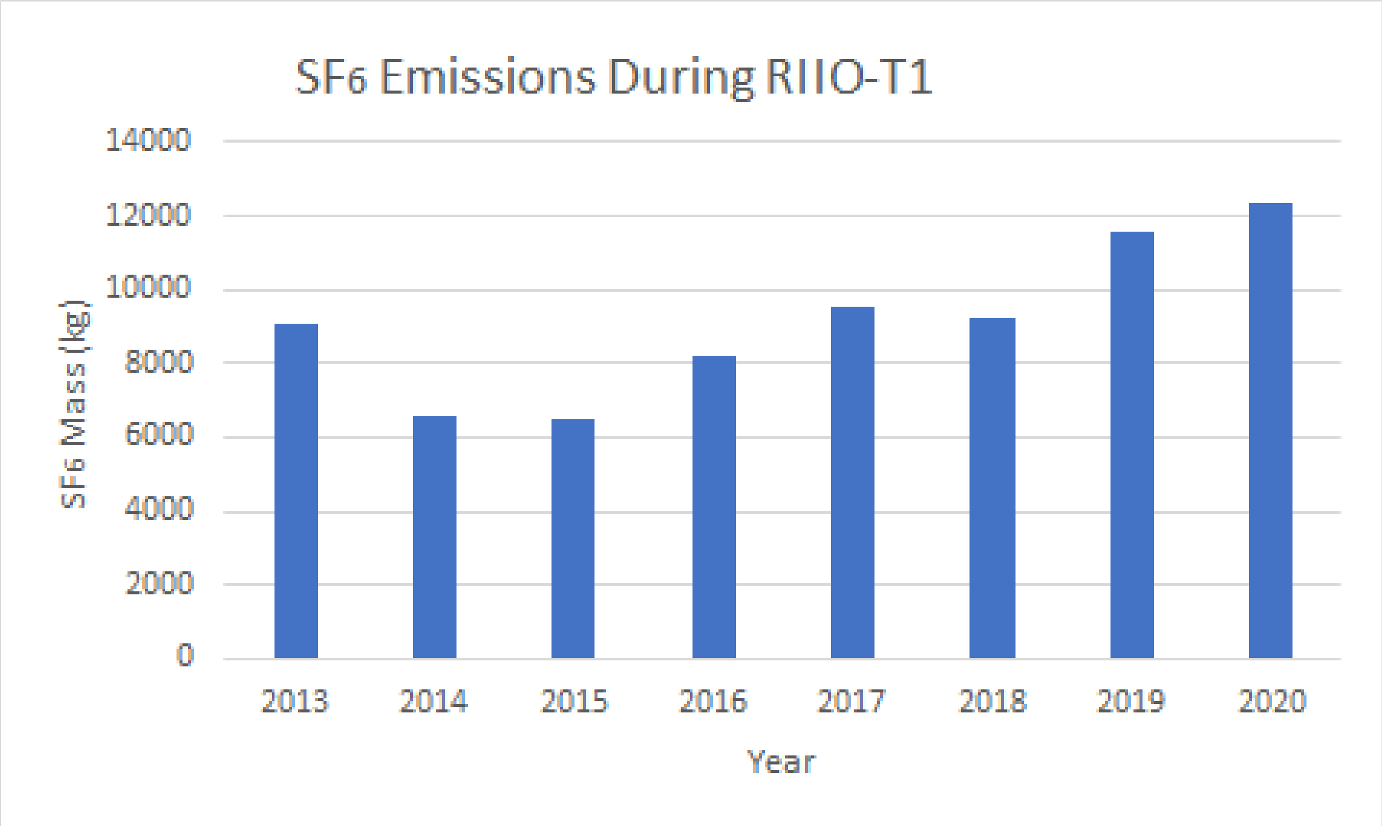


Figure 2 - NGET annual SF_6 emissions during RIIO-1 period

During RIIO-1, we have improved collation and reporting of SF_6 emissions and have established a programme of SF_6 repairs to mitigate loss of SF_6 to the atmosphere. A reactive approach based on repairing leaks means an ongoing loss of SF_6 in the period between leak detection and leak repair. Such an approach is therefore fundamentally unsuitable to achieve long-term abatement of SF_6 emissions to levels consistent with equipment design values. To prevent the development of unacceptable leak rates, a proactive approach to SF_6 emission abatement is required that embodies the need to forecast asset leak performance and make timely, pre-emptive interventions.

SF_6 emission data gathered during the RIIO-1 period is now sufficiently complete and detailed to form the basis of an SF_6 forecasting capability. This capability is described in more detail in the forecasting section as well as in section 8 of this document.

Emission abatements delivered during the remainder of T1 will contribute to a well-defined RIIO-2 starting position. Variability in this starting position will have no influence on the need case for the 18 major, defined interventions detailed in this proposal; these sites require intervention under all scenarios. Uncertainty over the RIIO-2 starting position and variations between forecast and actual leakage development over the RIIO-2 period are catered for by the provision of the flexible portion of the PCD.

3. Our approach to SF_6 Asset Management

3.1. SF_6 Asset Health Assessment

All SF_6-filled equipment leaks. Closed pressure systems such as those used for high voltage switchgear typically have design leak rates in the range 0.1% to 1.0% per annum depending primarily upon when they were designed and manufactured. All in-service leak rates in-excess of the design value warrant intervention given the environmental impact of SF_6. The average leak rate across our portfolio in 2018/19 (the benchmark year) was 1.4%. This average is made up of many assets that are performing well within design limits, as well as a population of assets and asset families that performs very poorly against the same limits and which require early intervention.

The key measured parameter which we use to assess SF_6 tightness is the top-up mass over time. Single top-up events cannot be used to indicate unacceptable leakage as they provide no information on the leakage rate. Two or more top-ups on a single asset over time allow a leakage rate to be estimated. Assets with measured leakage rates significantly above the design value are candidates for intervention. For indicative purposes, we presently have approximately 880 functional positions (three phase asset locations) with leakage in excess of 1% per annum, which rises to approximately 1100 if the border is set to 0.5% pa. All of these locations are candidates for intervention if we are to achieve our long-term targets.

We record, via top-up data, all emissions of SF_6 from our assets so we have a good picture of present-day performance down to the individual asset level. Over the course of the RIIO-1 period, we have accumulated performance data that allows us to better understand evolving emission performance of SF_6-filled assets considering factors such as manufacturer, design type, installed location/environment, age, etc.

The Network Output Measures' Network Asset Risk Metric (NARM) framework includes a reactive, end-of-life scoring mechanism for SF_6 leakage from lead assets (circuit-breakers). Whilst not yet addressed by the NARM framework a similar approach has been applied to non-lead instrument transformers.

The scoring mechanism for these assets includes the following factors: mass of leakage (kg), leak rate (mass of leak per mass of asset SF_6 inventory) and a combined score which incorporates both the leak mass and leak rate if both exceed defined criteria. Further, a leakage duration score, based upon whether the asset has been leaking in the last two or five years (depending on the severity) is also assigned. These scores are combined to produce an overall index which will determine whether an intervention is required on the equipment within two years or five years. The type of intervention is cost justified and appropriate to the level of risk. It may not necessarily involve full replacement of the asset.

Using the example of circuit-breakers, NARM categorises SF_6 leakage of <10kg per annum or <5% leakage per annum as "insignificant" for asset health scoring. "Major leakage" thresholds are set at >50kg per annum or >10% leakage per annum. These categories remain appropriate when considering the ability of the asset to perform its intended function however they are not entirely effective for the purposes of minimising SF_6 emissions over time.

The NARM framework is effective for addressing gross leakage from discrete assets such as AIS circuit-breakers where interventions can be planned and delivered in isolation from interventions upon associated assets. Interventions triggered in this way are reactive and rely on there already having been significant loss of SF_6. As such they will not contribute to a year-on-year reduction in emissions. Such reductions require a more pro-active approach based on early detection of leakage, early intervention on leaking assets and pre-emptive interventions on assets with a high likelihood of developing similar leaks. This likelihood is influenced by factors such as operating environment (indoor/outdoor), design type/family and age.

Going forward, we intend to develop a monetised risk process for prioritising interventions on gas insulated switchgear (GIS) assets in line with the NARM Framework. This will involve developing a scoring methodology which incorporates condition and performance information, including condition monitoring and leak forecasting, to understand the probability of failure (PoF) and consequence of failure (CoF) which will feed into a risk model that will help determine which interventions are to be undertaken on the assets. We anticipate that the monetised risk will most likely be monitored at a bay/site level rather than an individual asset level within the GIS system due to the integrated nature of the assets.

Because interventions upon closely-integrated assets such as GIS have to be considered in the context of the actual and forecast performance of the associated assets, discrete asset interventions may be disproportionately costly or disruptive, so strategic interventions at the bay or site level must be considered. For example, if the outdoor GIS flanges of a particular asset design start to exhibit leakage and our forecasting predicts further evolution of leaks (number and magnitude) we would target the optimum cost-efficient intervention to mitigate existing emissions and prevent the development of further emissions for the remaining life of the installation.

Whilst our forecasting does not presently account directly for equipment design family type since this information is lacking from within our Ellipse asset register, for GIS there is a close to one-to-one correlation between design type and site geographical location such that we can assess correlations which may exist by design family. Improvements are being made to Ellipse to improve this situation which will, in turn, improve the specificity of our forecasting.

In the RIIO-2 period and beyond, we will continue to gather relevant data and use it to identify developing trends in emissions performance that will allow us to take pre-emptive action to prevent most potential leaks developing into real emissions. For example, if our data indicated that a small percentage of a particular asset type, under particular environmental stresses, had developed significant leakage after 20 years in service, we would look to develop a cost-effective intervention both to repair those assets and to prevent all similar assets degrading to the same state in the same way. Our aim is to maximise the emission-free performance of our assets over the long term at minimum equivalent annual cost. This means that low cost, preventative/palliative measures will be equally as critical as large-scale reactive interventions. As can be seen in the following section, environmental corrosion is a key factor in SF_6 leakage. By taking actions to prevent the ingress of moisture and pollution the onset of such leakage can be deferred or prevented.

To date, we have taken a largely granular, reactive approach to how we use this data, i.e. we have targeted leaks for intervention on an individual asset basis as-and-when they occur. If we are to deliver the step-change that we need to migrate from a reactive to a proactive emission abatement approach, making best use of all available intervention techniques: prevention, repair, refurbishment and replacement. Due in large part to the installation profile, shown in Figure 3, a concerted programme of intervention in the RIIO-2 period and beyond is essential if we are to deliver our environmental commitments.

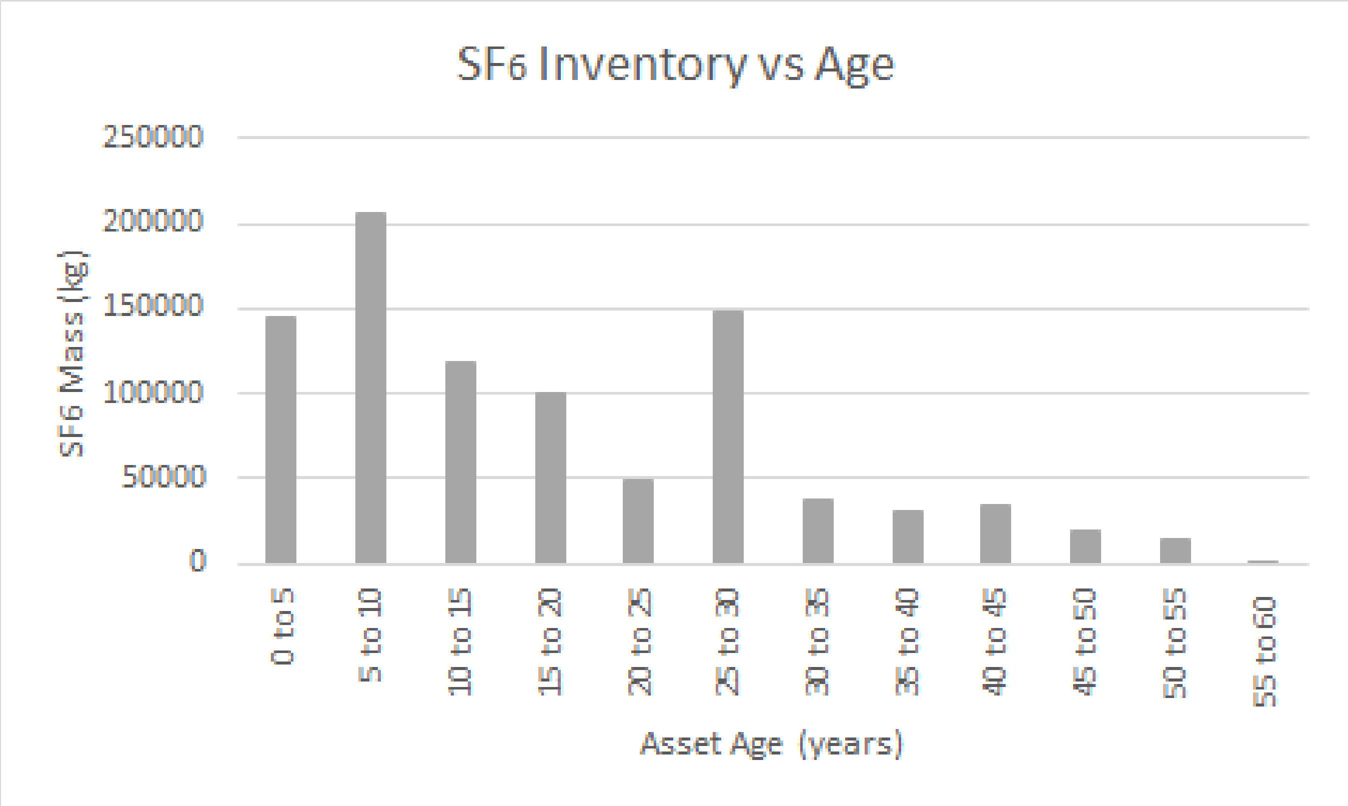


Figure 3 – SF_6 inventory by age

Figure 4 below normalises emissions with respect to inventory and shows the strong correlation between age and emission rate where emission rate is given by the volume of leakage per volume of inventory in five-year age groupings. The falling trend beyond 50 years results from "survivor bias" (i.e. the tendency for only the best performing assets to have survived) and the fact that the most leaking assets have already been replaced.

These graphs taken together show indicators such as a significant SF_6 inventory in younger assets (<25 years) with low leak rates presenting the potential for the application of preventive palliative coatings and a large inventory of 25+ year assets with potential for high leakage.

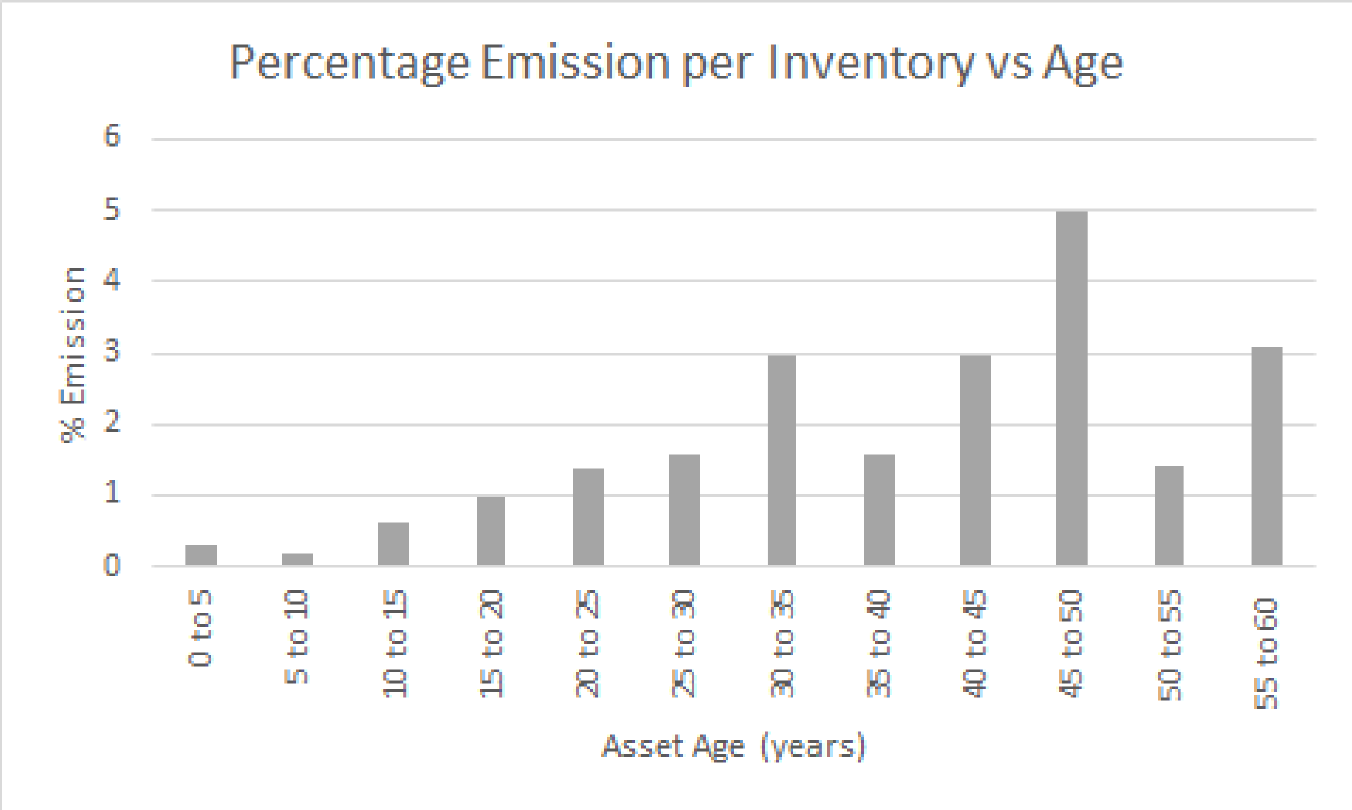


Figure 4 – Percentage emissions by age

We have used our granular, per-asset/per-functional position SF_6 leakage data to categorise assets requiring intervention. We have identified several relevant categorisations related to age, operating environment and design/installed location.

On this basis, we have identified 18 major GIS sites with excessive leakage affecting a significant number of individual assets that require strategic interventions in RIIO-2 if we are to achieve our abatement targets. These sites and a summary of key SF_6 emission related metrics are detailed in Table 1:

Table 1 – Summarised emission performance of selected sites

Site	Inventory (kg)	Indoor Inventory (kg)	Outdoor Inventory (kg)	Transitional Inventory (kg)	T1 average leakage (kg)	T1 Leakage (%)	2019/20 Leakage (kg)	2019/20 Leakage (%)	T1 Average of Funct'l Pos'ns Leaking >1% (%)	Indicative Age (Years)	Asset Design Family
BARK4	22310	10295	6404	5611	143	1	323	1	8	26	T155/1
DINO4	10622	10622	0	0	144	1	68	1	33	39	YG1
EASO4	7165	0	7165	0	106	1	109	2	28	27	YG2
EGGB4	833	683	72	78	77	9	208	25	25 (GIS=100)	27	YG2
HARK4	16365	15513	852	0	343	2	677	4	28	27	YG2
LACK4	17406				332	2	860	5	16	25	T155/1
LACK4 (I)		10570			85	1	130	1	10	25	T155/1
LACK4 (O/B)			3341	3495	247	4	730	11	31	25	T155/1
LITT4	24868	0	24868	0	1067	4	1173	5	67	40	YG1
NEEP2	8086	0	8086	0	667	8	738	9	68	46	YG1
NFLE4	17582	14495	3087	0	213	1	238	1	16	19	YG3
NORT4	25612	13687	11925	0	476	2	369	1	24	26	T155/1
OSBA4	4731	0	4731	0	98	2	350	7	50	16	T155/1
RASS4	5834	0	5834	0	266	5	103	2	10	26	T155/1
SEAB4	8833	5483	462	2888	290	3	589	7	13	23	T155/1
SELL4 (excl SELL4B)	26267	19588	5668	1011	734	3	946	4	22	34	GMS41
SIZE4	22213	19432	2781	0	471	2	609	3	39	28	YG2
STSB4	2445	0	2445	0	204	8	485	20	69	15	YG2
WHAM4	27640	20910	6730	0	126	0	214	1	13	28	GMS41
WIMB2	852	780	72	0	156	18	23	3	53	31	YG1

The table above demonstrates the poor emission performance of the targeted sites in terms of absolute leakage rates, percentage leakage rates and percentages of assets leaking excessively. For sites with both indoor and outdoor assets we can also distinguish the relative performance, and intervention driver for these asset subsets; Lackenby 400kV is provided as an example within the Table. This forecasting data-set pre-dates the preparation of the detailed site-specific annexes associated with this AGS and has been found to contain a small number of inaccuracies, particularly with regard to indoor/outdoor classifications which have previously not been used within our Ellipse system. The inaccuracies are highlighted in the relevant annexes and the investment proposals have been developed based on the correct categorisation. These inaccuracies have no material impact upon our network level forecasting conclusions and corrections will be incorporated in Ellipse and all future iterations of our forecast.

Also clear from Table 1 is the linkage between leakage performance and asset design type where three asset families dominate excessive historic leak performance; T155/1, YG and GMS41. Information of this type will inform our future asset heath assessments, forecasting and intervention planning.

The contrasting indoor and outdoor performance at these specific sites aligns with the broader, network-wide performance comparison shown in the following Figure 5.

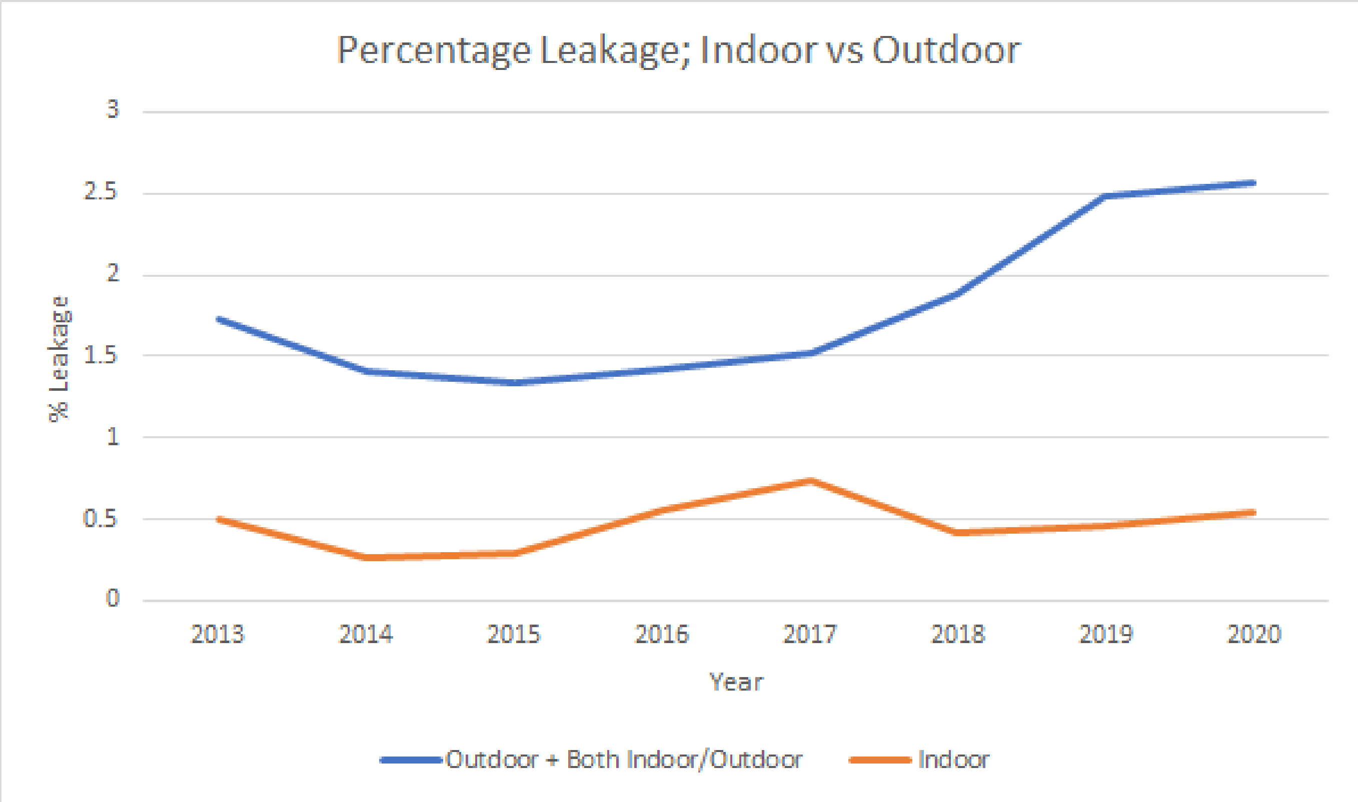


Figure 5 – Comparison of indoor vs outdoor leakage rates

Whilst only a proportion of the relevant assets at each site are presently leaking, we predict that similar, non-leaking assets of the same design types at the same sites will develop similar leaks within the short-term. As such we are targeting these sites for focussed, defined, strategic interventions upon both leaking & non-leaking assets. Further details are presented in site-specific annexes to this document.

These are not the only sites that are exhibiting unacceptable leak rates from several assets, potentially requiring strategic intervention in RIIO-2. A summary of the site level situation is shown in Table 2 below with the 18 target sites highlighted in the list which is ranked by RIIO-1 average leakage. Analysed at this level 146 NGET sites exhibit leakage more than 0.5% per annum. The optimum investments to mitigate excessive leakage at these sites requires site and/or asset specific scheme development which we have not yet had the capacity to develop in detail. We expect to plan and deliver interventions on a proportion of these sites. For AIS sites these interventions will deploy similar techniques and at similar unit cost to those applied for NLR. For GIS sites these interventions will deploy similar techniques and at similar unit cost to those for the defined list of 18 sites. The selection of these sites will be prioritised based on leakage performance (actual and forecast) and contribution to achieving the SBT.

Table 2 – Sites with excessive SF_6 emissions ranked by RIIO-1 average emissions; extract of full list for indicative purposes

Site Code	Inventory (kg)	T1 average emissions (kg)	Percentage Leakage
LITT4	24868	1067	4.3
SELL4	31510	708	2.2
NEEP2	8086	621	7.7
NORT4	25612	506	2.0
SIZE4	22213	502	2.3
LACK4	17406	343	2.0
PENT4	3840	248	6.4
SEAB4	8833	245	2.8
HARK4	16365	263	1.6
RASS4	5834	255	4.4
STSB4	2445	228	9.3
WIMB2	852	193	22.7
GRAI4	31339	176	0.6
NFLE4	17582	192	1.1
DINO4	10622	136	1.3
KEMS4	18990	145	0.8
HEYS4	6663	132	2.0
EASO4	7165	109	1.5
PEWO4	3873	88	2.3
DRAX4	6355	68	1.1
GREN4	2701	105	3.9
OSBA4	4731	84	1.8
HAMH4	5093	31	0.6
DAIN4	792	62	7.8
RYEH4	4908	72	1.5
THOM4	2830	75	2.6
LAGA4	7770	62	0.8
NHYD6	36	11	31.0
EGGB4	833	65	7.8
WBOL2	731	10	1.4
BEDD2	1211	37	3.0
CANT4	6724	45	0.7
RASS1	114	53	46.3
HURS2	621	43	6.9
HARK2	418	49	11.8
COWL4	1463	43	2.9
MONF2	3111	48	1.5
AXMI4	684	22	3.2
IVER2	576	40	6.9
DRAK4	2493	78	3.1
NINF4	1239	49	3.9
BRWA1	109	33	30.3
WASF2	48	47	96.9
PELH4	1514	35	2.3
CARR2	544	38	6.9
WYMO4	2170	22	1.0
KIBY2	1140	24	2.1
SKLG2	323	25	7.8
BARK2	2152	24	1.1
WALP4	1492	26	1.7
BRLE4	4699	29	0.6
CHIC1	72	24	33.2
HAWP2	859	20	2.3
WWEY2	419	22	5.3

We can also categorise GIS assets that presently show no significant or excessive leakage which are candidates for pre-emptive intervention to defer or prevent the onset of unacceptable leakage levels. Based on our observations that corrosion of outdoor GIS assets is the critical contributor to excessive leakage and that the onset of significant leakage occurs/becomes critical after 15-20 years in service we have identified a portfolio of assets to which we intend to apply preventive, palliative coatings.

Regarding the application of palliative coatings, corrosion due to the ingress of moisture and pollution is the primary factor in the development of SF_6 leaks particularly for outdoor assets (see Section 3.2). Early applications of palliative coatings within NGET and experience gained from other industries indicates that timely application of additional protective coatings can prevent or defer the onset of significant leakage by the service life of the specific coating applied; typically in excess of 10 years. These coatings can be re-applied during the life of the asset. Considering the relationship between asset age and excessive emissions, application of such coatings within the first 20 years of an asset's life is required to gain maximum benefit. As shown previously we have a large inventory of "early-life" SF_6 -filled assets that will benefit from this intervention approach.

We also have comprehensive leakage data for discrete non-GIS assets which is already used within the NARM framework to prioritise interventions that mitigate gross leakage. Where early (pre-NARM) interventions upon discrete assets or families of assets are demonstrated to contribute to achieving our SBT cost-efficiently we will prioritise these under the flexible part of this proposal.

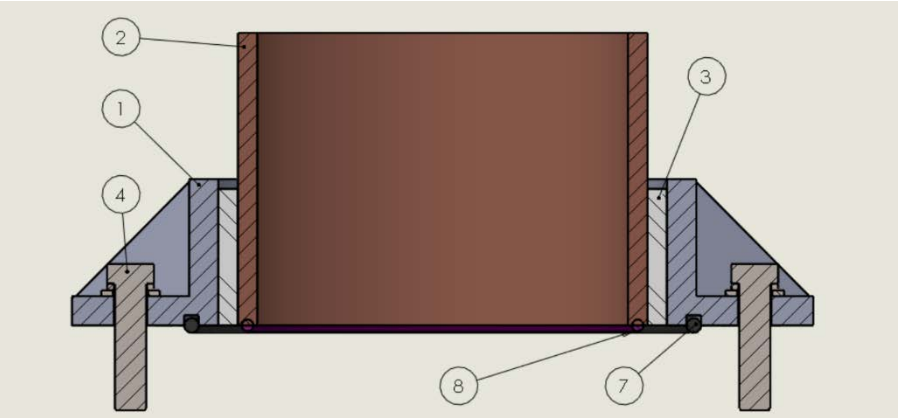
Considering the flexible element, we have comprehensive, per asset leakage data for all of our SF_6 -filled assets however our per-asset forecasting capability is not yet mature. As an indication of scale, circa 880 SF_6-filled functional positions within Ellipse (of a total of circa 7450) have actual leakage rates greater than 1% per annum. The proposed GIS interventions defined in Table 1 account for only a small part of this number. Without a programme of intervention, we would expect this number to increase. We will use our actual leakage data and forecast to maintain and deliver a list of target interventions required to deliver our 2026 and intermediate year-on-year targets. These interventions will be dominated by repairs and refurbishments, given the time and complexity involved in developing site-replacement interventions.

3.2. SF_6 Failure Mechanisms and Asset Condition

The failure mechanisms that lead to SF_6 emissions can be broadly categorised as being directly associated with the primary gas volume (e.g. GIS enclosure flanges, bursting disks) or with ancillary parts (e.g. SF_6 connecting pipework). When excessive leak rates are detected through top-up information, site surveys are used to identify the specific location of the leak and inform the choice of the most appropriate intervention.

The corrosion of outdoor sealing arrangements is the dominant factor in SF_6 emissions, with the deterioration of flanges being the precursor to leaks. There are two elements for this failure mode: metal to metal flanges and porcelain to metal flanges. Due to the presence of cement as a bonding agent within porcelain assets, these tend to deteriorate more quickly than the metal-to-metal flanges.

A cross sectional drawing of a simplified version of this joint is shown below:



ITEM NO.	PART NUMBER	QTY.
1	Metal flange	1
2	Porcelain section base	1
3	Cement Joint	1
4	BS EN 28765 - M16x1.5 x 65 x 38-N	12
5	Black washer BS 4320 - M16 (Form E)	12
6	Square section spring washer BS 4464 - 16 (Type A)	12
7	Outer O-Ring	1
8	Inner O-Ring	1

Figure 6 – Cross section of bushing flange assembly

The SF_6 containment failures occur when rainwater enters the top of the cement joint (item 3 above) and permeates down through the joint to the bottom, in between the two O-Rings and between the porcelain section and the joining plate (not shown in the diagram). As the water runs through the cement joint, it picks up some of the water-soluble salts within the cement mixture. This forms an alkaline solution that will then form a reaction with the aluminium plates it is mounted to. A similar reaction occurs within steel components.

This reaction creates aluminium salts, which are white powdery substances that will defeat the sealing elements of the asset as they sit over the O-Rings. The pressure differential between the interior of the asset and atmosphere then exploits the weak point within the joint and the leak occurs. In doing so, it is possible for the flow path of gas to dislodge the aluminium particulate leading to secondary leaks. The SF_6 gas will then take the path of least resistance to atmosphere – this could be back through the cement joint or out over the outer O-Ring if it has been compromised – either through corrosion, compression set or other mechanisms.

The photos below are taken from some of our assets showing this issue. These are a mixture of AIS & GIS assets.

The photos below show an AIS Gas Circuit Breaker (GCB) – Type FG1 – installed at Washway Farm (CB180). This was the sole leak site on the GCB, and the asset leaked 217.16 kg in 2018/19 prior to being repaired. The asset is now not leaking. The photo on the right demonstrates the low level of corrosion that can lead to SF_6 leaks.

Figure 7 – Photos of leaking FG1 circuit-breaker

The photo below shows the same type of deterioration, this time on an LTB145 AIS GCB. This contamination is made more complicated by the addition of grease within the flanges.

Figure 8 – Photos of leaking LTB145 circuit-breaker

A final example shows corrosion on an FE type GCB.

Figure 9 – Photos of leaking FE circuit-breaker

This photo shows the location of the SF_6 leak after being sprayed with leak detection solution:

In terms of GIS assets with porcelain sections, the photos below show a T155/1 bushing that had exhibited SF_6 leakage. There is extensive corrosion on the key sealing areas. The asset was around 20 years old.

Figure 10 – Photos of leaking T155/1 bushing

The photos below indicate the condition of outdoor GIS assets.

Figure 11 – 19 year old YG3 design GIS at Northfleet East showing evidence of corrosion

Figure 12 – 31 year old 275kV SP1 at Wimbledon showing evidence of corrosion

These photos illustrate the nature and location of the corrosion that can be found on the SF_6 assets. The condition survey information for specified interventions is presented in greater detail in the relevant site Annexes.

3.3. Intervention Options

We have a range of possible interventions available to reduce SF_6 emissions namely: prevention, repair, refurbishment, replacement (full or partial). For the purpose of this paper, these interventions are defined as follows:

Prevention: Interventions applied to non-abnormally leaking assets in order to mitigate a future risk of leakage. This may include the application of external palliative coatings to outdoor components of gas insulated substations to prevent pollution ingress and environmental degradation of SF_6 seals. These are typically low cost, minimal outage interventions with an effective duration of the order of 10-15 years and the ability to be re-applied. The SF_6 gas remains installed in this option. This option is most effective when first applied to younger assets (up to 20 years old). Details of the specific assets targeted for this intervention approach are detailing in the relevant Annexe.

Examples of preventative coating can be seen in the images below:

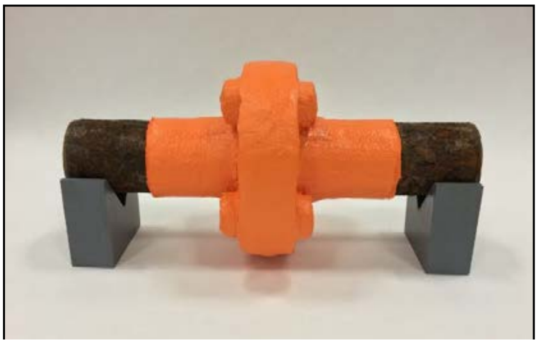


Figure 13 - Preventive coating from Belzona

Figure 14 - Preventive coating from Nashguard/Zerosion

Repair: Externally-applied encasement of leaking components such as collars or wraps provided by switchgear Original Equipment Manufacturers (OEMs) or third-party sealing specialists. Typically of medium cost and requiring limited outages, these have an effective duration of the order of 10 years. These could potentially be re-applied but are most likely to be applied in later life to manage equipment to its optimum condition-driven replacement window. The SF_6 remains installed in this option.

Refurbishment: Return of the critical SF_6 sealing components to "as-new" condition with an effective duration in-excess of 20 years. This activity includes physical dismantling of the equipment, cleaning & re-working damaged components and replacing seals and gaskets, etc. Costs are high and the work requires long outages. This activity may also include corrective activities on non-primary parts such as SF_6 pipework which is low cost but typically requires outages for de-gassing the equipment. The SF_6 gas normally remains installed in this option although SF_6 free options will be incorporated if/when they become commercially available.

Replacement: Substitution of the leaking equipment for new equivalent equipment. This may be individual components (e.g. gas to air bushings), partial (e.g. outdoor gas-insulated busbar sections) or full (e.g. replacement of an entire gas-insulated substation). Costs and outage durations are high. Partial replacement needs careful analysis of the equivalent annual cost of the full installation to avoid non-optimal investment. The ambition is that SF_6 gas would not be installed in this option to avoid perpetuation of the SF_6 inventory and the risk of future emissions, but this will be assessed on a case by case basis pending full commercial availability of SF_6-free alternatives for all applications.

We expect solutions for retro-filling of existing installations with non-SF_6 insulating gases to become available for some simple applications (e.g. gas-insulated busbar) within the RIIO-2 period however timelines are uncertain and we cannot, at present, commit to an adoption timescale. We are keen to implement such solutions and in section 3.5 below we propose a funding mechanism through which these solutions might be adopted as they become available. NGET has led innovation projects during RIIO-1 to facilitate the early adoption of such solutions.

Considering our SBT and the UK 2050 net-zero target we do not consider "do-nothing" as a credible long-term option for assets which have, or which are forecast to have, excessive leakage.

Identifying the optimum intervention on a case-by-case basis depends on factors such as: contribution to total emissions, present leak status, extent and likelihood of potential emissions, residual life of the assets (excluding SF_6 emission factors), cost of intervention, effective duration of intervention, deliverability, and technology availability.

The role of these factors in our decision making is described in more detail below:

Contribution to total emissions: We will prioritise interventions that maximise cost-effective emissions abatement, i.e. seek to deliver the most beneficial interventions first. It is important that we meet year-on-year targets (as determined by the SBT) as well as our long-term commitments. All planned interventions will be assessed and prioritised on this basis.

Current leak status: Assets with existing SF_6 emissions will be prioritised for early intervention since leak rates typically worsen over time. The condition and performance of these assets will be used to inform performance forecasts for similar assets.

Extent and likelihood of potential emissions: Based on asset condition data, particularly from assets which are leaking/have leaked, we will develop future emission scenarios based on relevant factors such as design, age, operating environment, and previous interventions. These scenarios will be used to target cost-effective pre-emptive interventions in order to mitigate future emissions

Residual life of the assets (excluding SF_6 emission factors) and cost of intervention: We will focus upon minimising equivalent annual cost in that any investment in emissions abatement applied to an asset is assessed in terms of the expected life of that intervention. For example, applying a costly refurbishment solution to a substation with only 5-10 years' residual life is unlikely to deliver value.

Conversely, the repeated application of short-term repairs may prove non-optimal for an installation with decades of residual life where a more enduring approach may provide better lifetime benefit. If the effective duration of the intervention (see below), is less than the residual life of the installation, future interventions to achieve the residual life of the installation will also be included in the assessment.

Effective duration of intervention: As mentioned above, the various intervention options have differing lifetime expectations. The use of equivalent annual costing takes due account of this factor as described above and mitigates against any bias towards low-cost, short-term solutions.

Deliverability: Timescales for planning and delivering refurbishment and replacement interventions are measured in years depending upon factors such as outage availability, physical site constraints, and delivery resource availability. Hence, delivery of our ideal (unconstrained) SF_6 emission reduction plan is not possible and, to meet emission abatement targets, we will be forced to advance or postpone investments. For assets with significant existing/developing leakage, this may mean applying short-term, low-cost repairs pending the opportunity to undertake more significant interventions.

Technology availability: Our intention is to avoid the installation of additional SF_6 where practicable. Thus, where we identify replacement as a preferred option for emission abatement, we will assess the benefit of timing the intervention to align with the availability of SF_6-free technology against the impact of any delay upon achieving our emissions targets. Where we can achieve targets and avoid the installation of additional SF_6, this will be our preferred option.

3.4. Abatement Forecasting & Target Setting

3.4.1. SF_6 Top-up Mass Forecasting

Using the detailed top-up data that we have accumulated during RIIO-1 we have developed forecasting techniques that allow us to better understand the need for asset interventions to both address and prevent leaks. The modelling approach and the associated assumptions and limitations are presented in detail in section 8. A key output of the model is a forecast of network-wide SF_6 emissions in the form shown in Figure 15. This forecast represents the hypothetical case where we cease all current efforts (refurbishment, replacement, repair) to mitigate leakage from SF_6 filled assets.

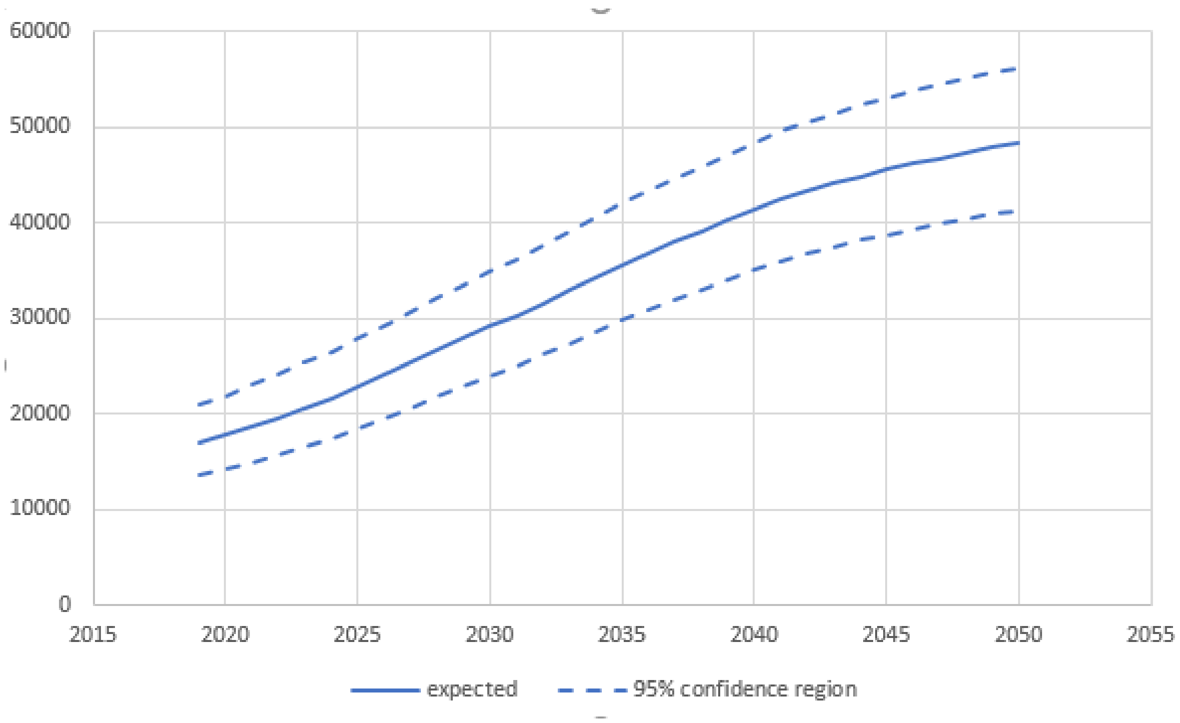


Figure 15 – Emissions forecast (kg) by year showing 95% confidence interval

Comparing this to our SBT provides a forecast of the total year-on-year emission abatement required from all sources; load, non-load and SF_6 PCD. This is shown in Figure 16 as the difference between the forecast (blue) and SBT (red) lines. By 2026 this difference is 15,717kg per annum. The embedded table of the Figure shows the forecast total mass of emissions of SF_6 in-excess of the target

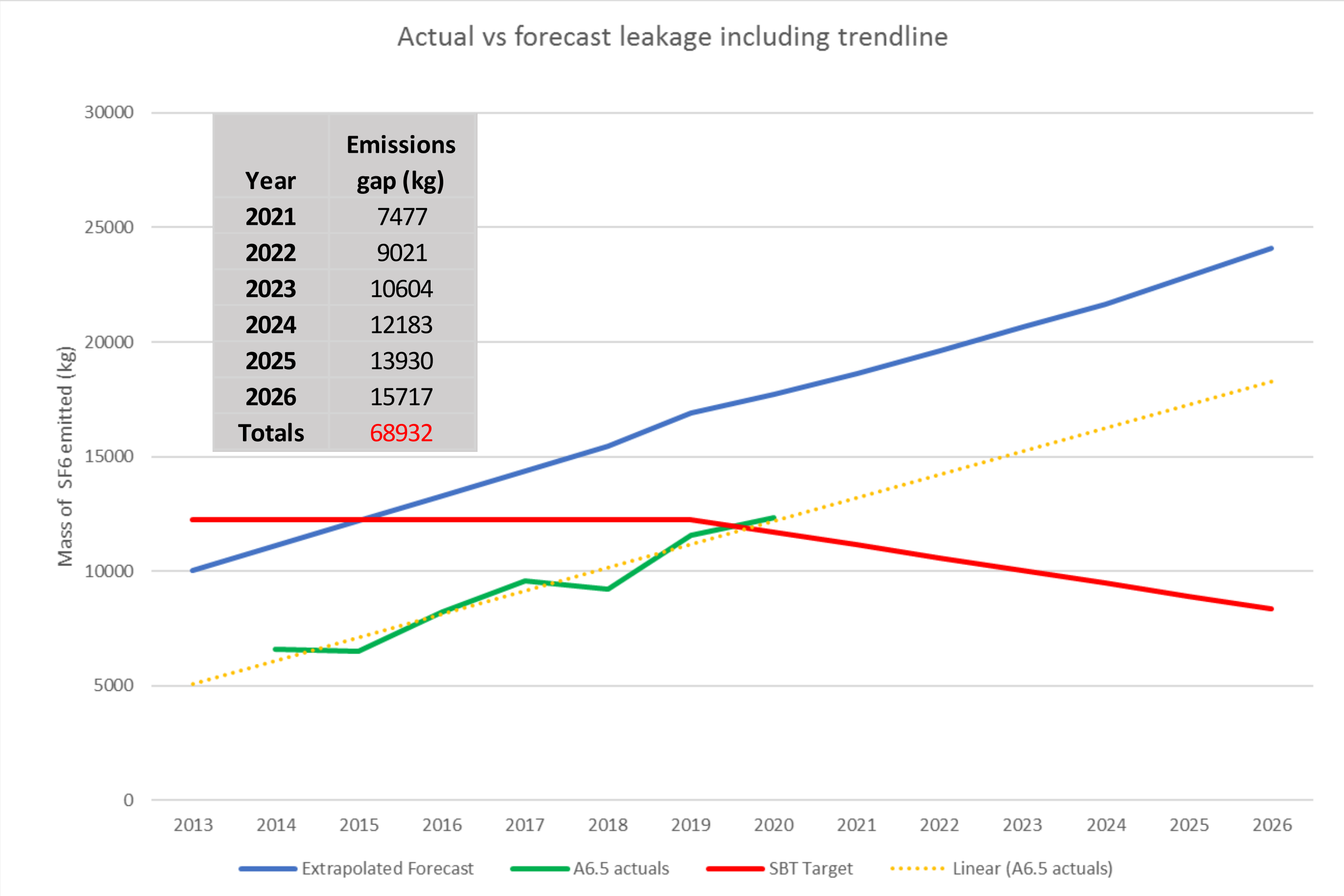


Figure 16 – Relationship between forecast, actual and target emissions

It is notable from the chart that the forecast rate of increase of leakage closely matches the same parameter over the period 2014-2020 (blue & green lines). This is linked to the modelling approach that we have adopted which does not cater for emission rate of assets progressively worsening as the continue to age beyond certain limits; represented by the black dotted lines on Figures 21a and 21b (section 8). We have very little data available to be able to incorporate such a predictive capability into our modelling since we do not allow assets to deteriorate without limit. In this respect we expect the forecast to underestimate the true rate of increase for the hypothetical case considered. However, as discussed below, we are confident that our present forecasting allows us to prioritise the optimum investments and, as such, the forecast vs actual magnitudes abated at asset level are of limited importance in this regard.

Also notable is a differential ("step change") between actual and forecast performance. An analysis of this step-change is presented as part of section 8.

As expected, our forecasting also supports the case for focussing our efforts in certain areas, such as outdoor assets, as shown in the following charts.

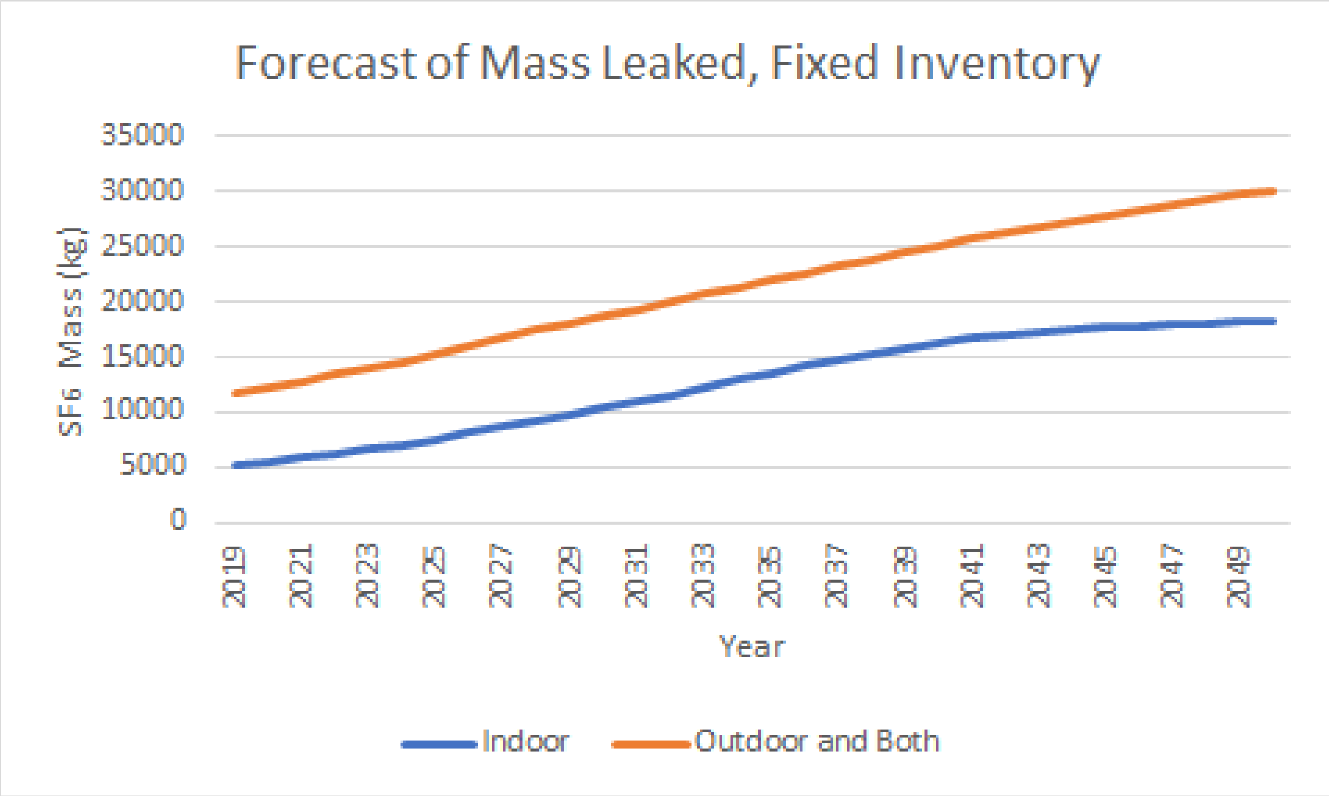


Figure 17 – Forecast leakage (kg); indoor vs outdoor

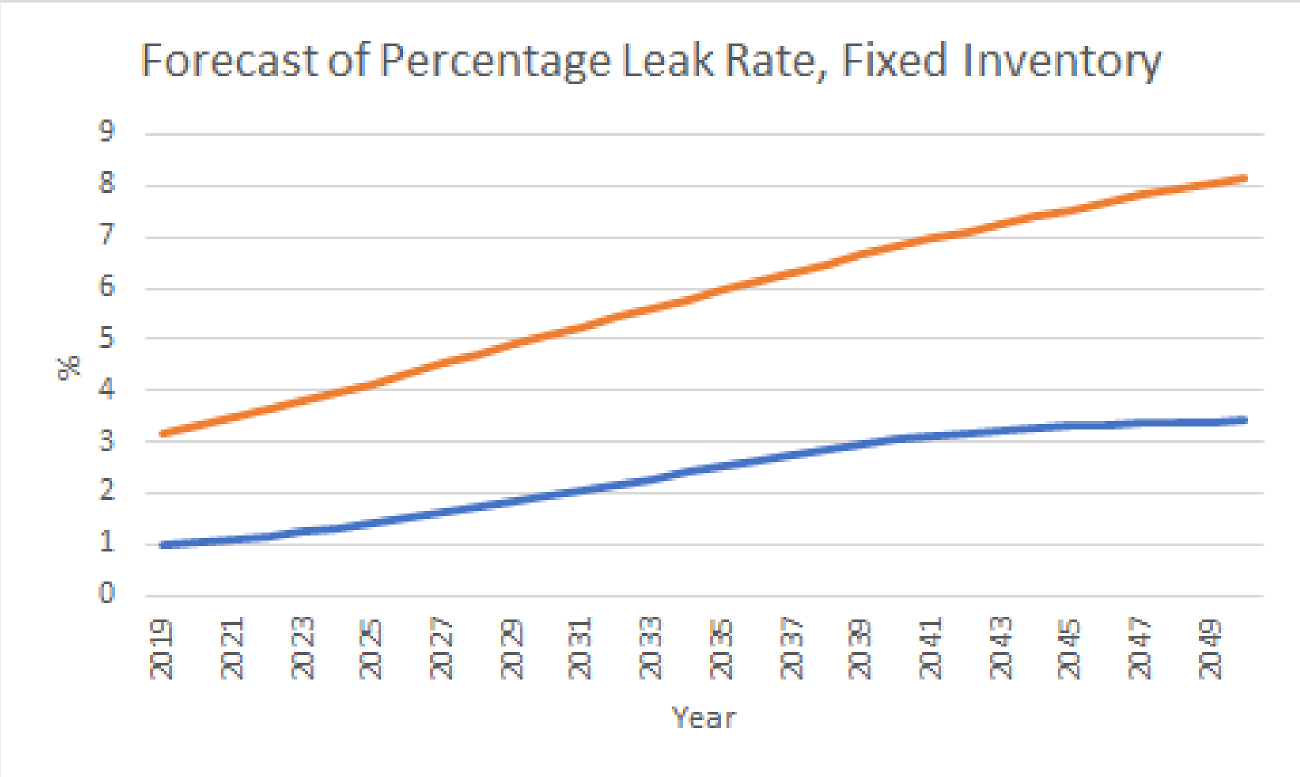


Figure 18 – Forecast leakage (%): indoor vs outdoor

It is important to note that our present forecasting tools focus on network level emissions. Individual assets are categorised primarily by age and location type (indoor/outdoor) and all assets within a category are treated equally within the model based on these factors. No account is taken within the forecast of the specific condition and performance of individual assets. Using this approach, we can identify categories of assets that exhibit network-level poor performance e.g. outdoor GIB greater than 25 years old (Figures 4 & 5). We can then refine our assessment using site performance and asset health information to identify the most beneficial interventions within these categories. Due to the network level approach of the forecasting there will typically be large discrepancies between forecast leakage at an asset level and actual leakage experienced by those assets; this is well understood since individual asset leakage is unpredictable. We are confident that forecasting in this way, in combination with our knowledge of the historic performance of individual assets, allows us to target the most beneficial interventions to achieve our abatements targets. In terms of SF_6 emissions the net position of abating more emissions associated with greater leakage than forecast is unchanged since our target is to return those assets to acceptable emission performance regardless of starting position. The main value of forecasting at a site level is that it establishes a common basis for efficient cost comparison across intervention types and locations. Assessment of the cost of forecast emissions abatement against forecast emissions allows us to establish and compare the value of individual investments in a consistent manner.

3.4.2. Abatement Target Setting and Intervention Prioritisation

Based on the asset health approach summarised above, this proposal can be considered in three parts:

- Strategic GIS interventions at defined sites
- Flexible interventions upon leaking/at-risk assets (GIS and AIS)
- Application of palliatives to prevent or defer future leakage

As stated above we identified 18 major GIS installations with excessive leakage affecting a significant number of individual assets which require interventions in RIIO-2, if we are to achieve our abatement targets. These are shown in Table 3 below, which also summarises the maximum potential contribution of each intervention to our SBT on an annual basis. This Table is indicative and does not account for the implementation date of specific interventions which is considered in the individual site Annexes.

Table 3 – Forecast maximum abatement potential of interventions at defined sites

Year	**20**	**21**	**22**	**23**	**24**	**25**	**26**							
Target emissions	11710	11059.5095	10409.019	9758.5285	9108.038	8457.5475	7807.057							
Forecast emissions	17730.34952	18629.8643	19615.71929	20641.59333	21663.09839	22852.1729	24081.4686							
Required abatement	6020.349515	7570.354795	9206.700285	10883.06483	12555.06039	14394.6254	16274.4116							
Year	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
Project	**Forecast Abatement**	**Forecast Abatement**	**Forecast Abatement**	**Forecast Abatement**	**Forecast Abatement**	**Forecast Abatement**	**Forecast Abatement**	**Residual Abatement Req'd**	**Residual Abatement Req'd**	**Residual Abatement Req'd**	**Residual Abatement Req'd**	**Residual Abatement Req'd**	**Residual Abatement Req'd**	**Residual Abatement Req'd**
No intervention	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**6020.349515**	**7570.354795**	**9206.700285**	**10883.06483**	**12555.06039**	**14394.6254**	**16274.4116**
LITT4	1614.015859	1624.549532	1631.219097	1633.053288	1643.091751	1653.264649	1662.88931	4406.333656	5945.805264	7575.481188	9250.011547	10911.96864	12741.3607	14611.52229
NEEP2	816.035492	813.4210678	806.8696918	814.7632884	813.2127928	806.2363974	811.861131	3590.298164	5132.384196	6768.611496	8435.248258	10098.75585	11935.1243	13799.66116
DINO4	272.3120587	264.8416477	271.6160847	273.4628365	268.6342458	275.547736	270.592365	3317.986106	4867.542548	6496.995411	8161.785422	9830.121601	11659.5766	13529.06879
SIZE4	519.1175106	531.9057994	539.0790491	556.5414725	569.8046933	585.4860837	600.830813	2798.868595	4335.636749	5957.916362	7605.243949	9260.316908	11074.0905	12928.23798
STSB4	72.6871219	75.70174802	80.34172777	83.46912089	86.89998921	92.97450387	96.2459616	2726.181473	4259.935001	5877.574634	7521.774829	9173.416918	10981.116	12831.99202
HARK4	258.1634229	269.4322186	283.8703499	297.2466906	311.4689938	327.6399586	343.26539	2468.01805	3990.502782	5593.704285	7224.528138	8861.947925	10653.4761	12488.72663
NORT4	309.4225866	315.3001118	326.3794781	332.3227107	345.7205274	358.3057427	368.477742	2158.595464	3675.20267	5267.324806	6892.205427	8516.227397	10295.1703	12120.24889
BARK4	283.971733	294.9480624	304.6347047	317.3375795	325.9911925	346.9810456	356.2701	1874.623731	3380.254608	4962.690102	6574.867848	8190.236205	9948.18928	11763.97879
LACK4	217.4427163	246.3143554	272.2957098	299.8826756	325.3749003	356.5847738	382.875016	1657.181014	3133.940253	4690.394392	6274.985172	7864.861304	9591.6045	11381.10377
RASS4	190.6667751	205.6728295	222.3663018	238.1261026	259.1139472	278.6188337	298.64691	1466.514239	2928.267423	4468.02809	6036.85907	7605.747357	9312.98567	11082.45686
SEAB4	106.0037768	120.43671	137.0010061	149.472728	153.0768583	161.4113564	168.913234	1360.510462	2807.830713	4331.027084	5887.386342	7452.670499	9151.57431	10913.54363
EASO4	231.1232832	247.6819355	266.930718	290.9544777	312.3973325	338.4258812	361.781779	1129.387179	2560.148778	4064.096366	5596.431864	7140.273166	8813.14843	10551.76185
WIMB2	49.30173549	49.71927813	51.59888216	50.50576967	51.77820444	52.31438924	51.7761657	1080.085444	2510.429499	4012.497484	5545.926094	7088.494962	8760.83404	10499.98568
SELL4 total	804.8973367	811.5710705	817.4402943	823.524359	819.7185943	830.6960334	834.576092	275.188107	1698.858429	3195.05719	4722.401735	6268.776368	7930.13801	9665.409591
OSBA4	43.21249813	49.42346262	55.7601465	57.04967279	62.23952287	68.10284008	75.6693926	231.9756088	1649.434966	3139.297043	4665.352062	6206.536845	7862.03517	9589.740198
NFLE4	179.6116127	202.6850592	234.3005709	266.6015084	301.169026	342.162187	384.33961	52.36399607	1446.749907	2904.996472	4398.750554	5905.367819	7519.87298	9205.400588
WHAM4	492.8607688	518.042237	547.2662907	574.7165216	603.2265774	636.0877613	664.888681	-440.4967727	928.7076701	2357.730182	3824.034033	5302.141241	6883.78522	8540.511908
EGGB4	24.13103649	25.22321602	27.79082529	28.03622169	30.4827823	32.94738822	34.1210064	-464.6278092	903.4844541	2329.939356	3795.997811	5271.658459	6850.83783	8506.390901
Other CBs	617.6022831	640.2716844	667.6525554	691.8384068	708.8314618	726.6593092	751.317493	-1082.230092	263.2127697	1662.286801	3104.159404	4562.826997	6124.17853	7755.073409
ITs	474.6040985	476.1226077	480.6116848	484.982462	486.7154168	488.3927103	489.385309	-1556.834191	-212.9098381	1181.675116	2619.176942	4076.111581	5635.78581	7265.6881

Further details of individual investment proposals, optioneering and funding arrangements for each of these can be found in the attached site Annexes.

The balance of the required abatement to deliver the SBT will be delivered by intervention on a range of AIS & GIS assets.

3.5. Inventory Reduction and Retro-filling Options

The primary focus of this proposal is upon leak repair, leak prevention and modifications to asset "hardware" that can facilitate conversion to SF_6-free solutions. Long term endeavours to abate SF_6 emissions to zero must also include specific actions addressing inventory reduction. Figure 19 indicates the SF_6 inventory challenge out to 2050. Assuming an ambition to eliminate SF_6 emissions from our network by this date, and recognising that all transmission level SF_6 equipment has a measurable leak rate in the 0.1% to 1% range, the optimum environmental solution is to eliminate our SF_6 inventory by 2050.

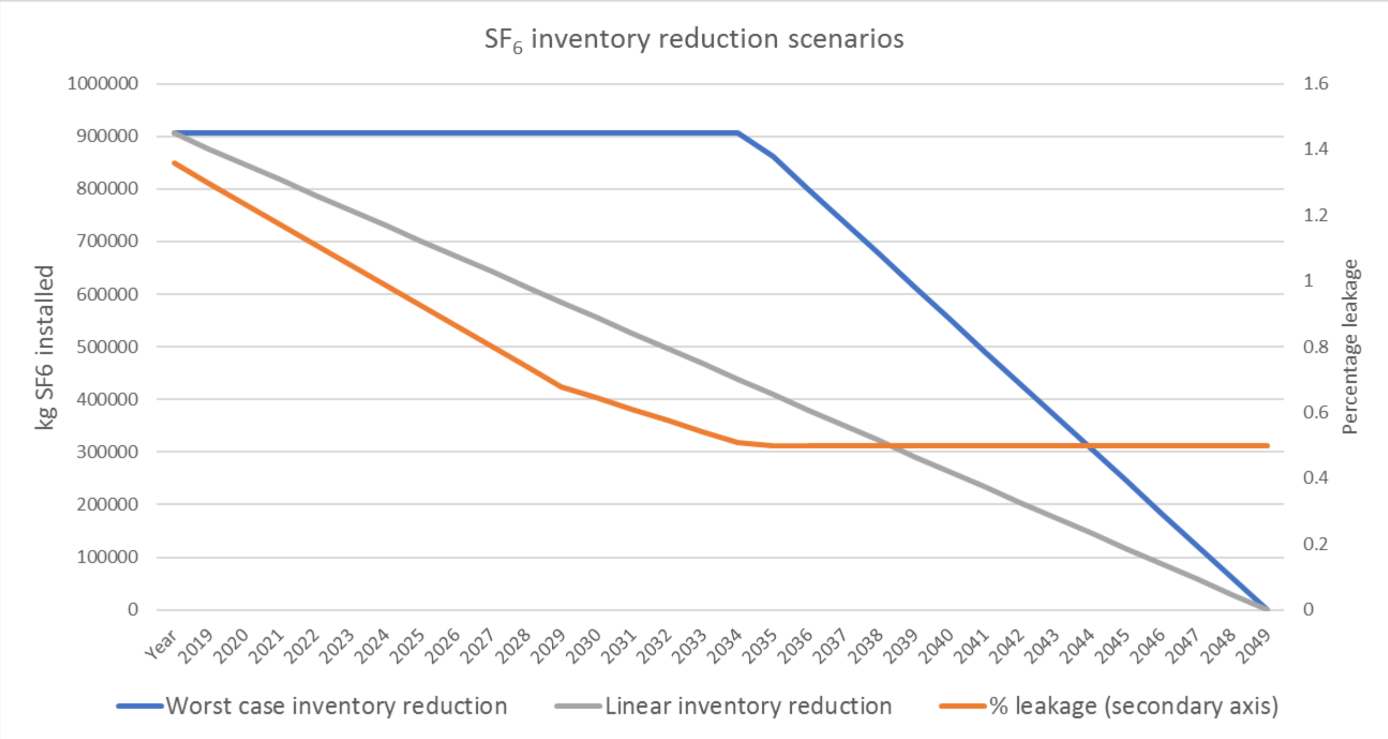


Figure 19 – SF_6 inventory reduction scenarios towards net-zero (2050)

Based on a linear trajectory from today this equates to the net removal of ~30 tonnes of SF_6 inventory per year (grey line of Figure 19). With no specific actions to remove inventory and a focus solely upon emissions reduction in accordance with SBT through leak repair and prevention there is a "designed-in" limit to the emission reduction that can be achieved. With reference to Figure 19, assuming a minimum achievable fleet-wide leak rate of 0.5% (orange line of Figure 19) and no significant reduction in inventory until this level is reached, inventory reduction becomes the only major influence upon emissions from 2036 onwards (blue line of Figure 19). Under this scenario the annual inventory reduction target is approximately doubled to ~60 tonnes per annum. Neither of these scenarios represent an accurate forecast of future developments however it is clear from both that greater early focus upon inventory reduction is essential.

A source of inventory reduction that we expect to become commercially available within the RIIO-2 period is the retro-filling of simple GIS components (e.g. gas insulated busbar sections) with SF_6-free alternatives. We propose that there should be a funding mechanism for adoption of this technology based on the NTCC and the differential between the GWP values of SF_6 and of the alternative. This funding would be based on the following formula for the **allowed investment per kg of replacement of SF_6 inventory**:

$$(NTCC/1000) \times (GWP_{SF6} - GWP_{Alternative}) \times (\text{leak rate}) \times (\text{effective duration of substitution})$$

Assuming:

- NTCC (2024 reference) = £74/CO_2
- GWP_{SF6} = 23500
- $GWP_{Alternative}$ = 500
- Leak rate = 0.01 (1%)
- Effective duration = 20 years

this formula returns a value of [redacted]/kg of SF_6 substituted.

Small leakage rates cannot be assessed effectively or accurately through top-up monitoring due to the very long periods expected between top ups. However, these are the assets which are targeted by this proposed mechanism. As such, we propose to fix the value of leakage rate within this mechanism at 0.01 (1% per annum) for all assets with no significant indication of excessive leakage.

The essential incorporation of the leak rate within this formula could lead to the situation where retro-filling of already severely leaking assets appears justified. Whilst this may occasionally be the case it would not be our intention to adopt this approach in anything but extreme circumstances. The main intended use of this mechanism is to address the long-term necessity to address equipment with stable low levels of leakage which nevertheless make an important contribution to our overall emission performance.

4. Scheme Development Status

Scope of Development Stage Scope and Associated Assumptions

Each stage involves a process that is controlled via Gates A-E, which manage the movement and, as such, the maturity of investment schemes within the development framework. Figure 4.1 shows the timescale, or runway, for the movement of investment schemes through the framework. Each scheme's runway is dependent its ability to transition through control gates based on the maturity of the assumptions that have been made. The need and driver for each scheme is checked at each control gate to ensure the scheme is still needed and continues to provide the benefit our stakeholders have requested.

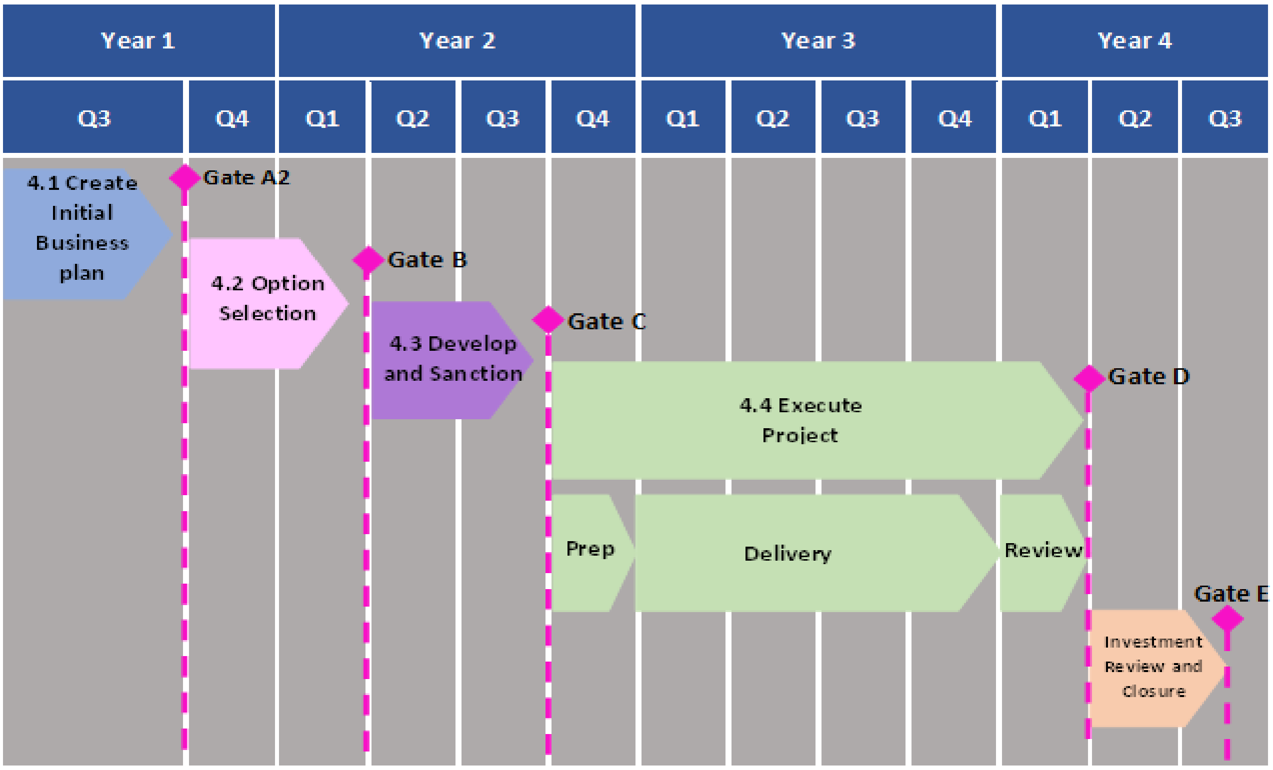


Figure 20 - Runway Visualisation

Stage 4.1 – Establish Portfolio

The aim of this stage is to establish a portfolio of investments with associated SF_6 Leakage drivers and to identify provisional costs and milestones. An initial business plan entry is created, which records the driver for investment and any other associated regulatory outputs. The focus of this stage is to identify any high-level changes needed to candidate schemes. An assessment is undertaken of different solutions taking consideration of interactions with other investments in the plan (e.g. NOA, Customer, Non-Load) and system access availability. The assets detailed within this proposal shall only support interventions against SF_6 leaking assets which are not already bundled as part of existing Site schemes or submitted network reliability investments are excluded.

Once the portfolio of assets has been identified, we undertake further analysis to identify any high-level changes needed to candidate schemes. We assess different solutions taking consideration of interactions with other investments in the plan (e.g. NOA, Customer, Non-Load) as well as system access availability. At stage 4.1, intervention options and the associated costs and life impact are applied at a general family level to ensure that the selected intervention achieves the desired Monetised Risk Reduction.

The following assumptions are made during Stage 4.1:

- Cost estimates are based on historic normalised outturn data;
- Stock from our framework suppliers and storage facilities is available to meet our investment plan;
- Supplier unit costs have not changed significantly from our cost estimates;
- Supplier unit costs have not changed significantly from the data used for our cost estimates; and
- System access is available to deliver in the planned year;[1]

The initial business plan entries are reviewed each year to account for any changes associated with the monetised risk driver (e.g. the latest policies or asset condition reviews that may result in changes to EOL modifiers), as well as any other developments that could change the preferred solution as the scheme matures through the development framework.

Stage 4.2 – Select Option

At this stage, the SF_6 drivers for the schemes are reviewed and confirmed, along with the initially proposed solutions, before optioneering work is undertaken to provide greater certainty of scope, programme, forecast cost and risks associated with a full set of options. Condition and Leakage Surveys will further refine decision making for individual and grouped assets at substations to ensure appropriate interventions are selected

As part of this analysis, we also account for any recent intervention history:

- Where interventions on asset families have already occurred in RIIO T1 and the available intervention options are understood, optioneering will be influenced by the lessons learnt from these schemes.
- Where asset families have not received interventions within the RIIO T1 Period, forecasting of costs where possible shall be based on generic intervention solutions which are applicable to equivalent families of assets.

During this stage we also confirm the required outage durations, opportunities to group or bundle assets from multiple investments and projects into single outages, system access availability and any third-party interactions.

The initial business plan entry has identified the preferred option through cost benefit analysis (on an NPV basis). This analysis incorporates non-capital cost for lifetime costs, which for Circuit Breaker schemes include cost associated with maintenance cycles and SF_6 leakage. The impact of associated systems such as air systems are not accounted for, unless the investment decision impacts all assets utilising that system onsite.

Stage 4.3 – Develop & Sanction Scope

This stage seeks to confirm commitment to the preferred option, refine the design to identify efficiencies and address outstanding risks and opportunities, and provide baseline scope, outputs, programme and forecast costs for future tracking. At this stage for SF_6 abatement schemes, we start to complete Site Visit Reports and update SF_6 Leakage Surveys if required. Contracting is dependent upon intervention option selected and will be aligned prior to handover to delivery.

To ensure delivery of SF_6 remediation is completed efficiently in terms of both spend and abatement, the SF_6 working group is responsible for monitoring the Current and Planned delivery of interventions to ensure that allocated targets are met. To prevent breaches in these targets, the working group will assess assets in later periods to understand if there are opportunities to bring forward work, thereby balancing the delivery of the portfolio.

The assumptions made during this stage of the development framework are:

[1] We use our in-house power system analysts to determine system accessibility and manage information flow between TO and SO.

- Booked outages will remain viable with both access and resource confirmed; and
- Where relevant, Customers have been notified of relevant works and no objections raised.

Finally, we reconfirm the validity of the SF_6 driver and refine our financial analysis before proceeding with the investment.

Stage 4.4 & 4.5 – Delivery Scope and Investment Closure

This stage encompasses delivery of the intervention, including physical works on site as well as the commissioning of the asset and completion of asset data drawings. When the physical works have been completed, we report on the delivery of the regulatory outputs identified in the initial business plan.

The assumptions made during this stage of the development framework are:

- Unforeseen events not captured on the risk register (with allocated contingency) do not occur;
- The Delivery Body performs as expected.

Following delivery, we complete financial closure and notify the system operator of scheme completion as well as providing relevant technical performance details.

5. The Investment Plan

5.1. Costing Approach & Uncertainties

Costing of work with an established technical scope and prior delivery experience (e.g. substation and asset replacements) has been quoted in accordance with the NGET cost-book. Activities such as targeted refurbishment of outdoor GIB, partial replacement of outdoor GIB and encapsulation based repairs are relatively new solutions for which we have limited or no established benchmarks for delivered cost. The costs on which these solutions have been developed are derived from supplier quotations and early applications.

- Encapsulation based repairs which are deployed selectively to address existing leaks for up to 10 years are costed on a per-flange basis with repair of a three-phase set of flanges costing [redacted].

- Bushing replacements are costed at [redacted] per three phase set.

- Refurbishment of GIB involves strip-down and re-sealing of leaking and potentially leaking gas sealing points, particularly enclosure sealing flanges. The cost of this intervention type varies considerably depending upon the scale of the intervention. Refurbishment of a single three-phase set of flanges may cost up to [redacted]. However, the same scope, as part of a multi-asset refurbishment programme at a single site has been quoted in the range of [redacted]. Our optioneering costs have been based on this lower value however uncertainty remains regarding the delivered costs.

- Whilst partial replacement of outdoor GIB separately from the main substation is not an established practice, costs have been derived based on NGET cost-book data per length of GIB. A cost of [redacted] per metre of three phase GIB has been used.

Where the opportunity exists to convert to an SF_6 free solution as part of refurbishment or replacement activities we expect there to be a small percentage premium over the equivalent like-for-like SF_6 activities. We propose that any cost premium associated with this aspect can be addressed by the mechanism described in 3.5 above.

5.2. Defined Projects

The 18 sites targeted for specific interventions have been assessed against the principles and criteria laid out above in section 3.3 of this document. This analysis is presented in detail in site specific annexes; one for each of the 18 sites. The proposed interventions, costs, emission abatements and narrative summaries are brought together in Table 4.

The Table identifies funding requirements of [redacted] for defined interventions. The total abatement achieved from all sources included in the Table is 20930kg in the RIIO-2 period. This compares to a forecast required total abatement of 68932kg (Figure 16); a shortfall of 48002kg. On a per-site basis the target abatement is significantly less than the potential abatement values given in Table 3 above. These potential abatements assume abatement of all leakage whereas Table 4 reflects more realistic, deliverable and cost-efficient abatement at the same sites.

Table 4 – Summary of defined SF_6 abatement interventions

Site	Proposed Intervention	[redacted]	SF6 removed (kg)	SF6 added (kg)	Forecast total abatement in T2 (kg)	Forecast abatement to benefit end date (kg)	T2 investment benefit end date (max' 2050)	£/kg to benefit end date	Narrative Information
NEEP2	Do nothing pending imminent NLR	[redacted]	N/A	N/A	N/A	N/A	2022	0	Asset replacement will be completed early in T2. No interim measures proposed.
WIMB4	Do nothing pending imminent NLR	[redacted]	N/A	N/A	N/A	N/A	2026	0	Asset replacement will be completed early in T2. No interim measures proposed.
OBSA4	Outdoor GIB refurbishment	[redacted]	0	0	233	3073	2050	644	Simple installation consisting only of outdoor GIB & bushings
EASO4	Outdoor GIB refurbishment	[redacted]	0	0	315	2066	2040	1278	Refurbishment of outdoor sections of GIB to match anticipated life of indoor substation
EGGB4	Targeted replacement	[redacted]	78	0	42	348	2050	1293	Simple installation consisting only of through wall bushing GIS gas zones
SELL4	Targeted repair	[redacted]	0	0	4429	9350	2031	1311	Repair of leaking assets predicted to last for 10 years. Does not mitigate new & developing leakage, site leakage levels may still increase during T2
RASS4	Outdoor GIB refurbishment	[redacted]	0	0	526	3515	2044	1334	Refurbishment of outdoor sections of GIB to match anticipated life of indoor substation
WHAM4	Outdoor GIB refurbishment + indoor leaks	[redacted]	0	0	651	4049	2040	1531	Refurbishment of outdoor sections of GIB to match anticipated life of indoor substation
DINO4	Targetted repair pending planned replacement during T2	[redacted]	0	0	450	450	2026	2000	Short-term mitigation actions assuming completion of substation replacement as part of DINO-PENT cable reconfiguration in T2
NORT4	Outdoor GIB refurbishment	[redacted]	0	0	449	4954	2044	2321	Refurbishment of outdoor sections of GIB to match anticipated life of indoor substation.
NFLE4	Outdoor GIB refurbishment	[redacted]	0	0	389	2349	2040	2341	Refurbishment of outdoor sections of GIB to match anticipated life of indoor substation
LACK4	Outdoor GIB refurbishment	[redacted]	0	0	475	2566	2036	3001	Refurbishment of outdoor sections of GIB to match anticipated life of indoor substation
BARK4	Outdoor GIB refurbishment	[redacted]	0	0	422	3526	2044	4319	Refurbishment of outdoor sections of GIB to match anticipated life of indoor substation
SEAB4	Outdoor GIB refurbishment	[redacted]	0	0	194	1440	2046	4451	Refurbishment of outdoor sections of GIB to match anticipated life of indoor substation
HARK4	Whole site replacement	[redacted]	0	0*	0	10625	2050	5469	Substation replacement spans T2 & T3 at a total cost of £73.53m. In the event of LOTI applying to Harker this proposal would be revised to address interim repairs only
LITT4	Outdoor GIB refurbishment	[redacted]	0	0	1490	1490	2024	5611	Short term measures to mitigate extreme leakage in the short term pending full substation replacement
SIZE4	Targeted repair in T2.	[redacted]	0	0	1115	1651	2029	12253	T2 repairs pending replacement of substation in T3. Same T2 conclusion regardless of Sizewell C progress decision.
STSB4	Decommission site and relocate Quadrature Booster in advance of planned date of 2033	[redacted]	2445	0*	190	1009	2033	24519	High costs (£/kg). Potential to eliminate/reduce total SF6 inventory by advancing site decommissioning from 2033.
		[redacted]							
	Defined Intervention Totals	[redacted]			**11370**	**52461**		**3563**	
	Application of palliatives	[redacted]	0	0	2467	9972	2030	327	
	SF6 PCD Defined Totals	[redacted]			**13837**	**62433**		**3045.8**	
	Circuit-breaker Non-Load Interventions	[redacted]	0	0	4187				
	Instrument Transformer Non-Load Interventions	[redacted]	TBC	0	2906				
	Grand Totals	[redacted]			**20930**	**62433**			

0* assumes availability of SF_6-free solutions

Final reviews have identified a potential inconsistency of approach to the assessment of future abatement pertaining specifically to EASO4, NORT4 and EGGB4. Consequently, there are discrepancies between the abatements reported in the relevant site annexes and in the Table above. The values presented above are consistent with the approach adopted for other sites and the relevant Annexes will be reviewed as soon as possible to ensure proper alignment. These discrepancies have no influence on proposed scope and cost of the works and apply only to the method of application of the future forecast abatements.

5.3. Flexible Portfolio

As discussed previously in this document the specific interventions listed above are essential if we are to meet our challenging SBTs but are insufficient to achieve them. During RIIO-2 there will be need for us to identify and deliver further abatements within an agreed framework. We propose that this framework should cater for discrete asset replacements/refurbishments, targeted refurbishments of GIS assets, partial replacements of GIS assets and targeted repairs of the types described in this document. Due to the high degree of site specific variability we propose that the introduction of new whole-site replacements during RIIO-2 should be excluded from this framework.

With reference to the colour coding of Table 4 and using a reference NTCC of £74/tCO_2 ([redacted] per kg of SF_6) it can be clearly seen that delivery of our SBT within the constraints of the NTCC framework is not possible.

Green shading indicates costs justified purely based on NTCC.

Amber shading indicates costs which moderately exceed those justified by NTCC alone and pertain to mid-life strategic interventions such as GIB replacement.

Red shading indicates costs which significantly exceed those justified by NTCC which typically pertain to short-term mitigation of severe leakage pending asset replacements or substation replacement/decommissioning activities.

Green and Amber reflects works that we foresee being within the potential scope of the flexible element of this proposal. The Green and Amber shaded intervention achieve an abatement of 8575kg in RIIO-2 (37686kg in total in the longer term) at a cost of [redacted] Assuming a similar spread of interventions and costs would be required to achieve the forecast shortfall of 48002kg, additional funding of [redacted] would be required in RIIO-2. The average long term cost of these intervention based on the data in Table 4 is [redacted] per kg SF_6 abated based on 37686kg and [redacted].

We also foresee a need to intervene under this framework upon discrete assets such a circuit-breakers and instrument transformers in advance of asset health driven replacement. With reference to NARM this is potentially the case for assets with leakage rates of <5%; a value which exceeds the design value and our long-term emissions targets but which will not trigger an asset health intervention. A leakage rate more than the equipment design value but <5% is a clear indicator of asset deterioration which will worsen over time. If we are to achieve our long-term abatement targets all assets leaking in-excess of their design value should be candidates for intervention.

We propose a mechanism to fund intervention upon assets leaking more than their design leak rate but <5% which is based upon the NTCC and the predicted effective duration of the intervention as follows:

Max.allowance = NTCC value of SF_6 x effective duration of intervention x (0.05 x asset SF_6 inventory)

As an example a 400kV AIS circuit-breaker leaking 5% per annum (3.7kg per year based upon reference GE AIS circuit-breaker type GL316X gas holding of 74kg) with a residual life of 15 years would lead to an upper expenditure cap of:

[redacted] x15 x 0.05 x 74 = [redacted]

The actual expenditure on flexible element interventions in the RIIO-2 period will be optimised to achieve cost efficient delivery of our SBT within the framework of costs presented in this paper and relevant costs established more generally for non-load asset interventions. This expenditure will be influenced by the mix of interventions delivered, the evolution in actual (rather than forecast) leak performance in RIIO-2 and, in the longer term, the influence of palliative measures upon leakage rate growth.

5.4. Palliative Application

Full details of this proposal can be found in Annexe 11.09-7. We propose an investment of [redacted] for the application of pre-emptive, preventive coatings to a range of outdoor assets within the first 20 years of operational service which are not yet exhibiting excessive leakage. The benefits of this application span future price controls where forecast increases in leakage can be prevented or deferred. As presented in the relevant annexe, leakage growth of up to 9972kg of emitted SF_6 will be prevented for the period 2021 to 2030.

6. Summary and Conclusion

This document proposes funding required for us to meet our Science Based Target for SF_6 emission abatement and to reverse the rising trend of SF_6 emissions from network assets. The SBT is extremely challenging, requiring us to achieve an average leakage rate across our asset base of ~0.9% by 2026 compared to the present rate of ~1.4%. Based upon our forecasting this equates to a total abatement of 68932kg of emissions during RIIO-2.

To achieve our SBT we propose the following combination of funding:

- Defined interventions at 18 named sites to abate present and future leakage of ageing assets at a cost of [redacted] Section 5.2 refers.
- Application of pre-emptive, palliative coatings to assets within the first 20 years of service to abate future leak evolution at a cost of [redacted]. Section 5.4 refers.
- A flexible funding element to deliver the remaining interventions required to achieve our SBT. By definition the costs of this element are uncertain and we propose an upper bound of [redacted] as described in section 5.3.

Taken together these elements result in a proposed upper funding limit of:

[redacted] = £612.58m

Table 4 present further detail of the defined value proposals in terms of costs and abatements.

Finally, we recognise the long-term importance of SF_6 inventory reduction; removing the source of the emissions rather than managing them. We propose a funding mechanism to promote and facilitate the early adoption of SF_6-free retro-fill options within existing assets as these solutions become available. This should be based on the NTCC and we propose that the **allowed investment per kg of substituted SF_6 inventory should be**:

$$(NTCC/1000) \times (GWP_{SF6} - GWP_{Alternative}) \times (\text{leak rate}) \times (\text{effective duration of substitution})$$

No specific funding provision is included due to considerable uncertainty over the scope and effectiveness of such solutions during RIIO-2 however delivery of such options within this cost envelope should be prioritised. An example is presented in section 3.5 resulting is an indicative allowance of [redacted]/kg of SF_6 substituted.

7. Key Data

No specific inclusions

8. Top-up Forecasting Methodology

8.1. Introduction

A forecast has been developed to give an estimated view of our SF_6 top-up mass by functional position (FP) and year for the hypothetical scenario that we cease all current efforts to contain SF_6 within our physical items (PI), i.e. we model a scenario in which we do not refurbish, repair or replace leaking assets, including those requiring end of life decommissioning. Thus, we expect to see a systematic difference ("step-change") between forecast top-up masses relative to reported top-up masses.

The forecast is based on two predictions: the number of top-ups that will occur on each FP annually and the mass of gas topped-up during each of these events. The product of these two variables gives us our forecast SF_6 emission for each FP, each year.

The fundamental assumption is that the broad properties of historic top-ups are also representative of any future top-ups. We used a forecasting top-up dataset covering four-years of historic top-ups to make our forecast prediction.

8.2. The Forecasting Top-up Dataset

The forecasting top-up dataset is a combination of our top-up reconciliation dataset and our asset inventory dataset. For a given top-up, amongst the items recorded in the top-up reconciliation dataset are the associated regulatory reporting period (RRP), the date of the top-up, the mass of the top-up and the FP of the asset that was topped up. The top-up data set is built from data captured at the point of work which goes through a monthly reconciliation process to validate and resolve any issues identified in the data. At present the forecast has been undertaken at FP level.

The asset inventory dataset lists all assets currently on the network. For our purposes this is limited to SF_6 assets only. Amongst the items recorded in the asset inventory are the FP of the asset, the asset fitment date, the location of the asset (indoor or outdoor) and the mass of gas contained within the asset under normal operating conditions (the gas-holding).

To obtain the forecasting top-up dataset we merged the two datasets using the FP as the primary key. Since the top-up reconciliation records top-ups at the FP level and the inventory lists assets at the asset level, the two tables have a one-to-many relationship. Before undertaking the merge, we create a new view of the asset inventory table, which aggregates all assets under their respective FPs. This involves taking the gas-holding at the FP level by summing the gas-holding of individual assets and conservatively assuming the fitment dates of all assets under the FP are equal to the fitment date of the oldest asset under the FP. We also derive a further column which keeps a count of the number of assets under the FP. The two tables are then merged. In the merged table an age column is derived by taking the difference between the date of each top-up and the fitment date.

8.3. The Average Annual Number of Top-ups.

The average number of top-ups per FP that occur in a given year can be computed by dividing the number of top-ups recorded in that year by the number of FPs. There is a strong correlation between the number of top-ups that occur on a given FP and the age and location (indoor or outdoor) of assets installed at that FP. To incorporate this information into the calculation one can split the asset inventory into distinct subsets. For example, to calculate the average annual number of top-ups for indoor FPs with assets in the age interval 0-10 years old, one can limit the counting of leaks and FPs to those that fit into this subset before performing the calculation as described above.

We have taken this approach to estimate the relationship between the average number of total top-ups and the age and indoor-outdoor status of assets under FPs in our inventory. We compute this relationship for twelve different subsets consisting of indoor and outdoor FPs with assets in age intervals of 0-10, 10-20, …, 50-60 years old. These age intervals encompass our entire SF_6 asset inventory and thus for any FP falling into one of these subsets we can estimate the average annual number of top-ups.

The results of this process are shown for each RRP year and for indoor and outdoor FPs in Fig 21a and 21b respectively. The average number of top-ups in each age interval are shown by colour coded crosses on the charts.

In addition to the procedure described above, a correction has been made to the estimated number of top-ups. This correction is necessary because our top-up data implicitly includes the effects of our interventions to fix and replace leaking assets over the last four years. The correction is an attempt to include the number of top-ups beyond those recorded that would have been required had leaking assets not been intervened on. This is estimated by counting top-ups on assets that were topped-up in either or both of RRP years 2016/17 and 2017/18 and were not topped-up in 2018/19 and 2019/20. i.e. we conservatively assume that FPs that have not been topped-up for at least 2-years have been intervened on. The averages are calculated in subsets as above and these estimated "extra" top-ups are added to the results obtained previously.

The black dashed lines in Fig 21a and 21b describe the overall relationship between the average number of top-ups and age in indoor and outdoor assets. These lines represent least squares fits, over various intervals, to the values given by the colour coded crosses. Beyond the 20-30-year interval for indoor assets and the 30-40-year interval for outdoor assets, there is a clear and obvious reversal of the preceding trend that older assets are topped-up more frequently. We reject the notion that assets uniformly begin to perform better at these ages. More likely, this is a manifestation of survivor bias, which would materialise if all but the best performing assets were decommissioned beyond these ages. Beyond these ages, we are unable to measure this relationship for a full and fair sample of our assets. In lieu of this information, we conservatively assume that indoor assets aged beyond 25 years and outdoor assets aged beyond 35 years, behave like assets aged 25 and 35 years respectively. This in indicated by the flattening of the black dashed lines in Fig 21a and 21b. It is likely that the number of top-ups increases further with age, but due to the lack of a non-biased sample of assets in this age range we cannot confidently determine how strong that effect would be.

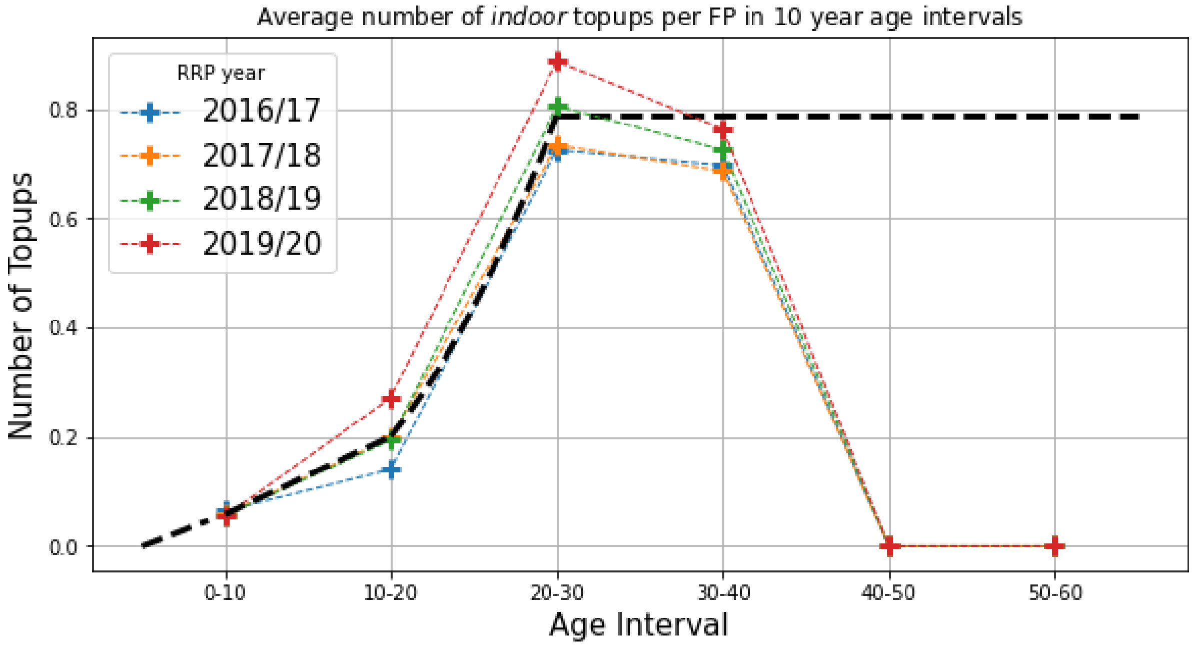


Figure 21a – Average number of indoor top-ups per functional position in intervals of ten years. Coloured crosses show average numbers calculated in each RRP year. The black dashed curve shows the modelled overall behaviour, which is found via a series of straight-line fits to the data over asset age intervals. The flatlining of this curve at 30-40 is included to exclude the effects of an apparent survivorship bias present in the data as described in the main text.

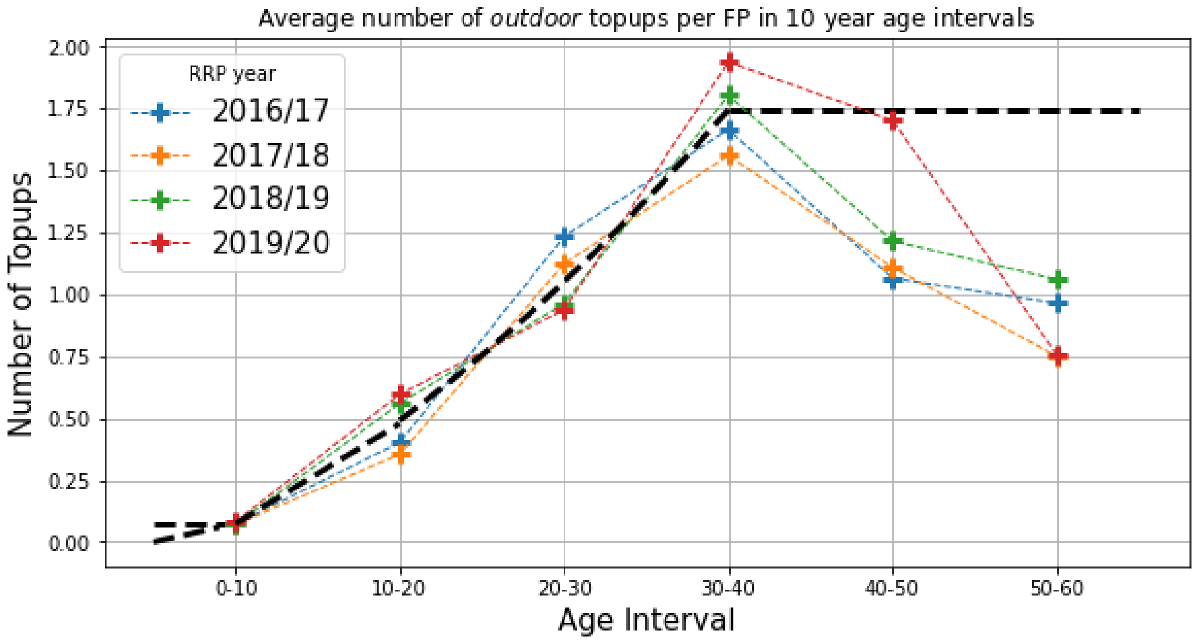


Figure 21b As in A1a but for outdoor top-ups.

8.4. The Mass of Gas Topped-up

The top-up dataset also keeps a record of the mass of gas topped up. The top-up mass distribution covers a very wide range, from tens of grams to a few hundred kg. The distribution is highly peaked towards smaller top-up masses, meaning that most top-ups are small, while there is a long tail towards large top-ups, meaning that a small fraction of top-ups are very large. When instead we consider mass topped-up on an FP as a fraction of gas-holding of that FP and view this distribution on a logarithmic scale, it is well approximated by a familiar bell curve distribution. This fact makes the distribution much easier to model.

There is a correlation between the top-up mass on a given FP and the age and location (indoor or outdoor) of assets installed at that FP, as well as the total gas-holding and number of assets at the FP. Based on these 4 parameters, we want to estimate log to the base 10 of top-up mass as a fraction of gas-holding, which for brevity, we refer to as the log-top-up-fraction going forward. Therefore, we require a fit to the log-top-up-fraction in 5-dimensions. We can generalise the process of least squared fitting (often done in 2-dimesnions denoted X and Y) to higher dimensions. We do this using a Generalised Additive Model (GAM), which unlike the higher dimensional generalisation of a straight line (a hyperplane) has some flexibility to fit non-linear features.

The distribution of the log-top-up-fraction with age is shown in Fig 22. The light blue data points show the true distribution while the dark blue data points show the prediction based on the model. Note that unlike a canonical 2-dimensional least squares fit, where predictions would be distributed along a line, the prediction here is distributed over a region. This is simply a result of us viewing a 5-dimensional model fit on a 2-dimensional axis. The prediction does a reasonable job of modelling the overall trend but it does not capture the full variation of the log-top-up-fraction with age, which is large. The situation is similar amongst the other three parameters.

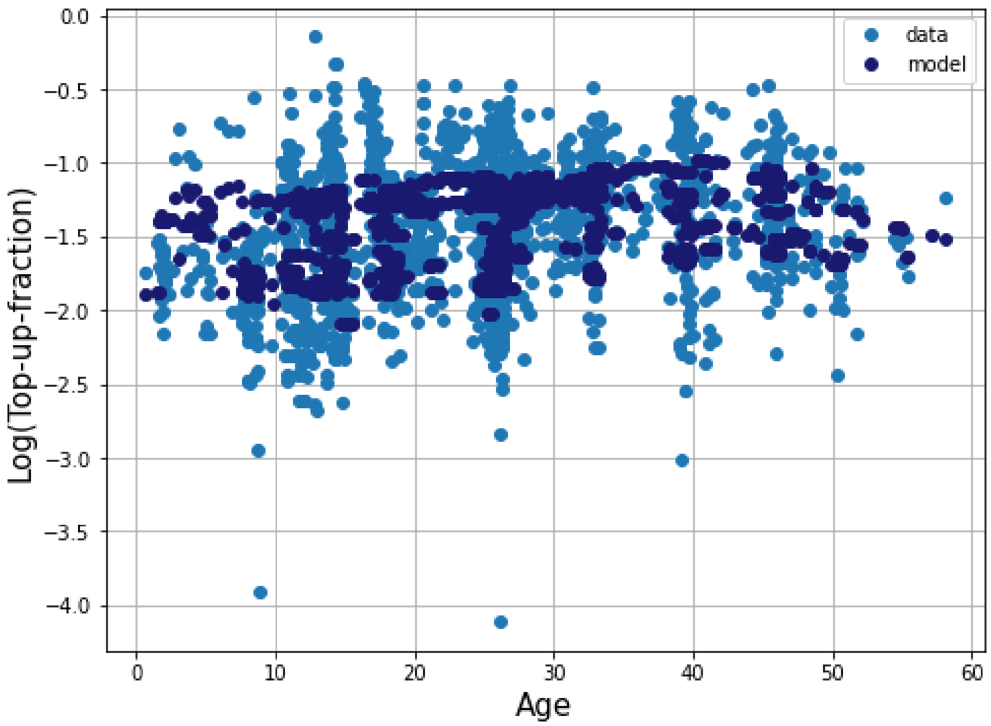


Figure 22 – The distribution of the log-top-up-fraction with age for the data, shown in light blue, and the model shown in dark blue. The model describes the overall trend with age in the data well but does not capture the variation around the trend.

In addition to fitting a GAM through the data, it is also possible to estimate the distribution of the data about the GAM. This allows us not only to model the overall trend in the log-top-up-fraction but it also allows us to model the variation about this trend. Fig. 23. shows the resulting fit of the log-top-up-fraction to age. The result now better captures the variation abut the trend. To reinforce this point, Fig. 24. shows the relative proportions of true and modelled log-top-up-fractions in histogram format. This view also shows the bell-shaped distribution of the log-up-fraction described earlier.

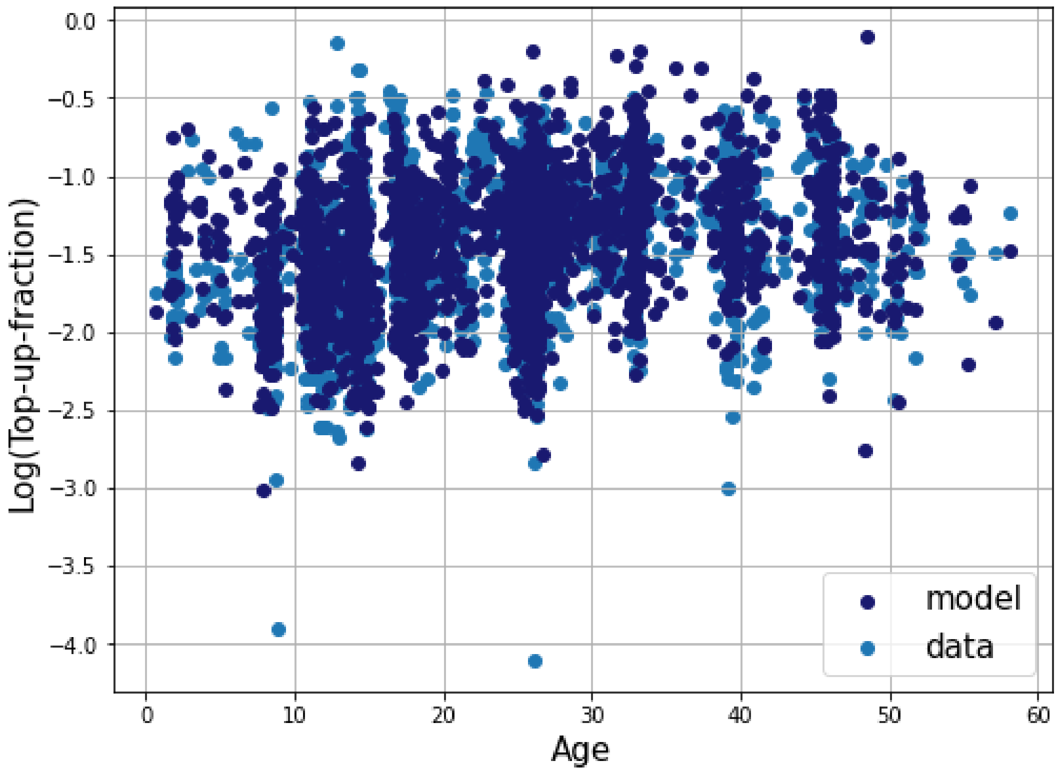


Figure 23 As in 22 but now the model incorporates an estimate of the variation about the overall trend in log-top-up-fraction with age.

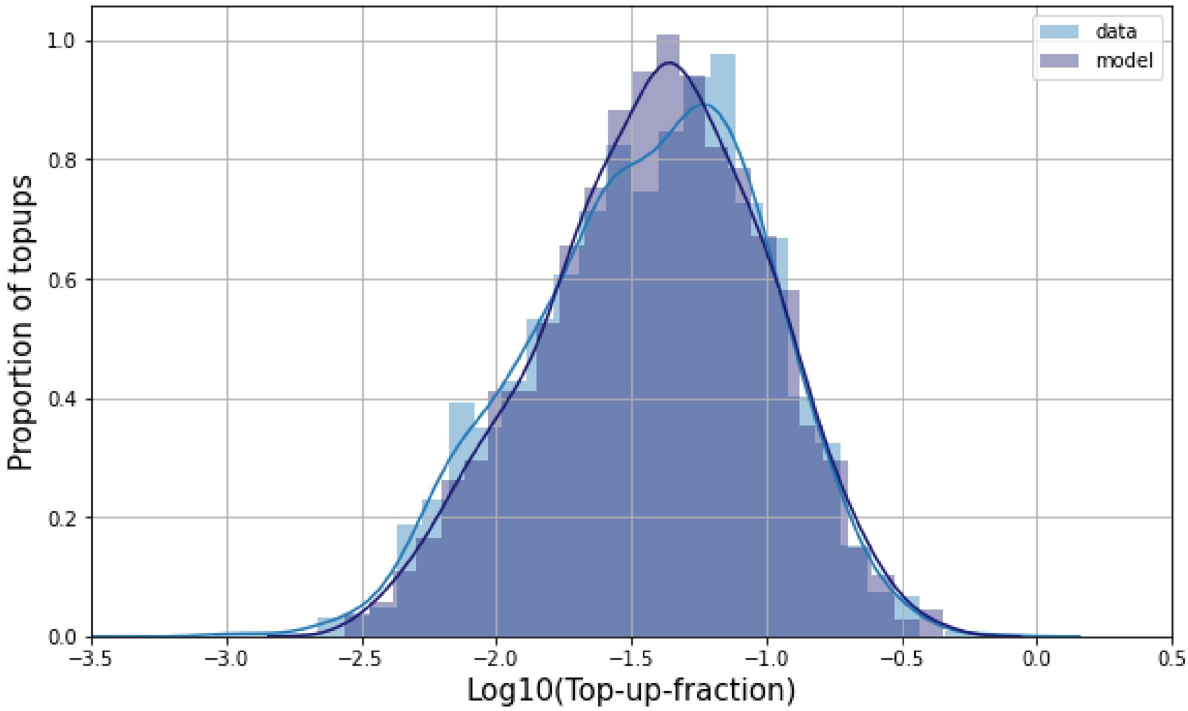


Figure 24 – The distributions of the relative proportions of the true (light blue) and modelled (dark blue) log-top-up-fractions. It is useful to think of this plot as a normalised view of A3, where we have collapsed all points along the age axis and onto the log-top-up-fraction axis. This then shows the density of points on the log-top-up-fraction axis.

8.5. Generating an Average Forecast and its Confidence Intervals

With a means to predict the average number of annual top-ups per FP and the mass of gas topped-up, the models are sampled at the relevant points for each FP during each of years 2019 to 2050. Two post-processing steps are then required.

First, the average number of leaks for a given FP is in general some fraction of a whole number. This is clear from Fig. 21a and 21b Fractional top-up counts can be dealt with probabilistically. This is best explained via an example.

If the estimated average number of top-ups per FP in a year is 1.8, then there is a 180% chance that a relevant FP will have a top-up. More rationally, there is a 100% chance that the FP will have at least one top-up and an 80% chance it will have a second top-up. To determine, whether this second top-up takes place we generate a random whole number between 1 and 100. There is an 80% chance that this number is less than or equal 80 and a 20% chance it is greater than 80. In the former case, we assign the FP a second leak.

The second post processing step relates to the mass of gas topped-up and is required to get from a state equivalent to that seen in Fig. 22, to that seen in Fig. 23. We again take a probabilistic approach, which requires a step along the log-top-up-fraction axis with a random direction and distance. Crucially these random steps are not made in a uniform manner but rather they follow the observed distribution of the log-top-up-fraction as seen in Fig. 24. Qualitatively this means that most of these steps have a direction and distance which places them closer to the centre of this distribution, while fewer of them populate the wings.

If an FP is predicted to have three leaks in a year, then the modelled log-top-up-fraction is sampled three times. Each of these results is then converted from a logarithmic value. The sum of these three values gives the top-up-fraction of the FP in the relevant year. The product of this result and the gas-holding gives the forecast top-up mass in kg.

The probabilistic nature of this procedure means that each time we run a new forecast we observe variation between one forecast and the next. This variation captures the natural variation in the datasets we have modelled. To generate the average (expected) forecast we generate 1000 independent forecasts and average the results. This is of course only an estimate of the average forecast. If we wanted to generate an infinitely precise average forecast, then we would need to take the average of all possible forecasts. This is not possible or necessary. Instead we can generate a confidence interval, which gives a region around the estimated average forecast in which estimates of the average forecast fall 95% of the time. We do this by finding the average of 100 different forecasts selected randomly from our ensemble of 1000 and repeat 1000 times. The spread in the 1000 different realisations of the average forecast allows us to place 95% confidence intervals on our expected forecast.

8.6. Model Assumptions and Limitations

The forecast model is under continual development and will continue to be improved throughout RIIO-2 as we push to further constrain our SF_6 emissions. Here we list the important assumptions and limitations of the model, which we aim to explore and improve throughout the development process:

- The model assumes that non-leaking assets will perform similarly to leaking assets if left to deteriorate without intervention. Leaking assets may represent a distinct population with a distinct set of attributes that make them liable to leak. In particular, family types share similar design attributes and it may be the case that particular designs are more liable to leakage than others. Data on family types is currently being compiled to allow us to adjust for this. Our expectation is that we may be slightly underestimating top-up mass on the worst family types (the ones we intend to intervene on) and slightly overestimating top-up mass on the better family types (the ones we are not intervening on).
- Assets that are new on the network today are assumed to exhibit the same deterioration and leakage properties as they age as older assets do today (despite the fact that typically they are from different family types). This assumption will need to be monitored and incorporated into our forecast as our assets age, but it is possible that newer family types will have lower leakage over the course of their lifetime – i.e. our forecast may be higher than the actual value.
- We have already discussed the flat-lining in our modelling of the average number of leaks due to survivor bias. This is very likely to underestimate the number of leaks for indoor and outdoor FPs older than 25 and 35 respectively. We also see a similar survivor bias in the log-top-up-fraction for outdoor FPs. This bias affects FPs older than 40 years so we have similarly flat-lined the log-top-up-fraction for these outdoor FPs. There are very few indoor FPs older than 35 years on the network and we are unable to model these assets with confidence. Therefore, we also flat-line indoor assets older than 35 years old. The overall effect is that we very likely underestimate the mass of top-ups on these FPs. These limitations are more pronounced in later years when larger fractions of our asset inventory meet these criteria.
- The model used to estimate the number of annual leaks on an FP returns an average. Averages smooth out variation, supress extreme values and therefore cannot capture the full range and distribution of leak counts. The result is that the number of leaks on FPs at upper extremes will be underestimated and the number of leaks on FPs at lower extremes will be overestimated. This would result in the forecast being slightly below the true average. This is a limitation of the model and is an area of active development.
- The historic leakage data we are currently using implicitly includes the effect of interventions. We have attempted to correct for this in leak count estimates but doing the same for leak masses would require us to estimate the quantity of mass leaked by these hypothetical top-ups. This is a much more difficult task and has not been attempted. We expect this to mean that we underestimate the overall top-up mass since we aim to intervene on larger leaks.
- The current model is based on the most up-to-date asset inventory available at the time. Our asset inventory data is currently undergoing improvement. As part of this work asset family type data is being compiled as described above. Data errors relating to asset fitment dates and location are also being identified and fixed. This is a manual and time-consuming process.

- The average number of annual leaks will have some variation. This is obvious from Fig. 21a and 21b, where we take the black dashed line as the overall estimate for the average number of annual leaks. However, the average within individual RRP years shows variation from this line. This year to year variation has not been accounted for in the forecast but subsequent analyses have shown that the effect on both the average forecast and its confidence intervals is small compared to the variation in leak mass, which is taken into account in the forecast. The overall effect is that the confidence intervals are widened slightly and the average forecast out to 2026 is slightly lower.
- All FPs are treated independently with respect to leakage development and do not have causal effect on one another. This greatly simplifies the modelling process and we expect this to be a very good approximation of the true relationship between FPs.

8.7. Glossary:

Substation Hierarchy: Substation hierarchy can be understood using an analogy where the entire substation may be thought of as a car park. The rows in the car park are akin to the bays of the substation. Within each row there are parking spaces which are the Functional Positions (FPs). Within each space there is a vehicle which is akin to a physical item. There can be multiple vehicles within a space, motorbikes for instance, we know which vehicles are in the space but if a vehicle in the space is filled up with petrol we generally don't know which one it was. Similarly, if a PI is topped-up with SF_6 we know in which FP the PI is located but we don't generally know which PI was topped-up.

Functional Position (FP): A functional position is an element of Substation hierarchy. See substation hierarchy for more information.

Physical Item (PI): A physical item is an element of Substation hierarchy. See substation hierarchy for more information. While it is common at National Grid to refer informally to both functional positions and physical items as "assets" in this Appendix the word asset should always be taken to mean physical item.

(Log-)top-up-fraction: We use this term for brevity to refer to the proportion of an asset's gas holding that is topped-up during any single top-up. This is a unitless number calculated by dividing the mass topped-up on an asset by the gas holding of that asset. To model this quantity, we first take its log to the base 10. There is no physical significance attached to this transformation, it merely makes the quantity easier to model. This means that our model makes predictions in log to the base 10 units. Before we interpret or report these predictions, we take the inverse of this transformation to return the quantity back to its original units.

8.8. The difference ("step-change") between observed and forecast top-up mass.

The forecast we are presenting is one in which no interventions are applied to reduce SF_6 leakage. This is different from the actual leakage seen in past years because we have been employing a strategy of interventions to reduce leakage. In fact, the reason we observe such a large difference ("step change") between observed leakage and our forecast is because our intervention strategy mitigates a significant amount of leakage each year. Note that this with and without intervention forecast approach is consistent with more established areas of the TO regulatory submissions (e.g. NARM).

The total top-up we observe in any particular year can be considered to consist of two elements:

1. New top-ups: Top-ups on assets that have not been topped-up in previous years.

2. Established top-ups: Top-ups on assets that have also been topped-up in previous years because no intervention has taken place.

The total top-up we have forecast contains an additional third element:

3. Mitigated top-ups: These are the hypothetical top-ups that would have occurred without interventions in previous years.

Comparing the forecast (which is without intervention) directly to historical observed top-ups (which are with intervention) is therefore misleading, as the former includes leakers that were repaired, but the latter does not.

Instead, we can think of established top-ups in a particular year as the top-ups on these assets in prior years plus the percentage growth in these top-ups since. Similarly, we can approximate mitigated top-ups as top-ups in prior years plus the hypothetical percentage growth we would have observed had no interventions taken place on these assets.

Given this, we can then express the observed leakage in any given year as

$$Top\ ups_{observed} = Established_{previous\ years} * (1 + \%\ growth) + New$$

Whereas the forecast can be expressed as:

$$Top\ ups_{forecast} = Established_{previous\ years} * (1 + \%\ growth) + New$$

$$+ Mitigated * (1 + \%\ growth)$$

These relationships are shown visually in the waterfall chart in Fig 25,

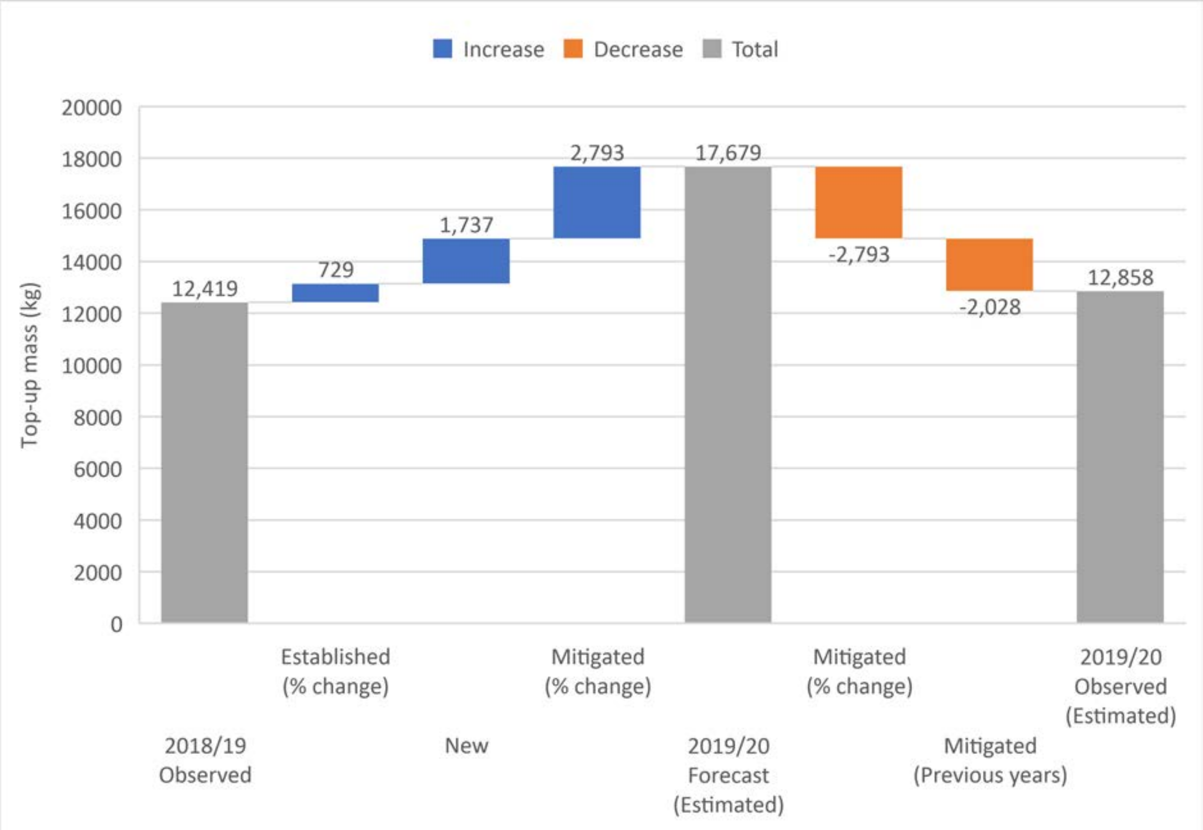


Figure 25 – Waterfall chart depicting the difference between observed and forecast top-up mass. The difference between the observed top-up mass and our forecast top-up mass in the same year can be thought of as the quantity of top-up mass mitigated in previous years plus the hypothetical percentage growth on those mitigated top-ups in the current year.

The chart begins at the total observed top-up mass in RRP year 2018/19. Adding the estimated growth from established leakers between 2018/19 and 2019/20, the contribution from new top-ups in 2019/20 and the hypothetical growth from mitigated top-ups in previous years, gives an estimate of the 2019/20 forecast ($Top\ ups_{forecast}$). Subtracting from this, the growth in mitigated top-ups in 2019/20 and the total mitigated top-ups in previous years, i.e. top-ups that will not reoccur in 2019/20, we arrive at an estimate for the total observed top-ups in 2019/20 ($Top\ ups_{observed}$).

Details of the calculations made to arrive at these numbers are given in the next section. This shows visually how the combined contributions of historical interventions can quickly build up and warrant a large step change between observed and forecast top-ups.

Given this there are two more appropriate comparisons that can be made.

1. Add the mitigated top-ups back into the observed top-ups and compare to the without intervention forecast. The without intervention forecast should be above the adjusted observed top-ups.
2. Add the mitigated top-ups plus an estimate of percentage growth back into the observed top-ups and compare to the forecast. We would expect the without intervention forecast to be broadly similar to the adjusted observed top-ups (but this is very sensitive to the estimated growth factor used in the adjustment).

Fig. 26 shows these comparisons, where the blue line shows observed top-up mass between RRP years 2016/17 and 2019/20. The orange line shows forecast top-up mass between 2019/20 and 2030/31. The green cross shows observed top-ups with mitigated top-ups added back in, as described in point 1) above. The Red cross shows observed top-ups with mitigated top-ups and estimated % growth added back in, as described in point 2) above.

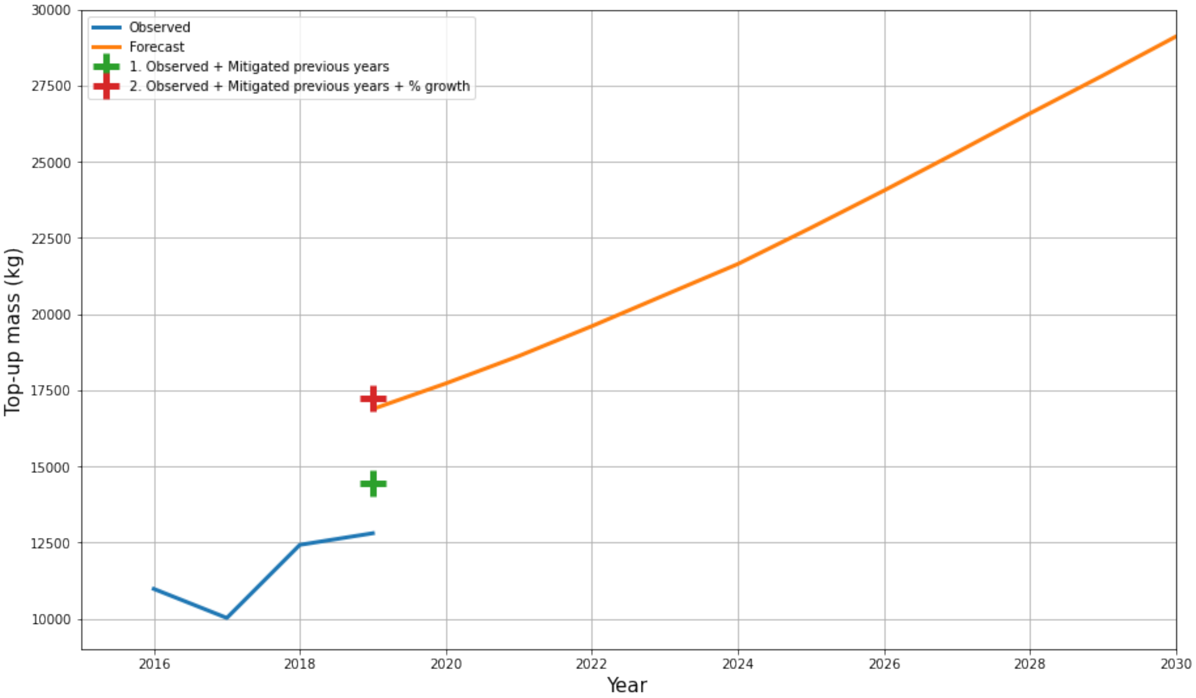


Figure 26 – Comparison of observed top-ups (blue), observed + top-ups mitigated in previous years (green), observed + top-ups mitigated in previous years + growth in top-ups mitigated in previous years (red) and forecast top-up masses (orange). The plot shows how the effect of mitigated top-ups can easily account for the expected difference seen between observed and forecast top-up masses.

The results of these comparisons indicate that the forecast is broadly in line with observed top-ups once the effect of interventions is removed. Detail of the methodology used to arrive at these comparisons is outlined is as follows

The results presented in the previous section require an estimate of new top-ups and established top-ups in 2019/20, mitigated top-ups in all previous years and an estimate of the percentage growth of the latter in the forecast year.

Our past methods of recording interventions were not designed for informing SF_6 top-up forecasting. As such we currently lack the ability to explicitly map historical interventions to their leak impact. Instead, we can approximate this impact by identifying assets that were topped up in the past but have since ceased to be topped-up for an extended period of time and assume these were all due to interventions.

The contribution from new top-ups is estimated as the sum of top-ups on assets that did not leak from RRP year 2017/18 onwards but did leak in 2019/20. We do not have visibility of new top-ups in RRP year 2016/17 because that is the earliest year available in our dataset.

To estimate the contribution from established top-ups in 2019/20 we find the sum of top-up mass from the subset of assets that were also topped-up in 2017/18 and 2018/19 as well as the subset also topped-up in 2016/17, 2017/18 and 2018/19.

To estimate the contribution from mitigated top-ups we sum top-ups from assets that did not leak beyond 2017/18 and therefore had two years of potential emissions growth capped and assets that did not leak beyond 2018/19 and therefore had one-year potential emissions growth capped.

The final estimate to be made is the percentage growth from mitigated top-ups in previous years. Since these top-ups are hypothetical, we cannot estimate this contribution directly. Instead we can estimate this from the percentage growth in established top-ups. We calculate the percentage growth as the average percentage growth in top-ups on these assets from 2017/18 - 2019/20 and 2018/19 – 2019/20. To illustrate this process, the figure below shows the distribution of percentage change in top-up mass between 2018/19 and 2019/20, where the solid vertical line indicates the average of the distribution.

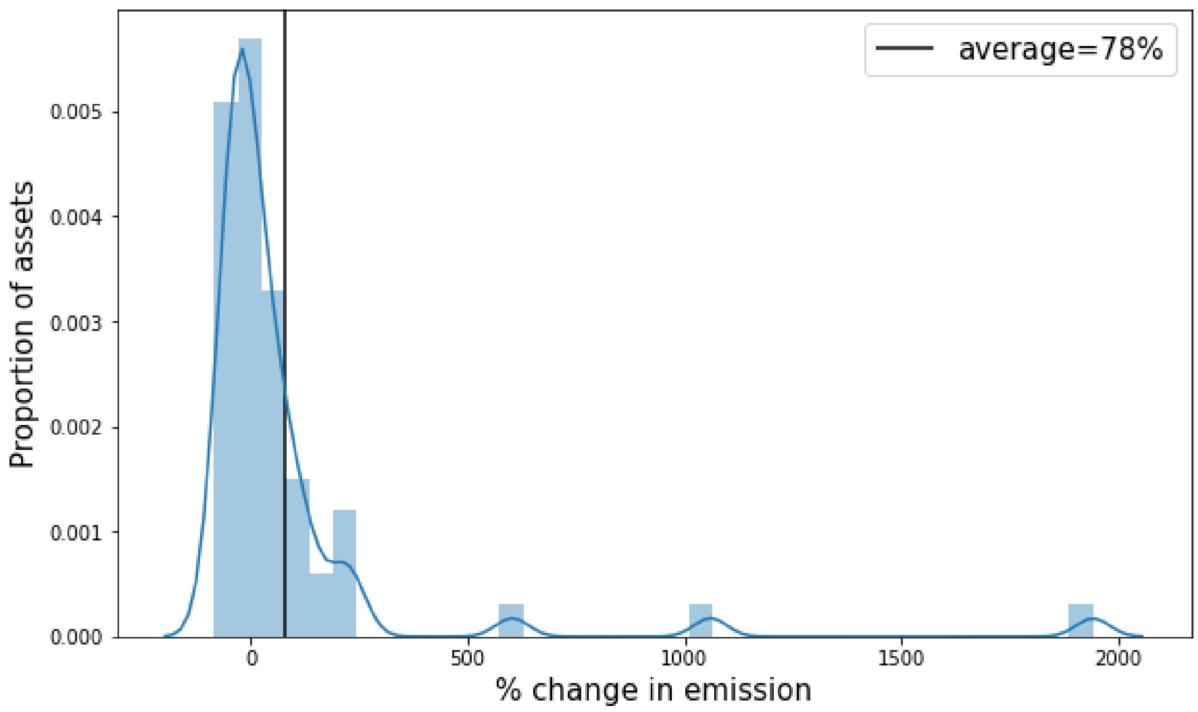


Figure 27 The proportional distribution of percentage change in top-up mass on FPs between RRP years 2018/19 and 2019/20. The solid black line shows the average of this distribution.

The quantity of gas topped-up on these assets in these years multiplied by their growth rates gives the contribution they would have made to the total top-up mass in RRP year 2019/20.

The following table summarises this result

	2017/18	2018/19
Top-up mass*	867 kg	1161 kg
Average % change to 2019/20⁺	218 %	78 %
Contributions to emission in 2019/20	1889 kg	904 kg
*Mass of top-ups on assets that were identified to have had interventions in that year. ⁺Average % change in top-up mass between for assets leaking in both that year and 2019/20.		

The full estimate of our forecast in 2018/19 is the sum of each of the elements outlined above plus the observed top-ups in 2018/19. The results are summarised in the following table and indicate that the forecast is broadly in line with observed top-ups once the effect of interventions is removed.

2018/19 Observed Top-ups	12,419 kg
2019/18 Established top-ups % growth	729 kg
2019/18 New Top-ups	1,737 kg
2018/19 Mitigated Top-ups % growth	2,793 kg
2018/19 estimated forecast **Total**	17,679 kg
2018/19 **Forecast**	16,878 kg

However, it is important to note the many necessary simplifications in this approach and it is useful to consider some of them here.

1) We assume that any asset that has stopped leaking from one RRP year to the next has had an intervention. It is probable that many of these assets have not been intervened on at all but are rather slow leakers that only require topping-up over durations greater than a year. Some of these slow leakers may be large gas-zones whose slow leaks represent significant annual emissions. Counting these as assets with interventions would cause us to overestimate growth rates and thus overestimate the result.
2) To calculate top-up mass on assets with interventions we calculate total top-up mass in the year the asset last leaked. If the intervention happened at the beginning of the year rather than the end of the year, then we underestimate the total annual leakage of the asset in that year. This would reduce the contribution of that particular asset to the results.
3) Not all interventions will result in a complete cessation of top-ups. Some interventions will only reduce the amount of gas required in a top-up and increase the durations between top-ups. These types of intervention do not contribute to the results since we assume an intervention leads to the cessation of all top-ups.
4) We estimate growth rates using assets that have not had interventions and therefore we assume that the hypothetical growth rate for assets that have had interventions is equal to the growth rate for assets that have not had interventions. The evolution of historical top-ups likely has a strong bearing on which assets are intervened on. Thus, calculating growth rate from assets that have not had interventions may cause us to underestimate growth rates.
5) Our dataset only gives us visibility of historical top-ups out to RRP year 2016/17. Thus, we are unable to include growth from mitigated top-ups prior to 2017/18. This could lead to a potential underestimate of contributions from mitigated top-ups.