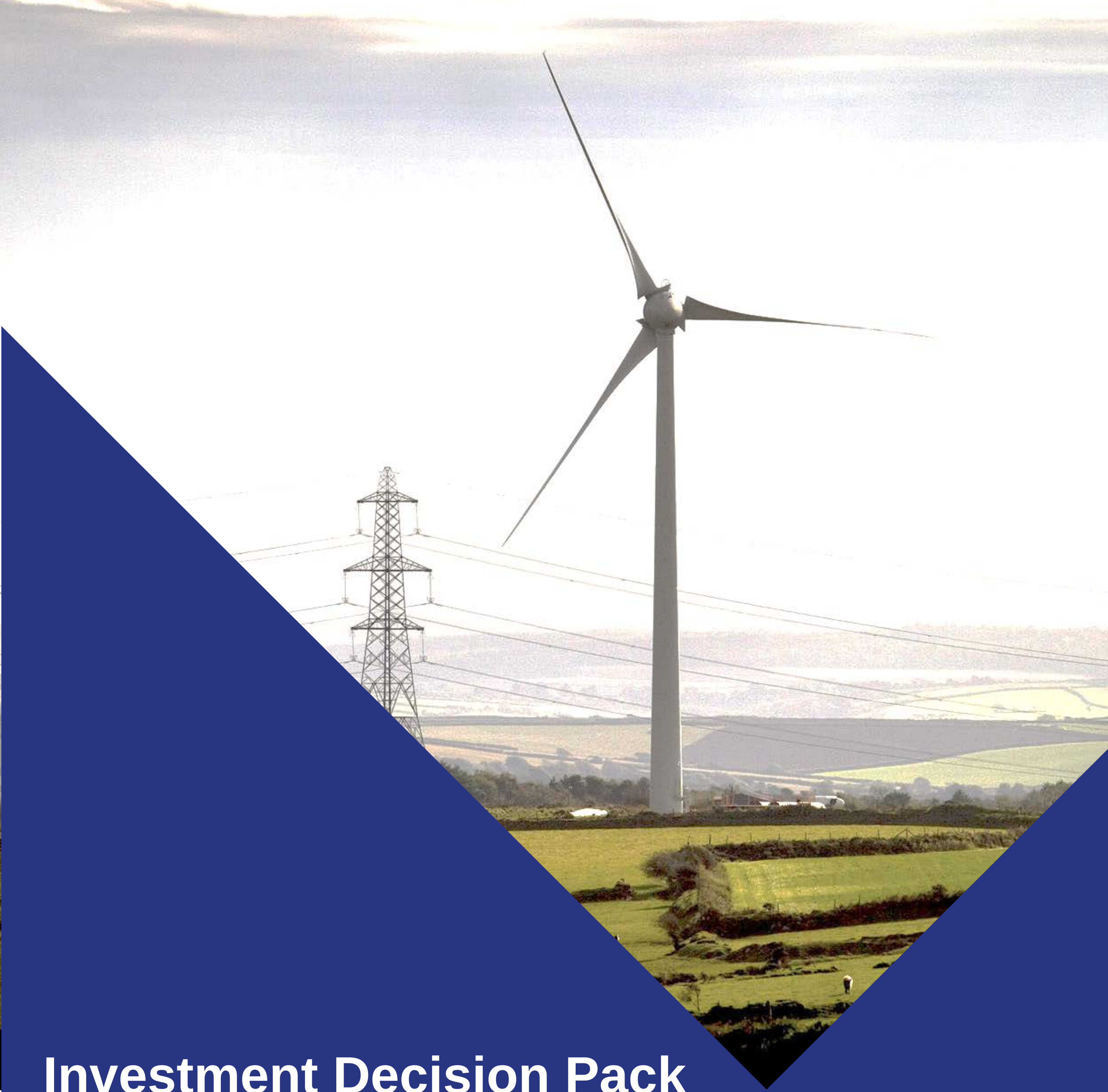

Investment Decision Pack
NGET_A9.16 - Transformers
December 2019

As a part of the NGET Business Plan Submission

nationalgrid

Engineering Justification Paper; Non-Load Related Transformers			
Asset Family	Transformers		
Primary Investment Driver	Monetised Risk (Lead Asset)		
Reference	A9.16		
Output Asset Types	Transformers		
Cost	£241.216m		
Delivery Year(s)	2021-2026		
Reporting Table	C2.2A		
Outputs included in T1 Business Plan	There are no volumes that are present in T1 (see explanation in Section 8)		
Spend Apportionment	**T1**	**T2**	**T3**
	£21.108m	£220.025m	£0.083m
Completion of T1 schemes		£6.057m	
Development schemes for T3		£26.953m	
Total	**£21.108m**	**£253.035m**	**£0.083m**

Contents

1. EXECUTIVE SUMMARY

This paper provides justification for a total spend of £241.216m to deliver the asset replacement of [redacted] transformers over the RIIO-T2 period. In addition to the [redacted] units covered in this paper, National Grid's RIIO-T2 plan also includes:

- [redacted] strategic spare transformers which are covered in a separate Justification Report (A9.18 – Strategic Spares)
- [redacted] transformers delivered by Wimbledon Substation non-load investment which are currently in delivery and excluded from our analysis in this justification report.

Transformers play an important role in connecting our transmission network with other parts of the energy system. Their failure can have large negative impacts both on security of supply and safety.

We have been able to achieve our RIIO-T1 network risk target for transformers by replacing a lower volume than originally envisaged. This is due to life extension which we were able to achieve based on research to improve our understanding of asset deterioration. This life extension means that we have reduced the volume of units requiring replacement over the RIIO-T2 period, embedding an efficiency of [redacted] units (equating to an estimated avoided cost of £97m) into our RIIO-T2 programme.

Our stakeholders have stated that maintaining the current level of network reliability is important to them. We have identified transformers for intervention during RIIO-T2 in order to maintain the monetised risk score from the end of the RIIO-T1 period to the end of RIIO-T2.

SuperGrid Transformer (SGT) replacements for RIIO-T2 have been determined using the Monetised Risk methodology. This identifies the most critical assets that are in poor health so that they may be addressed to maintain network reliability. Monetised risk modelling concluded that [redacted] SGTs would have to be replaced to maintain the same risk level across the RIIO-T2 period (in addition to the Wimbledon units).

Static Compensator Transformers (SCT) replacements for RIIO-T2 have been determined using the End of Life (EOL) methodology. This is because SCTs are components of Reactive Compensation equipment, which is a non-lead category and is not assessed using Monetised Risk. The EOL output identifies the replacement of [redacted] units during RIIO-T2, bringing the total volume to [redacted] units.

The annual volumes ([redacted] units including strategic spares and Wimbledon substation) proposed to be delivered over the T2 period are slightly higher than average annual volumes during RIIO-T1 ([redacted] units).

We have carried out optioneering around the identified RIIO-T2 interventions to ensure the most appropriate approach is identified.

Our initial identification of options was as follows:

i. Do minimum (maintain only and replace on fail)
ii. Planned programme of replacement based on monetised risk
iii. Transformer refurbishment.

Refurbishment was ruled out following a RIIO-T1 innovation project which found refurbishing shunt reactors (which are physically similar to transformers) was not feasible or cost effective. Option iii was therefore not taken forward for full Cost Benefit Analysis (CBA).

Our CBA found that Option ii was favourable to Do Nothing in NPV terms. Although investment costs and volumes ([redacted] interventions versus [redacted] under Do Minimum) were higher, the risk mitigation benefits gave a positive NPV overall. This therefore represents our preferred option.

The costs presented in this paper have been developed through a robust process informed by our extensive monitoring of the market and technical expertise. On this basis we have developed bespoke unit cost estimates for each of our RIIO-T2 interventions.

Our proposed transformer replacement strategy has been shared with DNOs to establish areas of interaction and best practice. In line with stakeholder feedback concerning their desire for network reliability, it will enable us to deliver the most cost-effective solution for end consumers and manages deliverability risks to reduce disruption to the transmission system.

Table 1 below provides costs and volumes of planned transformer replacements in our RIIO-T2 plan and compares them against RIIO-T1 data. In order to ensure comparability of the data, the volumes and costs in Table 1 include the [redacted] strategic spare transformers which are justified in Justification Report A9.18 - Strategic Spares. As these [redacted] spare transformers are not justified through this justification report, they are not included in the optioneering section of this paper.

Table 1: RIIO-T1 versus RIIO-T2 costs and volumes (excluding Wimbledon, including strategic spares)

	T1 Allowances	T1 Actuals	T1 Forecast	T1 (all years)	T2 forecast	T1 annual average	T1 annual av (actuals)	T2 annual average
Total cost (£m)	764	297.6	146.7	444.3	272.6	55.5	49.6	54.5
Total volume	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Cost per unit volume (£m)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Our RIIO-T2 costs per unit are lower than the average of the T1 period but higher than those forecast for the last two years of the current period. This is due to a combination of factors:

- In the early years of the T1 period, we had to undertake some expensive off-line replacements
- In the latter years of the T1 period, we have taken advantage of an unusual opportunity to procure a large number of units of two standard designs which meant that we achieved a highly competitive rate for units currently in delivery, whereas the T2 plan entails the delivery of smaller batches
- Rising commodity costs have already increased equipment purchase costs today for units which will be delivered in the early years of the T2 period.

We have sought to control rising costs as far as possible through:

- **Embedding RIIO-T1 efficiencies:** incorporating the benefits of the transformer asset life extension and seeking wherever possible to replace transformers 'in situ' rather than offline
- **Tying unit costs to industry benchmarks:** [redacted]

[redacted]

Figure 1: Drivers of change in annualised cost between RIIO-T1 and RIIO-T2

2. INTRODUCTION

The Electricity Transmission system's purpose is to transfer large amounts of power over long distances. High voltage is employed to do this is in an efficient way as, generally, the higher the system voltage the lower the transmission losses, thus providing the most efficient method of power transfer, minimising overall system losses.

Transformers are used where interconnected systems with different operating voltages need to interface. The transformer provides two functions, transforming the voltage and introducing an impedance between the systems, controlling fault currents to safe levels. Transformers are essential for the safe and reliable connection of the transmission network to:

- Generation
- Distribution Networks
- Railway traction supplies
- Directly-connected demand (such as steelworks and large customers)

In addition, they are also used to connect the two transmission network voltages (275kV and 400kV).

There are two main transformer types:

- **Supergrid transformers (SGTs)** are used at generator connections to increase voltage and at substations to reduce it again for onward for onward distribution to consumers.
- **Static Compensator Transformers (SCTs)** are used to interface power electronic compensation equipment to the transmission network and are a critical element of the National Grid system in that they allow effective voltage control of the transmission network.

Transformers are large, oil-filled assets, and catastrophic failure can threaten other substation assets. An example of this is low probability but high impact fires. Transformers are located where generators and demand connect, hence their failure can have an impact on energy supply to distribution networks, generators and directly connected customers (e.g. rail, steelworks).

3. RIIO-T1 VOLUMES AND PERFORMANCE

3.1 T1 Performance versus Allowances

Table 2 summarises intervention volumes carried out in RIIO-T1 by displaying the total volumes delivered (forecast until the end of RIIO-T1) and compares them to the RIIO-T1 allowance.

Table 2: RIIO-T1 costs and volumes versus allowances

	T1 Allowances	T1 Actuals	T1 Forecast	T1 (all years)	Annual average	Annual av (first 6 years)
Total cost (£m)	764	297.6	146.7	444.3	55.5	49.6
Total volume	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Cost per unit volume	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

The RIIO-T1 allowance was £764m to replace a total of [redacted] transformers. We are forecasting total spend over the same period to be £444m which is £320m below our allowance. The drivers of this change are summarised in Figure 2 and discussed below.

Figure 2: Drivers of RIIO-T1 performance

The key drivers for the reduction in costs between the start of RIIO-T1 and the current RIIO-T1 forecast are:

Life Extension through innovation (£215m reduction)

National Grid concentrated on delivering maximum value through our innovation projects, using new technology and specialist partners to deliver benefits for the industry and, most importantly, consumers. We have conducted long-term, extensive research, condition monitoring, forensics and modelling to better continuously refine our understanding of the condition of individual transformers, families of transformers and the fleet. As an example, during RIIO-T1 period we have:

a) Changed the way we carry out oil regeneration and prevent the oil becoming corrosive which is reducing the risk of transformer failure and unreliability resulting from corrosive sulphur in oil (see our TOPICS innovation project). As an example, our in-house Oil Management Unit has been used at

Bishop's Wood and Blyth substations, improving the asset health of deteriorating transformers and deferring their replacement, resulting in forecasted savings of around £10m during RIIO-T1.

b) Enhanced fire-resistant transformers using synthetic ester fluid ([redacted]) for cooling, reducing the need for fire protection systems.

c) Developed RESNET methodology which allow us to combine thermal models for transformers with climate data to consider the future impact on our assets.

The focus on innovation and better understanding of the deterioration of our assets has enabled us to investigate innovative methods and technologies to maintain or even extend the expected life of transformers. This innovation which has resulted in the life extension of transformers relates to all transformers of a particular type, not just transformers in RIIO-T1. The benefits are therefore seen in T1, T2, T3 and beyond.

Sourcing, contracting and scoping (£34m reduction)

- National Grid has broadened its supplier base beyond the 'traditional' markets and actively pursued new suppliers in lower-cost countries (e.g. the bulk purchase of transformers from South Korea). Bundling investments helps to provide full portfolio visibility to the market and allows early engagement with the supply chain. Investment bundling also enables us to reduce costs by providing a firm bulk purchase plan to manufacturers for a longer period so that economies of scale can be achieved.
- The scope of works required on each project is regularly reviewed and challenged, to provide maximum benefit to the consumer. For example, in the case of in-situ transformer replacements, condition assessments of the existing bay equipment and civil structures such as transformer plinths, oil bunds and fire barrier walls has meant where possible we re-used these structures, while not increasing the level of system risk.

External factors (£59m reduction)

During RIIO-T1 not all transformers which were removed required replacement, for instance it may have been because a new transformer was installed elsewhere on the transmission network or demand in a local area had changed since the transformer was originally installed. Actual volumes of transformer addition and removals, as well as a forecast for the remainder of T1, are presented in Table 3 below:

Table 3: Transformer removals and replacement over RIIO-T1

Year	Confirmed to date						Forecast		Total	Average per annum
	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21		
Volume Off	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Volume On	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

By the end of RIIO-T1, more transformers are forecast to be removed from the transmission network than had originally been installed. Appendix C shows: a) the [redacted] units taken off the system in RIIO-T1 with no like-for-like replacement required, and b) the [redacted] units added to the system which did not replace a removed unit.

Provision in the price control settlement (£12m reduction)

- **Under-utilisation of spares (£15m reduction):** Total under-utilisation of spares during RIIO-T1 has been £15m.

- **T1 spend for scheme delivery in T2 (£3m increase):** In 2019, the RIIO-T2 business plan has been further reviewed in light of the latest asset health information and monetised risk methodology. It has resulted in a £3m increase in forecast RIIO-T1 spend for scheme delivery early in the next price control.

RIIO-T1 Maintenance Performance

We maintain and operate our ageing transformer fleet in an efficient way. We participate in the International Transmission Operations & Maintenance Study (ITOMS) [redacted] The ITOMS study assesses the effectiveness of maintenance, which is measured by e.g. comparing maintenance costs and operational disturbance levels.

Analysis of the 2017 benchmarking report for transformer maintenance produced the following headlines with respect to our performance:

- **Maintenance cost per transformer is less than the Peer Average**
  - 275kV fleet is on the edge of the low cost/strong service quadrant
    - Lower cost than equivalent organisations across Europe (EUR)
    - Lower service level than EUR
    - Spend less than average per unit
  - **400kV fleet is in the low cost/strong service quadrant**
    - Lower cost than EUR
    - Lower service level than EUR
    - Spend less than average per unit
- **Transformer Outages per 100 Transformers is less than the Peer Average**

Given that maintenance costs increase as transformer components (such as fans, pumps, radiators) start to develop age-related faults, it would be reasonable to conclude that our asset management performance is cost-effective and good value as demonstrated by being categorised in the low cost/strong performance quadrant.

3.2 RIIO T1 Spend Profile

Table 2 showed higher costs per unit for the first 6 years of RIIO-T1. This is because the first six years included [redacted] expensive off-line replacements while there are [redacted] in the remaining two years.

Off-line replacements are typically double the cost of in situ replacements and for this reason it is not our preferred option for asset replacement (see box below). However, where physical space is a constraint or system access is likely to trigger high constraint costs, we undertake off-line replacement based on a whole system cost benefit analysis.

Replacement Options – In Situ and Major Works

Transformer replacements are categorised into:

- **In situ replacement** – 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 optimal re-use is made of existing assets within the wider transformer bay, e.g. switchgear and foundation structures
- **Major works asset replacement** – a higher cost option, as there are more works to be undertaken with a more substantial scope of work. (A comparison between straightforward replacement and what would be classed as a major replacement scope of work are presented below.)

Category	Key scope	Potential drivers for using this option
Major works asset replacement	• Demolition and removal of existing transformer and bund • New bund • New transformer • Possible modification to existing switchgear bays to connect new transformer including possible new cable or busbars • Possible new switchgear bays to connect the new transformer to the busbars	• Existing bund / bay are in a poor condition and cannot be reused – full rebuild required • Existing bund / bay are spatially incompatible with new transformer, e.g. new transformer is larger than the existing unit • Outages are not economically available to construct in-situ replacement, therefore offline build required – shorter outage requirements than in-situ replacement
Straightforward in-situ replacement	• Demolition and disposal of existing transformer • New transformer • Repairs / minor modifications to existing bund to accommodate new transformer • Installation of new transformer and connection to existing switchgear	• Existing bund is in relatively good condition and can be repaired if necessary • Existing bund can accommodate new transformer with only minor modifications, e.g. small extension to the bund • Sufficient outage duration available to construct – longer outage requirements than offline build.

Site-specific assessments for the RIIO-T2 portfolio have been undertaken via a mixture of desk-top analysis and site surveys to determine which assets require replacement with minor civil works only and which would require major civil works such as complete bund replacement

[redacted]

(a) [redacted]
(b)

4. INVESTMENT NEED

4.1 Investment Drivers

Feedback from our programme of stakeholder engagement indicates that consumers and customers want us to maintain network risk at current levels. If we do not intervene on assets during the RIIO-T2 period and beyond, network (or asset) risk will rise, which will increase Energy Not Supplied to our customers. The rate of this rising risk informs the volumes required to be replaced in any given period. This rate is informed by the probability of failure (PoF) and the consequence of failure (CoF), as set out in Ofgem's NARMs methodology.

The 275kV transmission network was built from 1954 onwards with the 400kV transmission network developed from the mid-1960s, and whilst we have a robust maintenance regime, this will not mitigate inevitable end of life asset issues.

4.2 Approach to Establishing Intervention Need for Transformer Assets

Transformer replacements for RIIO-T2 have been determined using two different methodologies:

- Monetised Risk methodology for SGTs
- End of Life methodology for SCTs

Section 4.2.1 provides an overview of these methodologies. Section 4.2.2 shows what factors drive the assessment of end of life for each of our transformer assets, and the frequency with which we gather this information.

4.2.1 Overview of methodologies

The principle we apply to end-of-life assessment is consistent across all assets. We are developing our approach to these assessments across the different fleets we own. This is in line with the RIIO-T1 direction from The Authority on the development of Network Output Measures (NOMs).

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 transformers or circuit breakers and is in line with the direction from The Authority.

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:

1. 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.
2. 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 provides 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 transformers 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 prioritisation between asset classes under the AHI and Criticality approach.

Since SCTs are classified as a Reactive Compensation asset, we undertake their assessment using the End of Life scoring methodology, and do not calculate monetised risk for these assets. The two approaches are summarised in Table 4:

Table 4: End of life assessment approaches

Principle	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 (non-lead assets)	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 (lead assets)	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, 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.

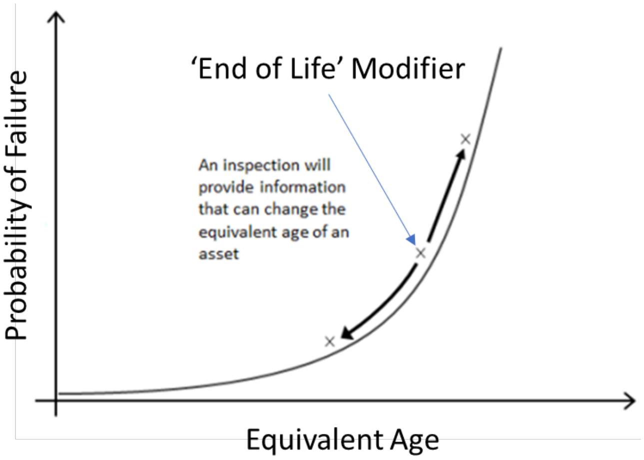

Figure 3 illustrates the principle of the End of Life Modifier. The rise in monetised risk is governed by an asset's probability of failure plot, the magnitude of the risk at any given point in time is a function of the probability of failure (variable) and the probability of an event with a monetised consequence (fixed). Appendix B shows where the transformers included in this report are on this curve.

Figure 3: EOL modifier principle

Our approach 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 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', the score that enables a probability of failure to be deduced.

4.2.2 How we monitor transformer asset health

Transformer End of Life scoring is based on condition. The bulk of interventions are driven by oil sampling, which identifies dielectric and/or thermal deterioration of the asset.

When a transformer is identified as requiring removal or replacement from the transmission network, due to the risk it poses, checks are made to ensure that a like-for-like replacement transformer is required. Following actual removal, post-mortem analysis is undertaken to improve our understanding of the asset condition of transformer families which further informs the Asset Health conditions rating. This approach ensures that our current knowledge of the condition of our transformer assets is the best it can be, resulting in a high confidence of the need to intervene on an asset.

In RIIO-T1 we had moved from a 'replace on age' to a 'replacement priority' based on safety, operational or environmental risk. Each transformer was assigned an Asset Health Index (AHI) based on condition assessment and service experience of similarly designed plant.

To support the end of life assessment of an asset, several different data types may be called upon. Transformer 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.

Table 5 below summarises the end of life scoring approach for transformers based on the types of data employed and the various factors that make up an assessment.

Table 5: EOL assessment drivers for transformers

EoL Assessment Factor / **EoL Assessment Input**	**Dielectric Factor** **Arcing, sparking and partial discharge faults**	**Thermal Factor** **Overheating faults; degradation of solid insulation ultimately leads to a dielectric failure**	**Mechanical Factor** **Damage to the winding, loss of mechanical clamping - reduces capability to withstand short circuit fault**	**Other Component Factor** **Combination of tap-changer issues, 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 dissolved gas, furans and methanol analysis (overheating fault, insulation ageing)	Winding Resistance Test Frequency Response Analysis	Exceptional oil top ups may dilute diagnostic markers
Performance Data	NA		Noise may initiate further assessment of clamping bolts and core	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			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

Based on this assessment, we plot the monetised risk contribution of T2 interventions in 2025 versus their current End of Life ('EoL') score. This has been completed for every asset, and is shown for our interventions in Appendix B. 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 for transformers that can aid in a description of each EoL band. Asset Health Index (AHI), although superseded in T2 for transformers, is helpful to those familiar with this methodology in T1. Table 6 shows the frequency with which transformers are inspected:

Table 6: Transformer inspection frequency

Inspection Type	Frequency
Oil Sample	Yearly
Enhanced Oil Sample including Online Monitoring	Based on findings
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

4.3 How We Have Established RIIO-T2 Intervention Volumes

This section sets out how we use our asset health information to arrive at a volume of interventions for RIIO-T2.

Stakeholders told us they want us to maintain network risk flat across RIIO-T2 period. In the absence of any intervention the level of monetised risk would increase over the RIIO-T2 (see graph in Figure 4).

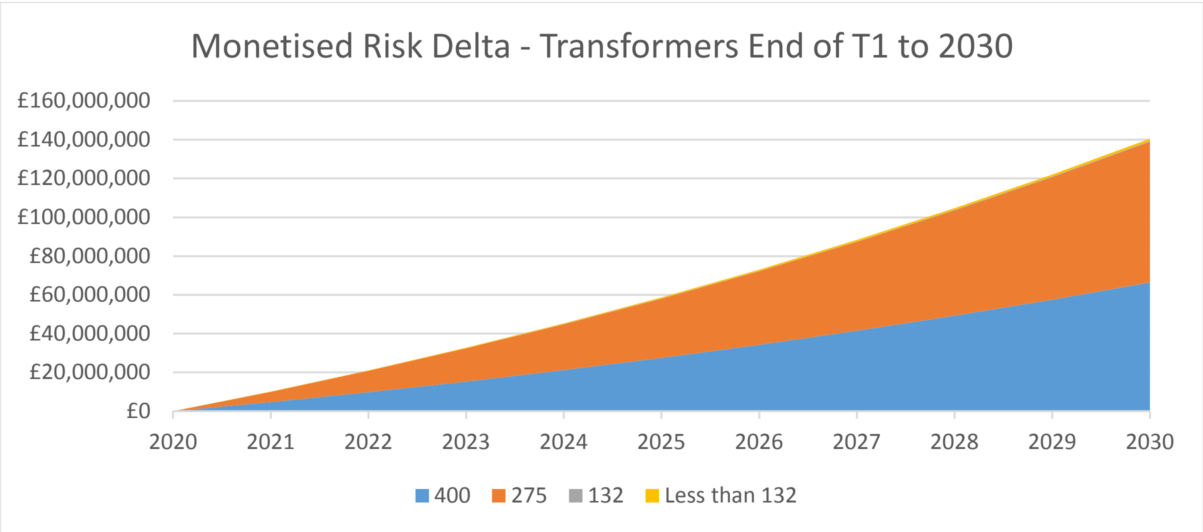

Figure 4: Unconstrained monetised risk, transformers (SGT only)

In the remainder of this section we show how we have identified interventions that will mitigate the increase in network risk over RIIO-T2.

4.4 RIIO-T2 Intervention Volumes

We have identified [redacted] transformer interventions for RIIO-T2. For SGTs, we have arrived at this volume of interventions by applying NARMs modelling which determined that [redacted] transformer interventions would be required to achieve the same level of monetised risk at the end RIIO-T2 as at the beginning of RIIO-T2. Three SCT interventions were identified through the AHI approach.

In addition to the modelled volumes, our RIIO-T2 programme will also include the following:

- [redacted] SGT replacements are delivered by Wimbledon Substation non-load investment which was considered as part of RIIO-T1 plan assessment. Wimbledon SGTs are currently being delivered so they are excluded from our analysis in this report.
- Our non-load plan for transformers includes [redacted] units to replenish Strategic Spares but they are covered in a separate Justification Report (A9.18 – Strategic Spares).

4.4.1 SCT intervention volumes

SCT interventions have been prioritised based on EOL scores. Table 7 below shows EOL scores for SCT assets based on a snapshot taken April/May 2019.

Table 7: EOL status for SCT transformer population

Asset Type	Asset Sub-Type	Rating / Description	No. in Service	End-of-Life (EOL) Status		
				R (89 - 100)	A (35 - 88)	G (0 - 34)
Static Compensator Transformers	400/7.9kV	170MVA	[redacted]	[redacted]	[redacted]	[redacted]
	400/14kV	150MVA	[redacted]	[redacted]	[redacted]	[redacted]
	275/16kV	192MVA	[redacted]	[redacted]	[redacted]	[redacted]
	275/14kV	150MVA	[redacted]	[redacted]	[redacted]	[redacted]
	400/56.6kV	150MVA	[redacted]	[redacted]	[redacted]	[redacted]
	66/33kV	60MVA	[redacted]	[redacted]	[redacted]	[redacted]
TOTAL Static Compensator Transformers			[redacted]	[redacted]	[redacted]	[redacted]

We have prioritised for intervention at RIIO-T2 the three SCTs with the highest EOL scores ([redacted] with Red RAG score, [redacted] with Amber RAG score).

Table 8 below shows the proposed breakdown of the SCT replacements in RIIO-T2:

Table 8: Proposed Static Compensator Transformers (SCTs) interventions in RIIO-T2

Type	Output Year	T2							T1	
		2021	2022	2023	2024	2025	TOTAL	Average per annum	TOTAL (Planned)	Average per annum
SCTs	Volume On	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		-

4.4.2 SGT intervention volumes

We have identified [redacted] SGT transformer interventions for RIIO-T2 (excluding Wimbledon). We have prioritised those assets most in need of intervention and have developed a work programme which (subject to system access constraints) addresses highest risk assets first.

Table 9 shows our SGT intervention profile over RIIO-T2, together with average EOL score per intervention for each year: this falls year on year, showing how our interventions target the assets most in need of intervention first. The EOL scores by asset are shown in Appendix C.

Table 9: Intervention profile and average annual EOL score per intervention, SGTs

Type	Output Year	RIIO-ET2							RIIO-ET1	
		2021	2022	2023	2024	2025	TOTAL	Average per annum	TOTAL (Planned)	Average per annum
SGTs	Volume on	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	EOL score per intervention	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Volume off	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Following our learning from RIIO-T1, where volumes on and off were different to planned, we have undertaken further engagement with DNOs and the ESO to understand demand forecasts and ensure an accurate plan in RIIO-T2. We therefore have high confidence that volumes on and off will be aligned in RIIO-T2.

4.4.3 Summary of intervention volumes and RIIO-T1 comparison

Table 10 summarises interventions across the RIIO-T2 period, including Wimbledon SGTs and Strategic Spares. Under the planned programme we are forecasting to replace on average [redacted] SGTs per annum which is slightly higher than the average annual volume during RIIO-T1 of ten. The increase in volume is driven by the stakeholder requirement to maintain risk flat across our asset base and subsequent output from NARMS methodology (see below).

Table 10: Transformer intervention volumes, RIIO-T2

Type	RIIO-T2							RIIO-T1	
	2021	2022	2023	2024	2025	TOTAL	Average per annum	TOTAL (Planned)	Average per annum
SGTs	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
SCTs	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Wimbledon SGTs	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Strategic Spares	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
TOTAL Transformers	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

4.5 How Our RIIO-T2 Interventions Mitigate Network Risk

We seek to mitigate the increase in risk that would occur during RIIO-T2 across the whole transformer portfolio if no interventions were undertaken (see Section 4.3 above).

Figure 5 shows how our interventions mitigate risk. There are [redacted] transformers in the T2 plan (including Wimbledon SGTs) contributing to the monetised risk position. The risk impact of these interventions leaves a residual growth in risk of approximately £10m. As risk reduction is a product of probability of failure and consequence of failure, an optimal plan must consider these factors alongside other assets. Optimal selection of assets is conducted both at an asset and overall level to ensure the plan is deliverable to maintain overall risk. The plan build annex provides further detail of this decision making across all our assets.

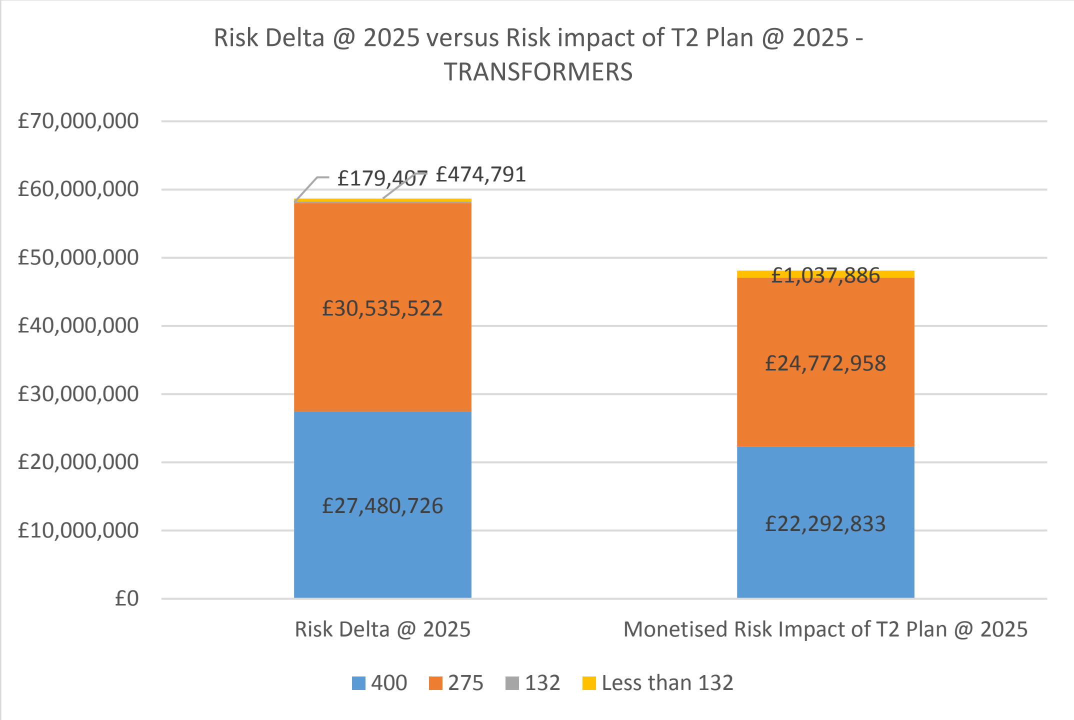

Figure 5: Risk mitigation through RIIO-T2 interventions versus increase in unconstrained network risk

Table 11 provides a breakdown of the number of interventions versus monetised risk.

Table 11: Intervention volumes by asset subdivision

Relevant asset subdivision (i.e. Highest Voltage for SGTs)	Risk delta (£m) @ 2025	Number of interventions	Risk Impact (£m) of Interventions @ 2025
400kV	27.5	[redacted]	[redacted]
275kV	30.5	[redacted]	[redacted]
132kV	0.2	[redacted]	[redacted]
<132kV	0.5	[redacted]	[redacted]
Monetised Risk Sub-Total*	**58.7**	[redacted]	[redacted]
400kV SCT**	0	[redacted]	[redacted]
Non-Load Total	**58.7**	[redacted]	[redacted]

*Total includes Wimbledon transformers

**Static Compensation Transformer (SCT) not subject to Monetised Risk framework.

A breakdown of the total transformer risk addressed by our interventions, split by EOL risk rating, is given in Figure 6 below. This shows that our RIIO-T2 plan prioritises the assets at most risk of failure.

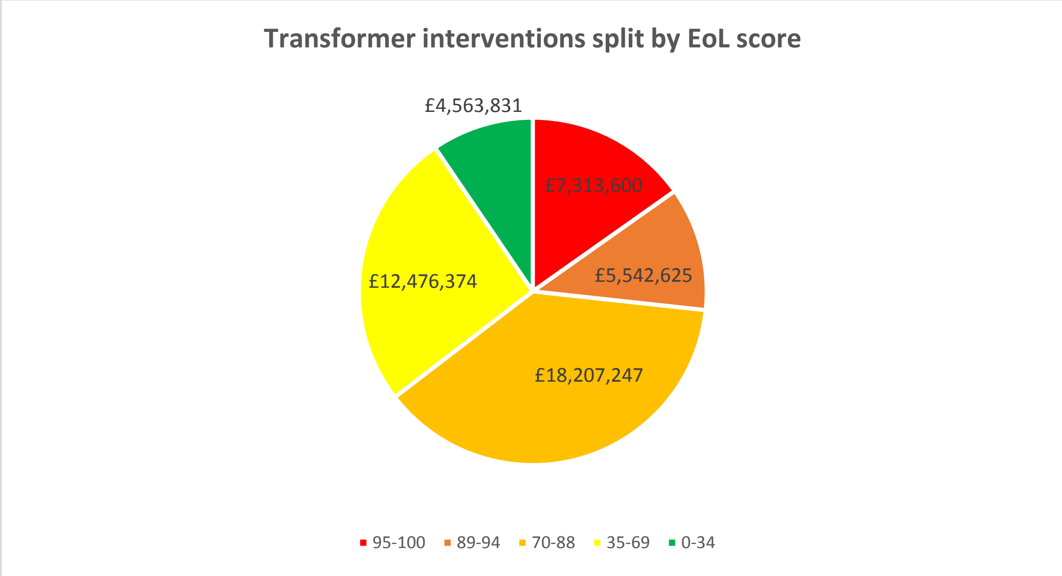

Figure 6: Monetised risk contribution by EOL modifier score

Figure 7 shows what is driving that EOL score; the descriptions map across to the EOL assessment drivers in Table 5 (Section 4.2). This shows that all of our transformer interventions are justified through recent condition information.

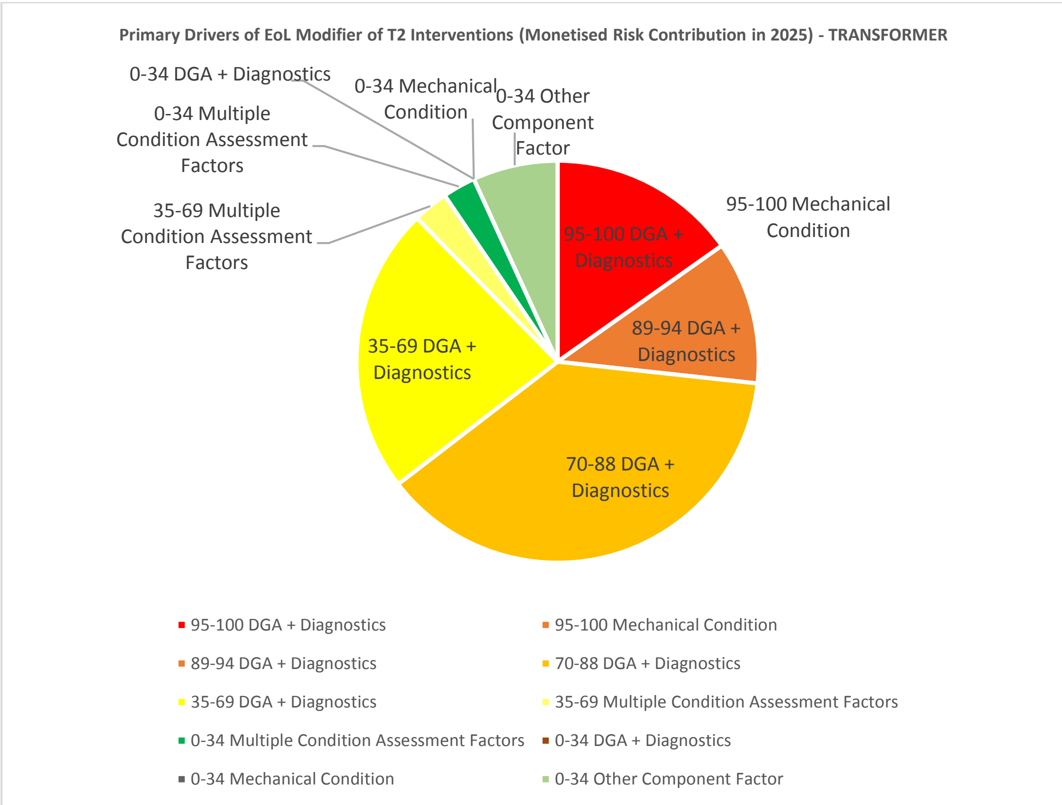

Figure 7: Monetised risk contribution by EOL modifier driver

4.6 Timing Considerations

[redacted] transformer replacements are proposed for RIIO-T2 in total, varying between [redacted] to [redacted] replacements annually. Deliverability and timing of the plan is assessed as a whole with other assets, in particular the delivery of other transformers as part of customer-driven investments. For transformers, the following potential deliverability constraints are considered:

- **Transformer condition** - Generally, assets with the highest EOL scores are progressed for delivery earlier in RIIO-T2 to minimise the risk of their failing in service.

- **Outage Availability** - A transformer is anticipated to be out of service for approximately [redacted] to allow an in-situ replacement. A shorter outage of approximately [redacted] is possible if an offline build of the transformer replacement is progressed. An offline build involves constructing a new bund elsewhere on the substation site, and during the outage, connecting the new transformer to the existing site. Offline transformer builds are more expensive than an in-situ replacement and are normally only considered where a relatively short outage is available, i.e. where the ESO advises that the constraint costs of a longer outage would be uneconomic.

  Transformer replacements must be carefully planned to ensure demand at a site can be met and the wider transmission network is still compliant with security of supply standards. It is common for transformer 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 transformer 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 National Grid Electricity Transmission resource is required at each site to support a transformer replacement, including specialist commissioning personnel. This is a finite resource and planning involves managing 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 transformer replacements that can be progressed to delivery annually.

- **Transformer Supply Chain** - There are a limited number of transformer suppliers worldwide and the total volume of new transformers manufactured and delivered annually needs to be optimised to ensure efficient use of factory slots and hence lower costs. Lead times for the different types of units may vary between 10 months for commonly used units to 24 months for more bespoke units which require, for example, bespoke factory acceptance testing.

- **Contractors** - In addition to the transformer installation on the plinth, which is typically undertaken by the transformer supplier, there are normally associated works to be undertaken e.g. transformer bund works and installation of new switchgear. Smoothing delivery volumes over multiple years therefore enables more efficient use of the contractor base and avoids incurring additional “distressed client” costs.

4.7 Outputs Included in RIIO-T1 Plans

RIIO-T1 allowances were not set against specific asset interventions; it is a portfolio deal to deliver a network risk outcome at the end of the period. Since the initial submission, specific asset plans have changed, for instance substitution to other assets requiring more immediate interventions, internal policy improvements, lack of access to specific sites due to customer or DNO work, or other external market changes.

Overall, across the asset classes, we are forecasting to deliver the required Network Output Measures we have received allowances for during the RIIO-T1 period.

For transformers, we have been able to reduce the volume of work and still achieve our RIIO-T1 network risk targets for RIIO-T1 because we have extended the technical asset lives. This affects the entire population of assets in that family (not just the ones that were forecast for replacement in RIIO-T1). Consequently, some of the assets which were forecast for replacement in RIIO-T1 will now require replacement in RIIO-T2. Equally, other assets which would have been replaced in RIIO-T2 can now be planned in RIIO-T3 (and so on). As a result, replacement volumes are reduced on an enduring basis. This is illustrated for transformers in the following graph which plots forecast network risk over time if no more investment is made after the end of RIIO-T1. The forecast level of network risk is lower in all years following life extension, meaning that fewer units will need replacement out to at least 2040. This drives long-term benefits for consumers, as demonstrated in Figure 8 below:

[redacted]

Long term risk impact:

Illustrated for transformers, this graph plots forecast network risk over time if no more investment is made after the end of RIIO-T1.

The forecast level of network risk is lower in all years following life extension, meaning that fewer units will need replacement out to at least 2040.

[redacted]

Consumer impact:

Again for transformers, this waterfall shows that, although NGET retains 47% of any savings over RIIO-T1 (£90m), the longer-term impact (as the life extension rolls out over the whole asset population) for future price control periods means that customers will benefit (all other things being equal) by an estimated £210m by the end of RIIO-T3.

Figure 8: Long-term consumer benefits overview

nationalgrid

5. OPTIONEERING

To determine the optimum mix of interventions for transformers, a CBA was undertaken.

5.1 Approach to Estimating Costs and Benefits

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

1. Firstly, we have identified **potential intervention strategies,** and tested the options on this long list for feasibility/applicability. They include a 'Do Minimum' option. We have not considered non-network or whole systems options here since these cannot substitute for the type of investment we are considering in this paper.
2. For the set of feasible options, we have undertaken **quantitative CBA** to identify the most cost-effective option, supplemented by wider qualitative considerations.

We have used the Net Present Value (NPV) calculation approach in the Ofgem template to identify the most cost-effective option. As well as the costs of investment, we also incorporate the benefits in terms of health/safety and reduction in network risk from our interventions that result under each option.

We are therefore confident that our identification of the preferred option, through quantitative analysis supplemented by wider considerations, is robust, and that the choice of option would not change if wider impacts were incorporated into our quantitative analysis.

5.2 Options Considered

The long list of options we identified for the delivery of the transformer interventions is set out in Table 12 below:

Table 12: Summary of Protection and Control intervention options

Option	Detail	Taken forward for full CBA?
1. Do Minimum (maintain only and replace on fail)	This option would end the planned replacement of transformers and would allow them to fail in service. Under the Do-Minimum scenario, no planned transformer replacements would be undertaken during T2 and the transformers would be replaced post-failure.	**Taken forward**
2. Planned programme of replacement based on monetised risk	This strategy would plan to replace [redacted] transformers over RIIO-T2 based on the output of the Monetised Risk methodology	**Taken forward**
3. Planned transformer refurbishment	This option considers the refurbishment of SGTs instead of full replacement. While refurbishment of transformers is often considered for sub transmission voltages it is rarely utilised at transmission levels. The size of the transmission transformers in our fleet, it is very rarely that an effective repair or refurbishment of the active part (core and windings) of the transformer can be economically achieved i.e. refurbishment does not offer a significant advantage over procuring a new transformer to meet the current technical specification. Given that the fundamental life limiting process is paper ageing, where a transformer 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. Between 2014-17 an innovation funded project sought to explore the feasibility of refurbishing 13kV shunt reactors; the hope was that by refurbishing the active part but keeping the existing tank the replacement time and site works could be kept to a minimum. It was thought that if this could be successfully applied to Reactors the same exercise could then be undertaken for transformers. The key findings included:	**Not taken forward** Refurbishment not a feasible option following results of innovation project

Option	Detail	Taken forward for full CBA?
	• Cost was significantly greater (>40%) than buying a new reactor from National Grid Electricity Transmission's bulk purchase 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.	

5.3 Cost Benefit Analysis

The NPV results for our two options are set out below in Table 13 below.

For the Do Minimum option, there is uncertainty around the maximum lifespan of transformers, although based on historic asset health data, given the risks to the transmission network a median age of 65 years has been assumed. It is therefore possible that during T2, fewer transformers might fail in service versus the [redacted] planned replacements but it would be expected that the number of units failing per year would increase as the fleet condition deteriorates.

To derive the volume that would be replaced on fail for the T2 period a view was taken on the asset health of the existing transformers. Of the transformers on the system [redacted] are viewed as needing replacement with an EOL score, in the range 89-100. Units in this range are considered in urgent need of replacement. A further [redacted] units were considered in the range of 70-88 as needing replacement in planned timescales and are units that could suffer further degradation over the T2 period moving them into the 'urgent need of replacement' category. In any given period, there is a unit that moves to an area of concern for an unknown reason. As an example, SGT2 at Willesden has increased from an EOL in the 30's to one that would cause concern. A total of [redacted] transformers were considered as potential in service failures for the T2 period and this figure was used in the CBA analysis.

For lead assets, such as Transformers, as well as the direct costs of investment, the NPV also accounts for:

- Changes in Monetised Risk because of interventions (benefits vs Do Minimum baseline, shown separately in tables below)
- Safety impacts: preventative measures captured within investment costs, benefits versus Do Minimum baseline captured in NPV

Table 13: NPV results of two options

<table>
<tr><th>Option (lifetime)</th><th></th><th>Quantity (intervention volume)</th><th>RIIO-T2 investment cost (undisc, £m)</th><th>Total investment cost (undisc, £m)</th><th>Change in Monetised Risk (disc, £m)</th><th>NPV (disc, £m)</th><th>NPV inc monetised risk (disc, £m)</th><th>Decision</th></tr>
<tr><td rowspan="2">Do Minimum</td><td>CBA</td><td>[redacted]</td><td>-147.500</td><td>-253.700</td><td>296.224</td><td>-207.105</td><td>89.119</td><td rowspan="2">REJECT

This option is rejected because:
- It does not align with stakeholder requirements
- It favours current over future consumers
- It has high stakeholder impact at the point of failure
- It has high consequential costs</td></tr>
<tr><td>Other considerations (stakeholder, engineering, societal benefits</td><td colspan="6">Replace on fail has a higher unit cost (£[redacted]m) than planned asset replacement in part due to the additional equipment needing replacement as a result of catastrophic failure.

In addition, in order to manage a rise in in-service failures, the strategic spares holding would need to be increased significantly and team(s) of staff put on standby to manage emergency, unplanned replacements.

Although replace on fail interventions will mitigate some network risk, overall network risk will rise. This approach is highly likely to lead to energy-not-supplied scenarios. It is therefore incompatible with National Electricity Transmission System Security and Quality of Supply Standards (NETS SQSS) and there would be limited control over when replacements would occur (outages could not be planned to maintain SQSS compliance).

There are also significant health and safety risks which could severely restrict operations at a site level if we allow transformers 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 new customer connections and planned works on the distribution network which may be delayed until the system was secured.</td></tr>
<tr><td rowspan="2">Planned programme of replacement</td><td>CBA</td><td>[redacted]</td><td>-220.020</td><td>-241.204</td><td>336.534</td><td>-208.252</td><td>128.282</td><td rowspan="2">RECOMMEND</td></tr>
<tr><td>Other considerations (stakeholder, engineering, societal benefits)</td><td colspan="6">This option is a continuation of our current practice which allows us to maintain the high reliability levels that our stakeholders have indicated they wish us to maintain.</td></tr>
</table>

6. ASSESSMENT OF COST EFFICIENCY

The costs and volumes in our RIIO-T2 plan (as well as those for RIIO-T1) are set out in Table 14 below:

Table 14: Costs and volumes, RIIO-T1 and RIIO-T2 (including strategic spares, excluding Wimbledon)

Transformers, all kV	RIIO-T1							
	T1 Allowances	T1 Actuals	T1 Forecast	T1 (all years)	T2 forecast	Annual average	Annual av (first 6 years)	Annual average
Total cost (£m)	764	297.6	146.7	444.3	272.6	55.5	49.6	54.5
Total volume	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Cost per unit volume (£m)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

The drivers of the differences in unit costs between price controls [redacted]. This is explained in further detail below.

In order to make costs per unit comparable with the T1 period, table 14 includes Strategic Spares in the overall Transformer volume ([redacted]), giving a cost per unit of £[redacted]m[1]. This compares to £[redacted]m for the RIIO T1 period. The total option cost noted for the preferred option has been calculated using the specific planned interventions for [redacted] units (listed in Appendix B).

The forecast cost per unit in T2 is [redacted] during RIIO-T1. This is mainly due to a change in the mix of scope. [redacted] The voltage mix [redacted] between the two periods (see Table 15 below):

Table 15: SGT voltage mix

SGT mix	T1	T2
<=132kV	[redacted]%	[redacted]%
275kV	[redacted]%	[redacted]%
400kV	[redacted]%	[redacted]%

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

- **Transformer replacement:** Savings have been made in RIIO-T1 by challenging our approach to scoping the replacement of transformers. We have changed our policy for items that can be retained for longer without resulting in safety risks. This enabled transformers to be replaced in situ where previously offline replacements would have been delivered. This is because we were able to increase the reuse of existing foundation walkways around plant and reduce spacing to bund walls. These cost reduction measures are embedded into our RIIO-T2 plan

- **Works integration:** We have also achieved efficiencies by integrating transformer works with other works at the same site. For example, asset replacement of transformers and reactors [redacted] were let as one contract to achieve savings by being delivered as one portfolio of works.

[1] Emergency replacements are generally cheaper than planned because a reduced scope is delivered in order to get a unit back into service as soon as possible; the exception is if the failure is catastrophic (e.g. there is a fire) and exceptional clean-up costs are incurred

6.1 How We Have Estimated RIIO-T2 Unit Costs

The estimating methodology for capital projects is based around a standard and consistent approach. This is controlled by an in-house, central estimating team (e-Hub) within Capital Delivery Project Controls. The detail of this methodology can be found in NGET_A14.09_Internal Benchmarking of Capex unit costs.

The following graphs are aligned with Ofgem's requirements for reporting capital costs in the Business Plan Data Template, 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.**

Figure 9 shows (for 400kV projects):

- Unit costs for RIIO-T2 projects, based on the cost estimation process described above
- Mean unit costs for RIIO-T1 and the mean +/- one standard deviation for RIIO-T2
- TNEI industry mean
- Unit costs for projects due to fall in the years immediately before and after RIIO-T2, but that have spend in the T2 period.

Figure 10 below shows this information for 275kV projects.

[redacted]

Figure 9: Unit costs for transformer projects, plus TNEI benchmark, 400kV projects (in situ only)

[redacted]

[redacted]

Figure 10: Unit costs for transformer projects, plus TNEI benchmark, 275kV projects (in situ only)

[redacted]

[redacted]

6.2 How Unit Costs Compare to External Benchmarks

[redacted]

[redacted]

Figure 11: Costs versus TNEI benchmarks

[redacted]

7. KEY ASSUMPTIONS, RISK AND CONTINGENCY

The key risks to the deliverability of this programme of work, and how we will mitigate them, are set out in this section.

7.1 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 transformer replacements required to achieve the required transmission network risk. A requirement of [redacted] system access has been assumed per transformer replacement. Once individual projects are developed, these outage durations may increase /decrease depending on complexity.

7.2 DNO Outages

The majority of transformers planned for replacement are located at Grid Supply Point (GSP) substations and replacement of these assets may be affected by works on the DNO system. Early engagement with the DNOs has already taken place and will continue so works can be optimised and collaborative ways of working can be explored.

8. CONCLUSION

Transformers form a key part of the transmission network and their reliability is critical to customers, particularly at bulk supply points where coincident transformer failures could lead to extended supply interruptions. In this paper, we justify £241.216m of investment which meets the stakeholder priority of maintaining current levels of network risk in a cost-effective way.

Section 2 provides background to our transformer assets, describing the role they play in the system and the consequences of failure.

Section 3 sets out how we have achieved significant savings during RIIO-T1, driven mostly by innovative new approaches which have extended the lives of our assets, and partly by a procurement opportunity.

Section 4 sets out the need for investment during RIIO-T2, driven by the need to replace assets in poor condition in order to maintain current levels of network risk. We have identified [redacted] assets for replacement in RIIO-T2 (in addition to [redacted] units at Wimbledon), and have developed a programme of work which prioritises the replacement of assets in poor health.

Section 5 shows the optioneering we have undertaken, and how a planned programme of replacement best meets stakeholder objectives around network reliability in a way that provides best value for consumers. It also sets out the results of the quantitative CBA we have undertaken as part of optioneering.

Section 6 shows how our RIIO-T2 unit costs compare to those from RIIO-T1 and to an external benchmark. Unit costs for in situ replacement are expected to increase slightly compared to RIIO-T1, reflecting particular, one-off circumstances around RIIO-T1 procurement and increasing civils requirements. Our costs remain in line with wider industry benchmarks, and where they are above, we have committed to finding efficiencies to bring us into line with the industry standard.

Section 7 sets out the key risks to the deliverability of this investment programme, and how we will mitigate these.

APPENDIX A – Transformers replaced or planned to be replaced in T1

(NB Asset Delivery Year is calendar year not financial year)

The list has been redacted.

APPENDIX B – Transformers to be replaced in RIIO-T2

Transformers

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 C – Transformers added and removed in RIIO-T1 with no like-for-like removal/replacement

The list has been redacted