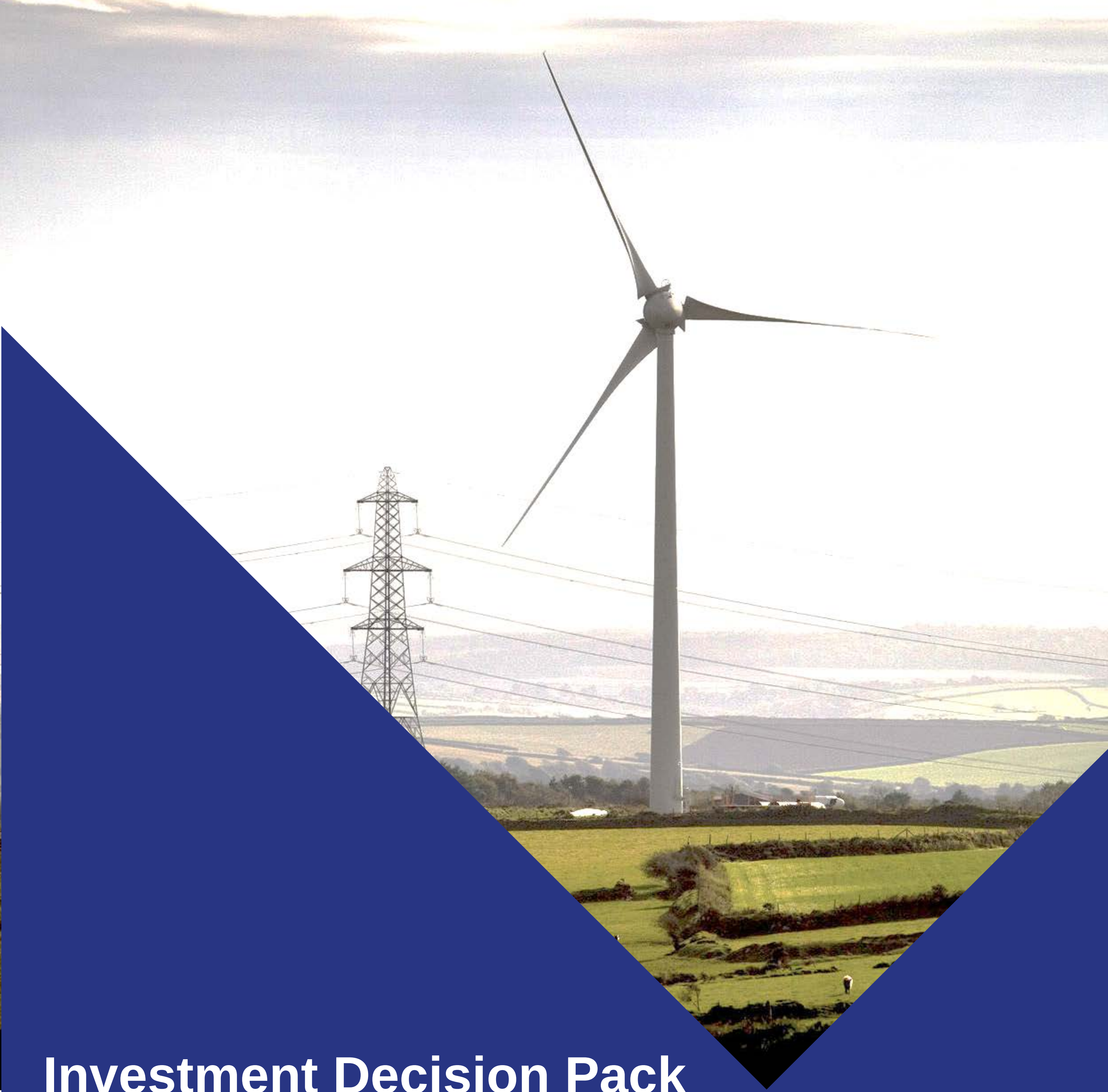

Investment Decision Pack

NGET_A9.17 - Reactors

December 2019

As a part of the NGET Business Plan Submission

nationalgrid

nationalgrid

Engineering Justification Paper; Non-Load Related Reactors			
Asset Family	Reactors		
Primary Investment Driver	Monetised Risk Methodology (Lead Asset)		
Reference	A9.17		
Output Asset Types	Reactors		
Total Cost for RIIO-T2 Periods	£51.092m		
Delivery Year(s)	2021-2026		
Reporting Table	C2.2A		
Outputs included in RIIO-T1 Business Plan	No		
Spend Apportionment	**T1**	**T2**	**T3**
	£1.588m	£49.470m	£0.035m
Completion of T1 schemes		£0.364	
Development schemes for T3		£4.958	
Total	**£1.588m**	**£54.792**	**£0.035**

nationalgrid

Contents

1. Executive Summary

Reactors provide a very significant function on the transmission network, ensuring that the voltage remains within quality of supply limits, and helping to reduce system constraints. Reactors are an important tool in managing a safe and reliable Transmission System.

By the end of T1 we will have delivered [redacted] reactors and [redacted] static compensator, against a forecast of [redacted] in our 2012 T1 Business Plan submission. The reduction is because some reactors were found to have deteriorated more slowly than forecast and several small reactors were replaced by fewer larger reactors with the same network functionality.

Our stakeholders have stated that maintaining the current level of network reliability in T2 is important to them. We have developed options to deliver this at minimum cost, benefiting the UK consumer in the longer term. Reactor replacements for RIIO-T2 have been determined using Monetised Risk methodology. The units identified for replacement have deteriorating performance and take account of the network criticality requirements set by the Electricity System Operator (ESO).

Two options were considered to determine the best reactor intervention strategy:

1. Do Minimum (Maintain only and replace on fail)
2. Planned programme of replacement based on monetised risk

A Cost Benefit Analysis (CBA) was undertaken to determine which option to progress. The CBA concluded that a planned programme of replacement based on monetised risk (i.e. Option 2) would deliver the most value to consumers. This is therefore the basis of the proposed plan for RIIO-T2 and, as requested by stakeholders, enables National Grid to maintain current levels of risk, while reducing disruption to the transmission system.

This paper proposes a total T2 spend of £49.470m for [redacted] reactor intervention schemes that deliver the output in the RIIO-T2 period. A further [redacted] reactor interventions will be delivered by other schemes within the non-load investment portfolio. Therefore, in total, in T2 there are [redacted] reactor interventions. Our plan also includes £5.322m to complete schemes initiated during RIIO-T1 and for the initial development of RIIO-T3 reactor replacements. This brings the total costs for reactor replacement in RIIO-T2 to £54.8m.

The annual volumes proposed increase from [redacted] reactors per year in T1 to [redacted] reactors per year in the T2 period. Based on an average of scheme costs, the unit cost of a reactor replacement is expected to be broadly consistent with that in T1 (£[redacted]m per reactor in T2 vs £[redacted]m per reactor in T1). The modest increase is driven by the unique scope requirements of the T2 schemes, and this is discussed in the relevant section.

2. Introduction

Reactors are widely used in power networks to enhance the stability of network systems and to increase grid efficiency. There are two main applications for reactors:

- **Shunt Reactors** are used to control network voltage, ensuring that the quality of supply to National Grid Electricity Transmission's (NGET's) customers is maintained in accordance with the transmission licence. They are employed to compensate the capacitive nature of the transmission network by absorbing reactive power (Vars) and are typically required to offset the use of underground cable and other capacitive loads e.g. LEDs.
- **Series Reactors** are used as current limiting reactors to increase the impedance of a system or to compensate reactive power in order to improve the transmission capacity across a transmission boundary.

This paper considered the asset management of these assets. There are [redacted] reactors across a variety of voltages and types on the transmission network. Note, the asset management of capacitive equipment is the subject of a separate paper.

There has been significant change in the total reactive power demand seen by the transmission network over the last two decades driven mainly through changes in consumer technology leading to energy efficiency, the increase in embedded generation and the decline of the UK manufacturing industry. The accumulative effect of this is an overall reduction in the requirements for capacitive compensation on the transmission network and an increase in the need for shunt reactors. To ensure that our asset replacement plan does not include expenditure on assets that are no longer required, we have checked to ensure that there is an ongoing need for any assets that are planned to be replaced.

3. Approach & Performance during RIIO-T1

Approach during RIIO-T1

In RIIO-T1 we moved from a replace on age to a replacement priority based on safety, operational, and environmental risk. This considered asset heath and asset criticality. Each reactor was assigned:

- an Asset Health Index (AHI) based on condition assessment and service experience of similarly designed plant; and
- a criticality score based on the impact of failure or unreliability from safety, system and environmental perspectives.

The reactors were then assigned a Replacement Priority (RP) as outlined in PS(T) EPS 12.0. The following table (Table 2) provides an example of what each RP means.

RP (years)	Description
0-2	AHI 1 and 2a transformers with criticality factors that justify replacement within 5 years and whose replacement is within 2 years. Transformers that have not failed but have a rapidly worsening condition and require emergency replacement usually using a spare transformer. This may include units which have been removed from service for safety reasons.
2-5	AHI 1 & 2a transformers with criticality factors that justify planned replacement within 5 years
5-10	AHI 2a, 2b & 2c transformers with criticality factors that justify planned replacement within 5-10 years
10+	AHI 2b, 2c, 3 & 4 transformers with criticality factors that justify planned replacement after a minimum period of 10 years.

Table 2 – Example asset health categorisation for transformers (including reactors)

When a reactor was identified as requiring removal from the transmission network due to the risk it poses, checks were made to ensure that a like-for-like replacement reactor is required. During T1 not all reactors which were removed were replaced on a like-for-like basis, for instance it may have been because a higher rated reactor was required on the transmission network to support changing conditions in a local area. The T1 interventions are summarised in Table 3.

Volume	Actuals						Forecast		Total	Annual Average
	2014	2015	2016	2017	2018	2019	2020	2021		
Off	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
On	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 3 – Reactor interventions in RIIO-T1

Performance during RIIO-T1

In RIIO-T1, we had an allowance of £42m to replace a total of [redacted] reactors. Table 4 illustrates the actual cost and volumes delivered together with our forecast for the reminder of the RIIO-T1 period.

Reactor Projects	RIIO-T1				RIIO-T1	
	T1 Allowed	T1 Spend Actuals	T1 Spend Forecast	T1 Spend (8-years)	Annual Average (8-years)	Annual Av (first 6 years)
Total cost / allowed (£m)	42	43.4	17.2	60.6	**7.6**	7.2
Total volume (Volumes On)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Cost per unit (£m/REA)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Volume from other projects	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 4 - Summary of volumes and costs for Reactors in RIIO-T1

Note that the T1 forecast cost per unit volume for the remaining T1 interventions (£[redacted]m per unit) is driven by two projects: one conventional reactor replacement in 2020; and the [redacted] 400kV static compensator replacement in 2020 for £[redacted], which dominates the unit cost. Static compensators are classified as reactors by the RIIO methodology but are a distinct asset with a with different network function. Specifically, the static compensator at [redacted] includes a variety of different wound plant types, multiple circuit breakers, and control systems.

As can be seen in Table 4, we expect total spend over the T1 period to be £61m, which is £19m above our allowance. A summary of the key drivers behind this is shown in Figure 2.

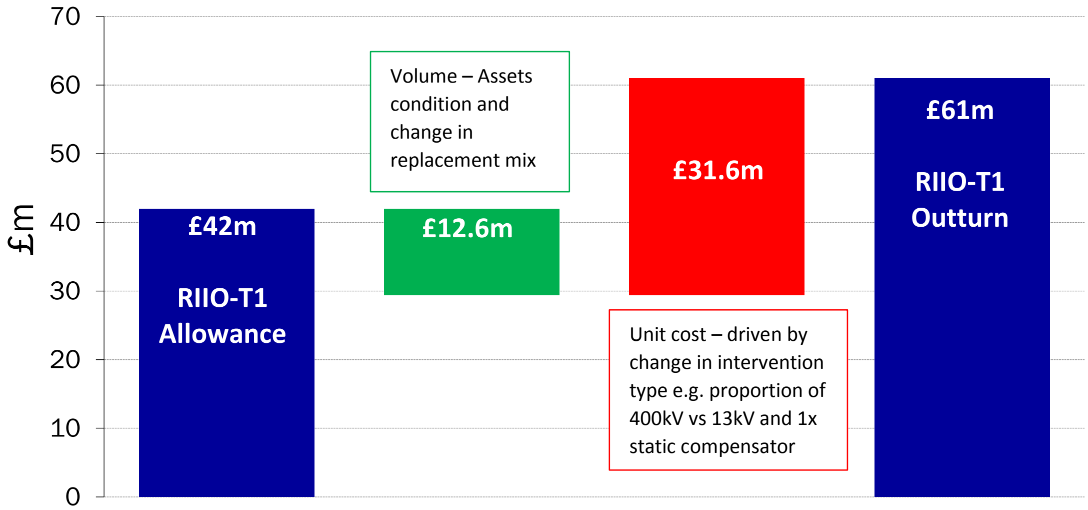

Figure 2 – Drivers for spend vs allowance in RIIO-T1

The following section summarises our volume and unit cost performance against our allowance.

Volume performance: Over T1 we are forecasting to remove [redacted] units and install [redacted] reactors against an allowance of [redacted] units. Key reasons for change in volume are:

- **Assets deteriorating slower than forecast**, resulting in [redacted] planned reactor replacements being reprioritised beyond T1; and
- **Replacing assets with larger capacity units to save operational costs.** The effects of increased embedded generation, lower industrial load, and changes to consumer behaviour has significantly increased the requirement for reactive compensation to control high voltage levels across the network.

  Where an intervention is required on life-expired reactor units to manage system risk, we have taken the opportunity to review the optimal solution. Where system studies and CBA have confirmed that reactive compensation installed at transmission voltages provides increased economic and operational benefits over a like-for-like replacement at lower voltages, then we have replaced them with larger capacity 275kV or 400kV units. These larger capacity replacement units have allowed us to deliver the system operation benefit with fewer replacements than planned.

Cost performance: Over the T1 period we are delivering reactor replacement with unit costs more than double that implied by our T1 allowance, and this is not expected to change for the reminder of T1. Table 5 shows the unit cost of reactors for the T1 period and the effect of removing the static compensator (1 unit on).

Basis of Unit Cost	£m / reactor
Units delivered (6-years actuals)	[redacted]
Full T1 (6-year actuals and 2-year forecast)	[redacted]
Full T1 excluding static compensator (and 1 reactor volume)	[redacted]

Table 5 - Summary of volumes and costs for Reactors in RIIO-T1

The proportion of 400kV reactor units identified for replacement during T1 are higher than other voltage types (see Figure 3), which pushed the average unit cost higher. This is partly an effect of our decision to replace lower voltage reactors with higher voltage reactors, as described above. In addition, the T1 allowance for reactors has been derived from a total allowance for all wound plant (including quad boosters, transformers, and reactors) which contributes to inconsistency between the unit allowance and the unit cost.

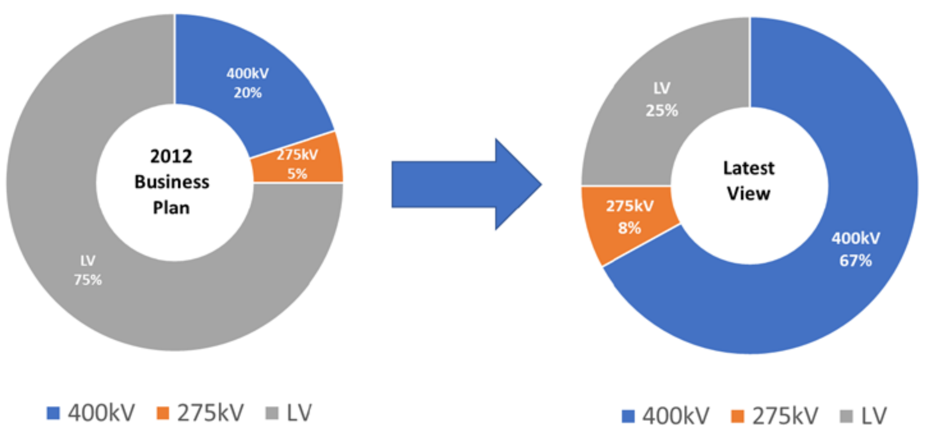

Figure 3 - Voltage mix for replacement volumes in T1 and change since 2012 Business Plan

nationalgrid

4. Investment drivers

4.1 Approach to identifying RIIO-T2 interventions (monetised risk)

For RIIO-T2, reactor replacement is based on a Monetised Risk approach which was informed by the End of Life (EOL) methodology, see Appendix 4 for further details. The approach can be summarised in Table 6.

Likelihood of Asset Failure	Consequence of Asset Failure	Risk is a function of Likelihood of an event and its consequence
Each asset has a probability of failure. This probability is arrived at by use of an 'End of Life Modifier'. This is a score that maps an asset to a place on a probability of failure plot, specific to each asset class.	For each asset failure event that may have safety, system, or environmental consequences, these are monetised.	The probability of failure of an asset multiplied by the probability of an event with a monetised consequence produces the monetised risk of asset failure. The monetised risk of asset failure can be aggregated to give us a whole network measure of risk. This allows us to make prioritisation decisions between different assets.

Table 6: Summary of Network Asset Risk Metric (NARMs) approach for identifying interventions

Our monetised risk calculations are underpinned by detailed condition information for each of our assets as detailed below.

4.2 Approach to assessing the EOL score

The Monetised Risk approach for reactors is aligned with our monetised risk approach for transformers and combines an asset's probability of failure, the probability of an event, and their monetised consequences, to produce its present and future risk values. Full details on the methodology employed can be found within the Network Asset Risk Annex (NARA).

Failure probability is calculated by understanding the four factors that drive the EOL score:

1. Dielectric – characterised by arcing, sparking and partial discharge faults or overheating of bare metal components – detected by dissolved gas analysis of reactor oil.
2. Thermal – characterised by slow degradation of solid insulation, ultimately leading to a dielectric failure – detected by furan analysis of reactor oil.
3. Mechanical – characterised by distortion of the winding or leads from short circuit forces or loss of mechanical clamping – detected by electrical testing of windings.
4. Other – Noise issues, excessive vibration, and severe oil leaks that may not be economically rectified without replacement.

4.3 How we monitor reactor condition

Basic maintenance is carried out on reactors every 3 years and major maintenance every 12 years. In addition to this, an annual oil sample is taken for Dissolved Gas Analysis (DGA). If issues are identified the frequency of this can be increased (e.g. 3-monthly, monthly, weekly) and ultimately an online dissolved gas monitor (hourly sampling) can be fitted.

Basic maintenance includes a general inspection, levels checks and focuses on protective devices on the main tank. Major maintenance also includes bushing inspections. Further detail of end of life assessment methods and inspection regimes for reactors are contained in Appendix 5.

4.4 Expected increase in monetised risk at RIIO-T2

In the absence of intervention, the monetised risk associated will the reactor asset class will increase by £11m over the course of RIIO-T2, as shown by the Figure 4 below:

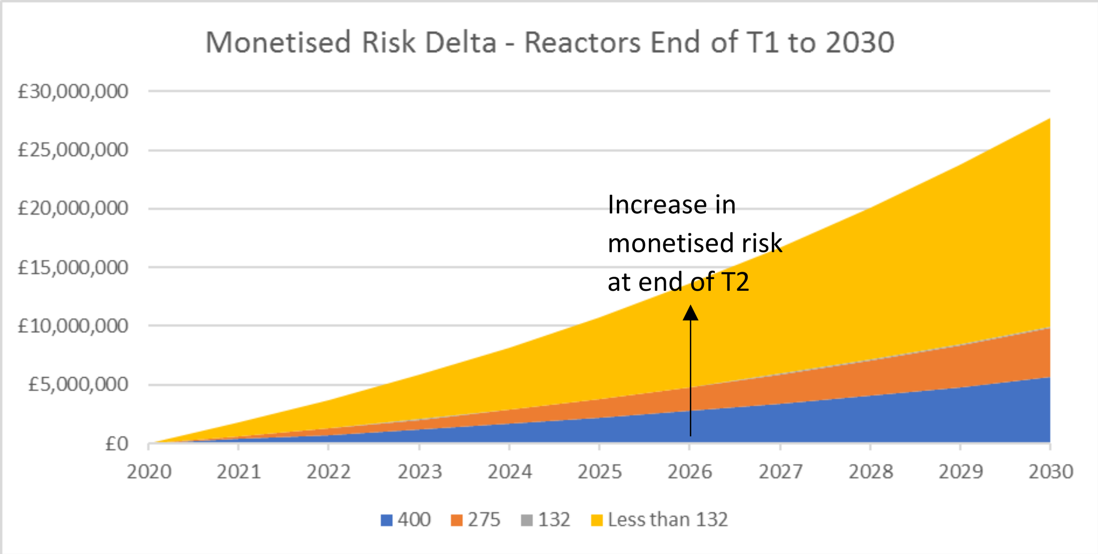

Figure 4: increase in reactor's monetised risk over RIIO-T2 with no interventions

In order to satisfy our stakeholders' priority to maintain current levels of network risk, our reactor interventions will mitigate the £11m increase in monetised risk across the reactor asset class.

4.5 Identifying RIIO-T2 interventions

NGET allocates reactors an End of Life (EOL) score based on the information available about their dielectric, thermal and mechanical condition, it also reflects other significant issues such as excessive noise or oil leaks.[1] The outputs of the scoring method can be compared with output from other internationally recognised bodies such as CIGRE, and the scores grouped by RAG status to give a high-level view of the health of the reactor fleet based on current available condition data in April/May 2019.

We use all available information to support the intervention decisions that we make, this also includes information gathered through post-mortem examinations of assets that have been removed; data from online and offline condition assessments; and the improving understanding of ageing markers in oil.

4.6 End-of-Life Drivers for the T2 volumes

In this section we identify how the T2 interventions align with the end of life assessment categorisation of the reactors, by comparing the monetised risk contribution of T2 interventions in 2025 versus their current EOL score. This has been completed for every asset in Appendix 3 but, to enable an overview in this section, these have been categorised into bands of EOL Score.

There are various discrete scoring methodologies such as the CIGRE code that can aid in a description of each EOL band, shown in Table 12. Asset Health Index (AHI), although superseded in T2, allows comparison with the methodology in T1.

[1] Scoring method and worked examples are available in National Grid TGN(E)306.

EOL Score	AHI	CIGRE Code
95-100	1	E – Very poor condition, high likelihood of failure
89-94	2a	D – Poor condition. Repair or replacement should be considered within the short term
70-88	2b	
35-69	2c	C – Acceptable condition with significant signs of ageing or deterioration
0-35	3/4	B/A – Good condition. Some/minimal signs of ageing or deterioration are evident

Figure 12 – Reactor end of life score categories

The chart below (Figure 6) shows the monetised risk impact of T2 interventions against their current EOL band. It can be seen that over 50% of the monetised risk reduction is delivered from interventions on reactors classified to be in the worst EOL band.

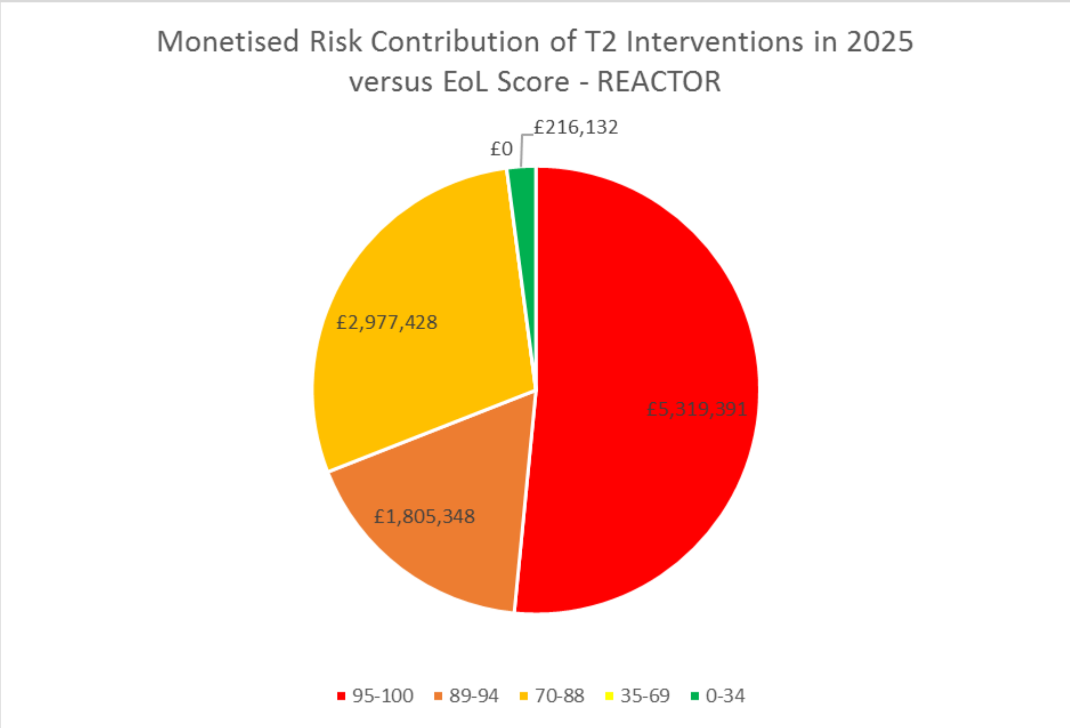

Figure 6 – Reactor interventions' monetised risk reduction by end of life category

Table 13 shows the number of interventions in each EOL band and the average monetised risk contribution in 2025 per intervention.

EOL Band	Volume of interventions	Monetised Risk £m per asset
≥95	[redacted]	[redacted]
89-94	[redacted]	[redacted]
70-88	[redacted]	[redacted]
35-69	[redacted]	[redacted]
0-34	[redacted]	[redacted]
Total Volume	[redacted]	[redacted]

Table 13 – T2 Reactor intervention summary by end of life categorisation

There are [redacted] interventions on assets that are currently within the 0-34 band, implying a low probability of failure. The justifications for these [redacted] interventions are:

- [redacted] unit is planned to be removed as part of a wider substation rationalisation scheme at Wimbledon currently in delivery; and
- [redacted] unit has been included for deliverability and network access synergies at Pitsmoor.

Figure 7 shows the condition assessment driver for the EOL assessments (that determine the probability of failure) against the monetised risk impact of the reactor plan.

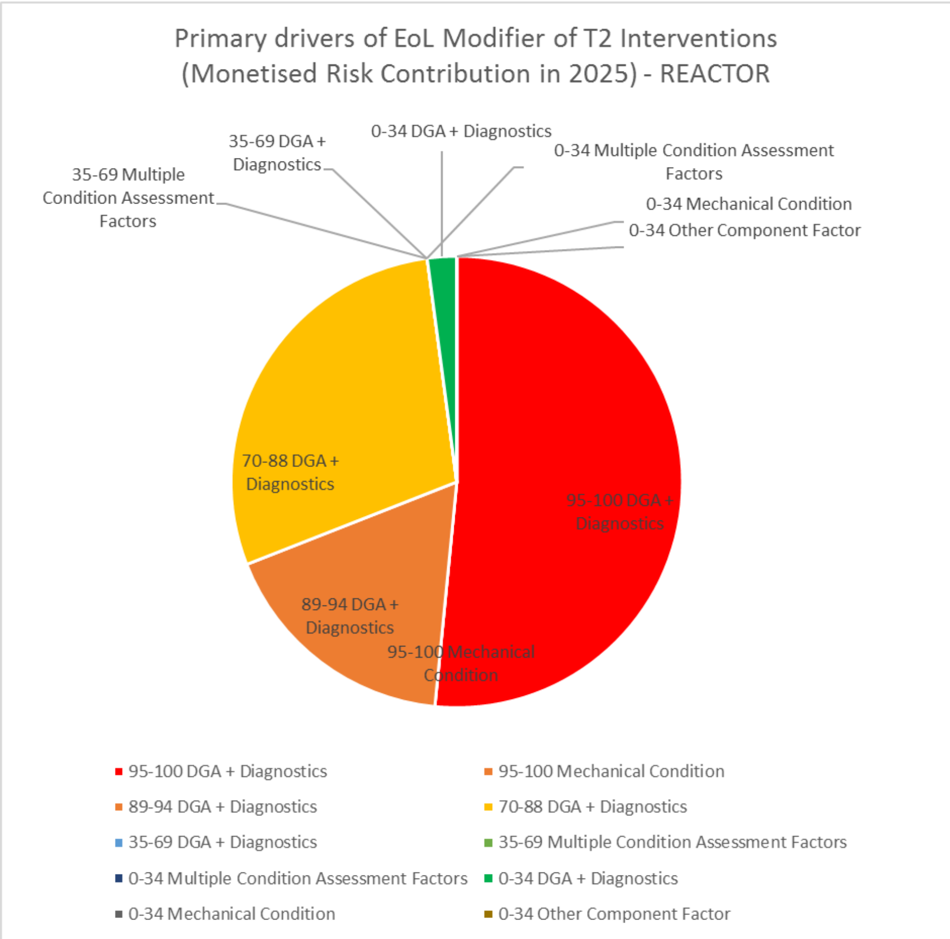

Figure 7 – Reactor interventions' condition assessment driver by end of life category

The bulk of interventions can be seen to be driven by dissolved gas analysis (DGA) oil sampling, which identifies dielectric and/or thermal deterioration of the asset. For more information see Appendix 5.

The EOL scores for different asset categories are shown in Table 6.

Asset Type	Asset Sub-Type	Rating MVar / Description	No. in Service	End-of-Life (EOL) Status		
				R (89 - 100)	A (35 - 88)	G (0 - 34)
Shunt Reactors	13kV	60	[redacted]	[redacted]	[redacted]	[redacted]
		30+30	[redacted]	[redacted]	[redacted]	[redacted]
	TOTAL 13kV		[redacted]	[redacted]	[redacted]	[redacted]
	275kV	100	[redacted]	[redacted]	[redacted]	[redacted]
	TOTAL 275kV		[redacted]	[redacted]	[redacted]	[redacted]

Asset Type	Asset Sub-Type	Rating MVar / Description	No. in Service	End-of-Life (EOL) Status		
				R (89 - 100)	A (35 - 88)	G (0 - 34)
	400kV	200	[redacted]	[redacted]	[redacted]	[redacted]
	TOTAL 400kV		[redacted]	[redacted]	[redacted]	[redacted]
Shunt Reactors (with tap changers)	33 kV	30-60	[redacted]	[redacted]	[redacted]	[redacted]
	TOTAL 33kV		[redacted]	[redacted]	[redacted]	[redacted]
Saturable Reactor	66kV	190	[redacted]	[redacted]	[redacted]	[redacted]
	TOTAL 66kV		[redacted]	[redacted]	[redacted]	[redacted]
Trackside Reactors	25kV	2x40	[redacted]	[redacted]	[redacted]	[redacted]
	TOTAL 25kV		[redacted]	[redacted]	[redacted]	[redacted]
Series Reactors	Multiple	20 or 90	[redacted]	[redacted]	[redacted]	[redacted]
		750 (single tank)	[redacted]	[redacted]	[redacted]	[redacted]
		1320 - 1500 - 1860 (single tank)	[redacted]	[redacted]	[redacted]	[redacted]
		2000 or 2640 (single tank)	[redacted]	[redacted]	[redacted]	[redacted]
		2000 - 2400 - 2750 (3 tanks)	[redacted]	[redacted]	[redacted]	[redacted]
	Total Series Reactor		[redacted]	[redacted]	[redacted]	[redacted]
All Reactors			[redacted]	[redacted]	[redacted]	[redacted]

Table 6: Reactor EOL score by sub-type

Across all sub-types there are [redacted] assets in the Red category (EOL 89+). Interventions on these [redacted] reactors would be required to achieve same level of monetised risk at the end RIIO-T2 as at the beginning of RIIO-T2. If we were not to undertake the [redacted] reactor replacements, less efficient interventions would be required elsewhere to maintain transmission network risk at the agreed level.

We are proposing [redacted] reactor interventions in RIIO-T2:

- [redacted] replacements based on the EOL score[2] as described above;
- [redacted] removal as part of a wider investment at Wimbledon[2] that is in delivery; and
- [redacted] replacement to take a bundling opportunity at [redacted].

Table 7 below shows the proposed breakdown of reactor replacements in RIIO-T2. The average number of replacements per annum is similar in RIIO-T1 and RIIO-T2.

Volume Performance: The increase from [redacted] reactors replaced per year in T1 to [redacted] reactors per year in T2 is driven by the anticipated deterioration of shunt reactor asset condition (as part of the Monetised Risk methodology). The interventions are summarised in Table 7.

[2] The Wimbledon rationalisation project replaces 1 reactor (with an EOL of 85+) and removes 1 reactor

	Vol	RIIO-ET2							RIIO-ET1	
		2021	2022	2023	2024	2025	Total	Average (p.a.)	Total (8-year)	Average (p.a.)
All Reactors (Total)	On	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Off	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Wimbledon*	On	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Off	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

*note that Wimbledon is included in the totals of all reactors

Table 1 - Proposed reactor interventions in RIIO-ET2

4.7 RIIO-T2 interventions by voltage

The details of the specific assets within the intervention plan, including their 'End of Life' assessment scores, probability of failure and monetised risk forecasts to 2031 are presented in Appendix 3 of this paper. A summary of the volumes by reactor voltage as justified by the risk-based CBA is provided below in Table 11:

Relevant asset subdivision	Risk delta (£m) @ 2025	Number of interventions (inc. Wimbledon)	Risk Impact (£m) of Interventions @ 2025
400kV	2.2	[redacted]	[redacted]
275kV	1.6	[redacted]	[redacted]
132kV	0.0	[redacted]	[redacted]
<132kV	7.0	[redacted]	[redacted]
Monetised Risk Total	**10.8**	[redacted]	[redacted]

Table 11 – monetised risk summary for T2 reactor plan

5. Optioneering

To determine the optimum mix of interventions to make on the reactor portfolio, a CBA was undertaken on the available intervention strategies. We have analysed the CBA output for each option, together with a wider technical and stakeholder justification for the work proposed. Detail of our analysis and outcome is presented below.

This justification report sets out the range of options we considered, which needs to be considered in parallel with our quantitative assessment of the main options which are contained within Cost Benefit Analysis spreadsheet with the following reference: NGET_A9.17_Reactors_CBA01. Together they provide comprehensive engineering and economic justification for our proposed volumes and costs.

5.1 Our approach to estimating costs and benefits

We have used a two-stage approach to identify the most cost-effective package of options for this paper.

1. Firstly, we have **identified potential intervention strategies**. This identified a 'long list' of intervention strategies which were then tested for feasibility / applicability. They include a 'do minimum' option. We have not considered non-network solutions since these cannot substitute for the type of investment we are considering in this paper.

2. Once the set of feasible options has been established, we carry out quantitative **Cost Benefit Analysis (CBA)** to identify which option is the most cost effective.

We have included investment costs and Monetised Network Risk into our quantitative CBA, using Ofgem's NPV approach, to determine an NPV estimate for each of the options.

5.2 Potential intervention strategies

Reactive support can be provided either by dedicated equipment on the existing transmission system, by existing synchronous generators on the system (although this pool of support is decreasing as generators decommission), and in the future potentially other sources. Before any replacement is considered, confirmation is sought from the ESO that the reactive equipment is still required due to the changing pattern and mix of generation across the National Grid system.

Additional reactive support, driven by the industry-agreed Common Energy Scenario, requiring the installation of new equipment ([redacted] new reactors by 2025/26), is covered by a separate paper called System Operability.

The long list of potential options for reactor interventions is set out in Table 9.

Option	Detail	Taken forward for full CBA?
1. Do minimum	This option would avoid the planned replacement of reactors (shunt and series) and would allow them to fail in service after which they would be replaced.	**Taken forward**
2. Planned programme of replacement based on monetised risk	This strategy would replace reactors over T2 based on the output of the Monetised Risk methodology Based on our historic and RIIO-T1 experience, it has been assumed for RIIO-T2 that all of the reactor replacements will be in-situ replacements (see Section 4.7 for more detailed description of what in situ reactor replacement involves).	**Taken forward**

Option	Detail	Taken forward for full CBA?
3. Planned reactor refurbishment	This option considers refurbishment of reactors instead of full replacement. While refurbishment is often considered for sub transmission voltage, it is rarely utilised on Wound Plant at transmission levels. In 2014-17 an innovation funded project sought to explore the feasibility of refurbishing 13kV shunt reactors. The hypothesis was that by refurbishing the active part (the core and windings) but keeping the existing tank the replacement time and site works could be kept to a minimum. The key findings were: • Cost was significantly greater (>40%) than buying a new unit from NGETS's bulk contract. • Warranty was limited to the refurbished elements only: sub-optimal warranty position. • Test guarantees on vibration and noise were not met as the refurbishment did not include the tank: sub-optimal noise levels. In addition to the above and given the size of reactors that we have in our fleet, it is very rare that an effective repair or refurbishment of the active part (core and windings) of the reactor can be economically achieved i.e. refurbishment does not offer a significant advantage over procuring a new reactor to meet the current technical specification. The fundamental life limiting process is paper ageing, where a reactor is showing signs of severe ageing the only remedy would be to replace the windings i.e. refurbishment is not an option. Such work could only be completed at a supplier's manufacturing facility, not on site.	**Not taken forward**[3] This option has been discounted for implementation at RIIO-T2 as: • Evidence from an innovation project suggested serious shortcomings with refurbishment approach • Effective refurbishment of the active part of a reactor cannot be economically achieved
4. Replace on poor asset health	This option considers replacing reactors once they have reached an EOL threshold of 89. It allows more planning compared with the Replace on Fail option, provides a chance to plan replacement, and reduces the risk of SQSS non-compliance. However, it does not take account of reactors with EOL scores that see an acceleration in their deterioration and this increases the risk that replacement cannot be achieved ahead of failure. Due to the specialist nature of reactors, there is limited manufacturing capacity and during periods of high demand lead times can exceed 18-months, which is clearly not acceptable when end of life failure is being predicted in a 0-2-year timeframe. This option does not address the risk that many reactors would exceed the EOL threshold, concurrent replacement would not be achievable and transmission network risk would increase.	**Not taken forward** This option has been discounted for implementation at RIIO-T2 because it does not address risk that a high number of reactors would exceed the EOL threshold, meaning that replacement could not be done in the required timeframes.

Table 9 – Reactor intervention options

[3] Please note that on-site refurbishment of other key items will continue to take place during RIIO-T2 e.g. routine oil analysis and regeneration/replacement; corrosion and cooler replacement; oil leaks and gasket replacement; fans, pumps and control maintenance.

5.3 Detailed Analysis & Cost Benefit Analysis (CBA)

Options 1 (Do Minimum) and 2 (Monetised Risk) have been taken forward for full CBA. The results of our CBA for these options are set out in Table 10. The assessment includes both the quantitative CBA results, as well as our assessment against other factors e.g. stakeholder priorities. Our NPV for each option takes account of:

- direct investment costs;
- changes in Monetised Risk as a result of interventions;
- societal benefits from reduced SF6 leakage and/or oil leakage (where applicable);
- avoided costs that would have been incurred by the ESO e.g. constraint costs; and
- safety impacts.

<table>
<tr><th>Option (lifetime)</th><th></th><th>RIIO-T2 Investment Cost (undisc, £m)</th><th>Total Investment Cost (undisc, £m)</th><th>Monetised Risk (disc, £m)</th><th>NPV (disc, £m)</th><th>NPV net monetised risk (disc, £m)</th><th>Decision</th></tr>
<tr><td rowspan="2">Do Minimum</td><td>CBA</td><td>-29.7</td><td>-54.5</td><td>0.0</td><td>-45.4</td><td>-45.4</td><td rowspan="2">REJECTED OPTION</td></tr>
<tr><td>Other considerations (stakeholder, engineering, societal benefits)</td><td colspan="5">Replace on fail has a higher cost than planned asset replacement in part due to the additional equipment needing replacement as a result catastrophic failure. We have discounted this option for two main reasons:
• Security and Quality of Supply Standards (SQSS) non-compliance. This strategy will increase the transmission network risk and may lead to additional transmission network constraints with associated costs. It is therefore incompatible with National Electricity Transmission System SQSS.
• Additional health and safety risk. There are safety risks which could severely restrict operations at a site level if we allow reactors to deteriorate such that they fail in service. For example, if we choose to ignore a developing dielectric fault, then there is a high risk of a catastrophic failure, which we could only mitigate by enforcing risk management hazard zones (sterilising the site for other works and potentially being forced to restrict access to third party land if it falls within the hazard zone), and accepting the fact that collateral damage could occur i.e. other assets might also fail as a result.
In addition, delivery would not be efficient, as the replacement work could not be planned with sufficient lead times to develop the most economical and efficient delivery strategy and scope. Unplanned outages, especially extended outages expected with a replace on fail strategy, would also have an inevitable impact on planned work including customer connections which may be delayed until the system was secured. In order to manage a rise in in-service failures, the strategic spares holding would need to be increased and team(s) of staff put on standby to manage emergency, unplanned replacements.</td></tr>
<tr><td rowspan="2">Planned programme of replacement based on monetised risk</td><td>CBA</td><td>-51.1</td><td>-49.5</td><td>39.2</td><td>-41.3</td><td>-2.0</td><td rowspan="2">CHOSEN OPTION</td></tr>
<tr><td>Other considerations (stakeholder, engineering, societal benefits)</td><td colspan="5">This option provides a planned programme of asset replacement activities. It allows the works to be tendered to achieve the best possible price for the consumer and a steady flow of units to be purchased from the manufacturers. Works can be planned with range of stakeholders (e.g. DNOs) in advance for optimum outage placement.
This option represents continuation of our current practice which allow us to maintain extremely high reliability levels that our stakeholder require. It also offers the balance maintenance cost and replacement volumes across multiple periods to minimize impact on our customers and probability of any consequential costs.
RIIO-T2 plans have been shared with the DNOs to establish areas of interaction whether with their own replacement priorities or outage plans. The opportunity has also been taken to explain the different types of interventions that can take place to understand their concerns over the planned works.</td></tr>
</table>

Table 10 – Reactors CBA

5.4 How RIIO-T2 interventions mitigate network risk

The outcome of the risk-based CBA shows that the most cost-effective solution for the T2 plan is the replacement of [redacted] reactors, contributing £10.3m towards risk reduction against an increase of risk of £10.8m. The risk impact of these interventions is therefore slightly outweighed by the predicted growth in risk over the period by approximately £0.5m. This is shown in Figure 5.

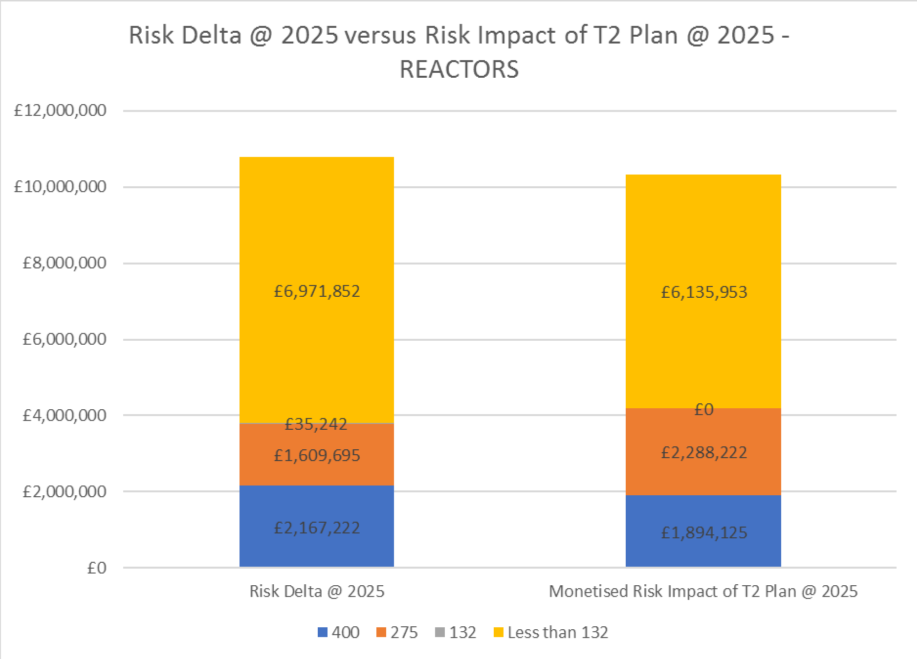

Figure 5 – Reactor risk increase over T2 compared with T2 plan risk reduction, by voltage (kV)

5.5 Reactors replacement options

Reactor replacements are categorised into:

- **In situ replacement** – represent the lowest cost option and preferred approach in our T2 plan. Policy guidance has been produced to ensure that in-situ replacements are considered as the first option, and that the maximum reuse of associated assets where possible is made of existing assets within the wider bay, e.g. switchgear and foundation structures.

- **Offline replacement** – represent the higher costs option, as there are more works to be undertaken with more substantial scope of work. Comparison between in situ and offline replacement scope of work are presented in Table 8.

Category	Key scope	Potential drivers for using option
Offline Replacement	• New bund/reactor housing • New reactor • Possible modification to existing switchgear bays to connect new reactor including possible new cable or busbars • Possible new switchgear bays to connect the new reactor to the busbars • Demolition and removal of existing reactor and bund	• Existing bund / reactor housing are in a poor condition and cannot be reused – full rebuild required • Existing bund / bay are spatially incompatible with new reactor, e.g. new reactor is much larger than existing • Outages not available in necessary timeframe to undertake in-situ replacement, therefore offline build required – generally shorter outage requirements than in-situ replacement

Category	Key scope	Potential drivers for using option
In-situ Replacement	• Demolition and disposal of existing reactor • Repairs / minor modifications to existing bund to accommodate new reactor • Installation of new reactor and connection to existing switchgear	• Existing bund /building is in relatively good condition and can be repaired if necessary • Existing bund can accommodate new reactor with only minor modifications, e.g. small extension to the bund • Sufficient outage duration available to construct – generally longer outage requirements than offline build.

Table 8 - Scope of works, in-situ replacement vs. offline replacement

Given the maturity of these investments in our Network Development Process, site specific assessments for the RIIO-T2 portfolio have not yet been undertaken to determine which assets can be replaced in-situ and which require offline replacement. However, based on our historic experience (including that during T1), it has been assumed for T2 that all of the reactor replacements will be in-situ replacements.

5.6 Timing and deliverability

[redacted] reactor replacements are proposed for RIIO-T2 in total (excluding Wimbledon), with up to [redacted] replacements proposed annually. The key deliverability considerations are:

- **Reactor condition**

  Generally, assets with the highest EOL scores are progressed earlier in T2 to minimise the risk of their failing in service.

- **Outage availability**

  A reactor is required to be out of service for approximately 16 weeks to allow in-situ replacement. A shorter outage of approximately 8 weeks is possible if an offline build of the reactor replacement is progressed. An offline build involves constructing a new bund elsewhere on the substation site, and during the outage, connecting the new reactor to the existing site. Offline reactor builds are more expensive than an in-situ replacement and are normally only considered where a relatively short outage is available in the timeframe necessary for replacement.

  Reactor replacements must be carefully planned to ensure the wider transmission network is still compliant with security of supply standards. It is common for reactor replacements to be limited to the summer months, as this is usually the period of lowest demand on the transmission network. This provides a relatively limited window for reactor replacement works to be undertaken. Undertaking works in the winter months to spread workload is always considered, however this is rarely possible from a transmission network access perspective.

- **National Grid resource**

  Specialised NGET resource is required at each site to support a reactor replacement, including specialist commissioning personnel. This is a finite resource and some smoothing would be required to manage this constraint.

- **Development timescales**

To ensure the most efficient solution is progressed for delivery, sufficient time is required to allow project development and contracting. This activity is reliant on finite internal and external design resource, limiting the number of reactor replacements that can be progressed to delivery annually.

- **Reactor supply chain**

  There are a limited number of reactor suppliers worldwide and the volume of new reactors that can be built annually is limited. Lead times vary typically between 10-18 months.

6. Assessment of cost efficiency

Table 14 provides costs and volumes of planned reactor replacement in our RIIO-T2 plan and compares them against historic RIIO-T1 performance.

Reactor projects	RIIO-T1				RIIO-T2	RIIO-T1		RIIO-T2
	T1 Allowed	T1 Spend Actuals	T1 Spend Forecast	T1 Spend (8-years)	T2 Spend Forecast	Annual Average (8-years)	Annual Av (first 6 years)	Annual Average
Total cost / allowed (£m)	42	43.4	17.2	60.6	54.8	**7.6**	7.2	**10.96**
Total volume (Volumes On)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Cost per unit (£m/REA)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Volume from other projects	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 14 - RIIO-T1 Cost and Volume (On) Performance and T2 forecast

In T2, [redacted] reactors will be replaced through reactor only schemes (i.e. excluding Wimbledon). Based on the total cost of the reactor portfolio and the number of replacements, the T2 unit cost is anticipated to be £[redacted]m per reactor. This compares to £[redacted]m per reactor replacement in T1, (table 5 in section 3 excludes the static compensator outlier which is included in the table above). Given the relatively small sample size of reactors in T1 and T2, the small difference is driven by variations in the scope for each unique scheme. These differences include, for example, whether a bund wall needs extending or whether a noise enclosure is required.

In section 6.1 we explain the differences in unit costs between price controls and show that our RIIO-T2 costs are efficient using external benchmarking.

It is important to also note that our RIIO-T2 unit costs embed efficiencies achieved in RIIO-T1, in particular:

- **Procurement strategy**: Savings were made by opening up the procurement strategy on wound plant to find new suppliers via a framework agreement from the global market. This resulted in new suppliers coming on board from the Far East. Prices were obtained on a volumetric basis as standard units and designs were used which could be deployed across several sites and orders placed indicating discounts for higher volumes.

- **Integrating works**: Further savings were made by integrating works with other works at the same site. For example, the asset replacement of both transformers and reactors at Iver substation were grouped to achieve savings by being delivered as one portfolio of works.

6.1 Unit Cost Background

Reactor replacements are categorised into two types: in-situ and off-line replacement. As noted in section 4, the lowest (and preferred) cost option is to replace reactors in-situ where possible. Our T2 business plan assumes all replacements are in-situ projects. Where it is not possible to use this approach, a more extensive offline replacement will be undertaken. The highest unit costs tend to be incurred for an unplanned (emergency) replacement. The key driver for the higher cost tends to stem from reduced opportunity to refine plans and secure the best prices from the supply chain. An unplanned in-situ replacement would cost approximately [redacted] more than a planned in-situ replacement.

6.2 Comparison of unit costs to external benchmarks

TNEI Services have carried out a benchmarking exercise which compares our unit costs to those of the wider industry. Figure 8 summarises how our unit costs compare to industry benchmarks. The graphs are aligned with Ofgem's requirements for reporting and calculating capital costs in the Business Plan Data Tables i.e. they exclude development, design and project management costs. **For this reason, they are systematically lower than all the unit costs discussed previously in this report.**

[redacted]

Figure 8: Costs versus TNEI benchmarks and number of T2 interventions

The following observations can be drawn:

- the unit cost of 400kV reactors in T2 [redacted] TNEI benchmark; and unit cost for 275kV reactors in T2 are [redacted] TNEI benchmark.
- while the unit cost of 400kV and LV reactors [redacted] T2 compared to T1, [redacted] for 275kV reactors. This is because the [redacted] of the T2 inventions for 275kV reactors [redacted] compared to T1.
- the unit cost of LV reactors [redacted] as they are typically 13kV 60MVA units, [redacted].

Please note that we are referring to primary voltage because this is how we have been required to split out units in the BPDT. However, for shunt reactors, cost also correlates to their capability in MVAr. Care must be taken when comparing units with external benchmarks in case they are of a fundamentally different capacity albeit connected at the same voltage.

6.3 Unit cost outliers

The following graphs are also aligned with Ofgem's requirements for reporting capital costs in the Business Plan Data Tables i.e. they exclude development, design and project management costs. **For this reason, as before, they are systematically lower than all the unit costs discussed previously in this report.**

Costs for a small number of reactors differ significantly from the average unit cost for each voltage category, we set out the explanations for each below.

[redacted]

Figure 9: Individual LV reactor unit costs against T1 and T2 averages

The significantly lower cost of the [redacted] shunt reactor replacement is because costs that were incurred on a terminated project can be reused in this project.

[redacted]

Figure 10: Individual 275kV reactor unit costs against T1 and T2 averages

The higher cost for [redacted] replacement is because of increased civil costs due to the additional cost of removing a fire wall at the site.

[redacted]

Figure 11: Individual 400kV reactor unit costs against T1 and T2 averages

The higher cost for [redacted] is mostly due to [redacted] associated with decommissioning 2 x 60 MVAr reactors and replacing them with one 200MVAr unit.

6.4 External Best Practice

NGET participates in the International Transmission Operations & Maintenance Study (ITOMS). For the purposes of benchmarking the maintenance of large oil filled plant, the outputs for transformers are pertinent to reactors. Headlines from the analysis of the benchmarking report for transformer maintenance 2017 can be found in the A9.16 Justification Paper – Non-Load – Transformers. This shows that we are in (at 400kV) or on the edge (at 275kV) of the low cost/strong service quadrant for large oil filled plant.

7. Key Assumptions, Risk and Contingency

7.1 System Requirements

As outlined in the introduction when a reactor replacement is triggered, studies will be performed to understand the transmission network need at that location. This may result in a direct replacement or decommissioning of the reactor. Replacement volumes per year are in line with actual volumes delivered in RIIO-T1.

Any new reactive compensation requirement is covered in separate load related papers which address reactive plant; Incremental Wider Works A7-8.08 & System Operability A7-8.08.

7.2 Transmission Network Access

Asset failure or faults on the transmission or distribution network may affect the availability of resource or outages. Delays or cancellation of outages may result in under-delivery of reactor replacements required to achieve the required level of transmission network risk. We work closely with the ESO to mitigate this risk.

7.3 DNO Outages

Most reactors planned for replacement are located at GSP substations and replacement of these assets may be affected by works on the DNO system. Early engagement with the DNOs is anticipated so works can be optimised or innovative ways of working can be explored.

7.4 Costs

Costs have been assessed across the whole of the RIIO-T2 reactors portfolio. The costs assumed in this paper are [redacted] replacements of existing assets.

8. Conclusion

A summary of T1 performance on reactors was provided. The investment drivers and approach for T2 was outlined. In developing the T2 reactor replacement plan, NGET has sought to balance stakeholder feedback, which values maintaining network reliability, with ensuring the plan delivers the best value to end-consumers.

A number of asset management options have been considered, including do nothing and replace on fail, refurbishment, or in-situ / offline replacement. A cost benefit analysis was undertaken that recommends a planned programme of in-situ replacement identified through the monetised risk model.

The monetised risk methodology has been used to determine that [redacted] reactor replacements are required in RIIO-T2 to ensure that monetised risk at the start of RIIO-T2 is no worse than monetised risk at the start of RIIO-T2. [redacted] further interventions ([redacted] replacement and [redacted] removal) at Wimbledon will occur during T2, as the rationalisation project that commenced in T1 progresses through delivery.

This justification paper proposes a total spend of £54.8m. A comparison of unit costs between T1 and T2 is given. Based on an average of scheme costs the average unit cost of a reactor replacement is [redacted] T1 (£[redacted]m per reactor in T2 vs £[redacted]m per reactor in T1). [redacted]

APPENDIX 1 – Reactors replaced in T1

The list has been redacted.

Remove ([redacted]) + Replace ([redacted]) = Total of [redacted] offs volumes

Replace ([redacted]) + New ([redacted]) = Total of [redacted] on volumes

APPENDIX 2 – Reactors to be replaced in T2 (excluding Wimbledon)

The list has been redacted.

Table excludes the replacement of [redacted] at Wimbledon.

APPENDIX 3 – RIIO-T2 Lead Asset Table for Reactors

Reactors

EoL Score	CIGRE Code
95-100	E – Very poor condition, high likelihood of failure
89-94	D – Poor condition. Repair or replacement should be considered within the short term
70-88	
35-69	C – Acceptable condition with significant signs of ageing or deterioration
0-34	B/A – Good condition. Some/minimal signs of ageing or deterioration are evident

**This is not related to AHI*

The list has been redacted.

APPENDIX 4 – The principle of monetised risk and its predecessor

To identify and prioritise assets in need of intervention we apply an assessment of failure *likelihood* and then the impact that any failure may have on the electricity system, the safety of people and the environment. This impact is described as the *criticality* or *consequence* of an asset, should it fail in service. This principle is consistent across the two approaches evident in our business plans.

Failure likelihood may simply be expressed as a probability up to 100% (or 1). This is the case for our lead assets such as reactors. A proxy for probability of failure is used in the form of a scoring system - the Asset Health Index (AHI) for other assets termed 'non lead' such as protection & control or overhead line towers. This scoring system, which places assets into discrete bands of '1' to '4' was used for all Lead assets for RIIO T1. It was combined in a matrix with an asset criticality score, again banded from 1 to 4 to arrive at 'Replacement Priorities'. The management of the volumes of assets in each replacement priority band was the basis for the capital plan submitted for RIIO T1 and one of the Network Output Measures in Special Licence Condition 2M.

The new approach developed for Lead assets and forming the basis of the Network Asset Risk Metric (NARM) achieves a greater level of maturity than the Asset Health Index and Criticality approach that preceded it. It does this in a number of ways:

A simple probability of failure for each asset provides for a greater resolution of asset risk of failure. The low number of discrete bands employed by the AHI and Criticality approach produces a lower resolution measure and doesn't allow for prioritisation within those bands.

By monetising the consequences of asset failures, it is possible to measure whole network risk and enable decision making between different asset classes. The AHI and Criticality approach outputs volumes of asset 'Replacement Priorities'. It does not define a monetised impact of this risk and there is no equivalency between asset types (e.g. a number of reactors in Replacement Priority '1' is equal to some volume of overhead line conductor in the same or different replacement priority bands). This impedes any network-wide measure of risk and plan optimisation across asset classes.

The two approaches can be summarised in the following table:

Approach	**Likelihood of Asset Failure**	**Consequence of Asset Failure**	**Risk is a function of Likelihood of an event and its consequence**
Asset Health Index and Criticality	Scores assets according to their health. AHI1 to AHI4	Each asset is scored according to its system, safety and environment impact should the asset fail. The maximum score is used.	A Replacement Priority is output based on a matrix of AHI and Criticality score. Poor health assets in highly critical locations are identified for intervention over good health assets in locations with a low criticality.
Monetised Risk	Each asset has a probability of failure. This probability is arrived at by use of an 'End of Life Modifier'. This is a score that maps an asset to a place on a probability of failure plot. An asset is assigned an 'equivalent age' determined by its place on the probability of failure plot.	For each asset failure event, there is a probability some other event will occur. These events have safety, system and environmental consequences that are monetised.	The probability of failure of an asset multiplied by the probability of an event with a monetised consequence produces the monetised risk of asset failure. As the same currency is used to define the consequences of asset failure, a whole network measure of risk is enabled as well as prioritisation between different assets.

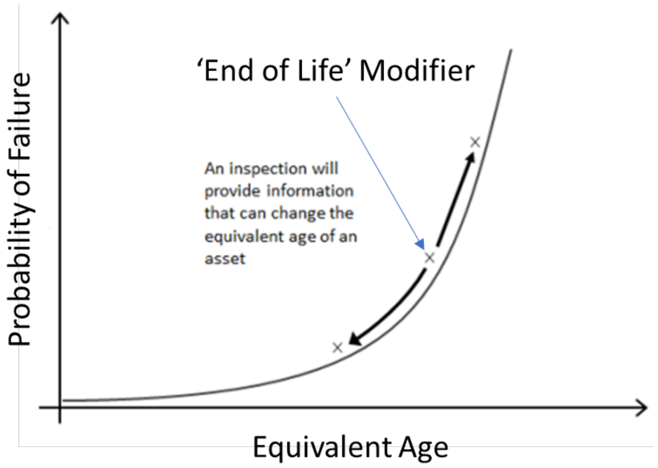

Chart depicting the principle of the End of Life Modifier. The rise in monetised risk is governed by an asset's probability of failure plot, the magnitude of the risk at any given point in time is a function of the probability of failure (variable) and the probability of an event with a monetised consequence (fixed).

Our method will continue to develop so that a greater number of assets contribute to a monetised measure of risk and enable enhanced optimisation of business plans. Both assessment approaches may be employed in the transition to a monetised risk methodology, translating for example, Asset Health Indices into its equivalent measure, an 'End of Life Modifier' and vice versa. The simple, discrete bounds of the AHI are useful in providing qualitative meaning to a continuous scoring system.

nationalgrid

APPENDIX 5 – EoL Assessment Factors and Inspection Frequencies for Reactors

To determine the end of life assessment of an asset, several different data types may be called upon. Reactor assessments rely heavily on condition data from Dissolved Gas Analysis (DGA), periodic inspection or more intrusive diagnostic tests if an event (e.g. a through-fault) or worsening condition indicator occurs.

The below table summarises the end of life scoring approach for reactors based on the types of data employed and the various factors that make up an assessment.

EoL Assessment Factor	**Dielectric Factor**	**Thermal Factor**	**Mechanical Factor**	**Other Component Factor**
EoL Assessment Input	**Arcing, sparking and partial discharge faults**	**Overheating faults; degradation of solid insulation, ultimately leads to a dielectric failure**	**Damage to the winding, loss of mechanical clamping – reduces capability to withstand short fault**	**Combination of tap-changer issues (only applies to a few reactors), oil leaks, vibration, tank corrosion issues**
Asset Inventory Data	Asset Family - Type/Manufacturer. Cross reference condition assessment and end of life scrapping (post mortem) reports with sister units to aid interpretation of and drive scores Age is not a consideration			Component Obsolescence (e.g. tap-changer) Age is not a consideration
Condition Data	Oil sampling for DGA (internal arcing and sparking faults)	Oil sampling for DGA including furans and methanol analysis (overheating fault, insulation ageing)	Winding Resistance Test Frequency Response Analysis	Exceptional oil top ups may be diluting diagnostic markers
Performance Data	NA		NA	Oil top-up data from the Oil Management Unit Corrosion defects 3rd Party noise complaint Tap-changer defects
Operational Duty Data	NA	Loading data	Initiates condition checks if suffers a through-fault	Tap-changer heavily used
Operating Environment Data	NA			Effects of corrosion managed through maintenance painting may be indirectly evident in oil top up data if tank corrosion has led to oil leakage or through recorded defects

Reactors are inspected on the following frequencies:

Inspection Type	Frequency
Oil Sample	Yearly
Enhanced Oil Sample including Online Monitoring	As Required
Bushing RFI and Thermography	3 Months
Winding Resistance Test	As Required
Frequency Response Analysis	As Required
Basic Maintenance	3 Years
Major Maintenance	12 Years
Tap Changer Op Test	Yearly
Tap Changer Intermediate	3 or 6 years (type variants)
Tap Changer Major	9 years