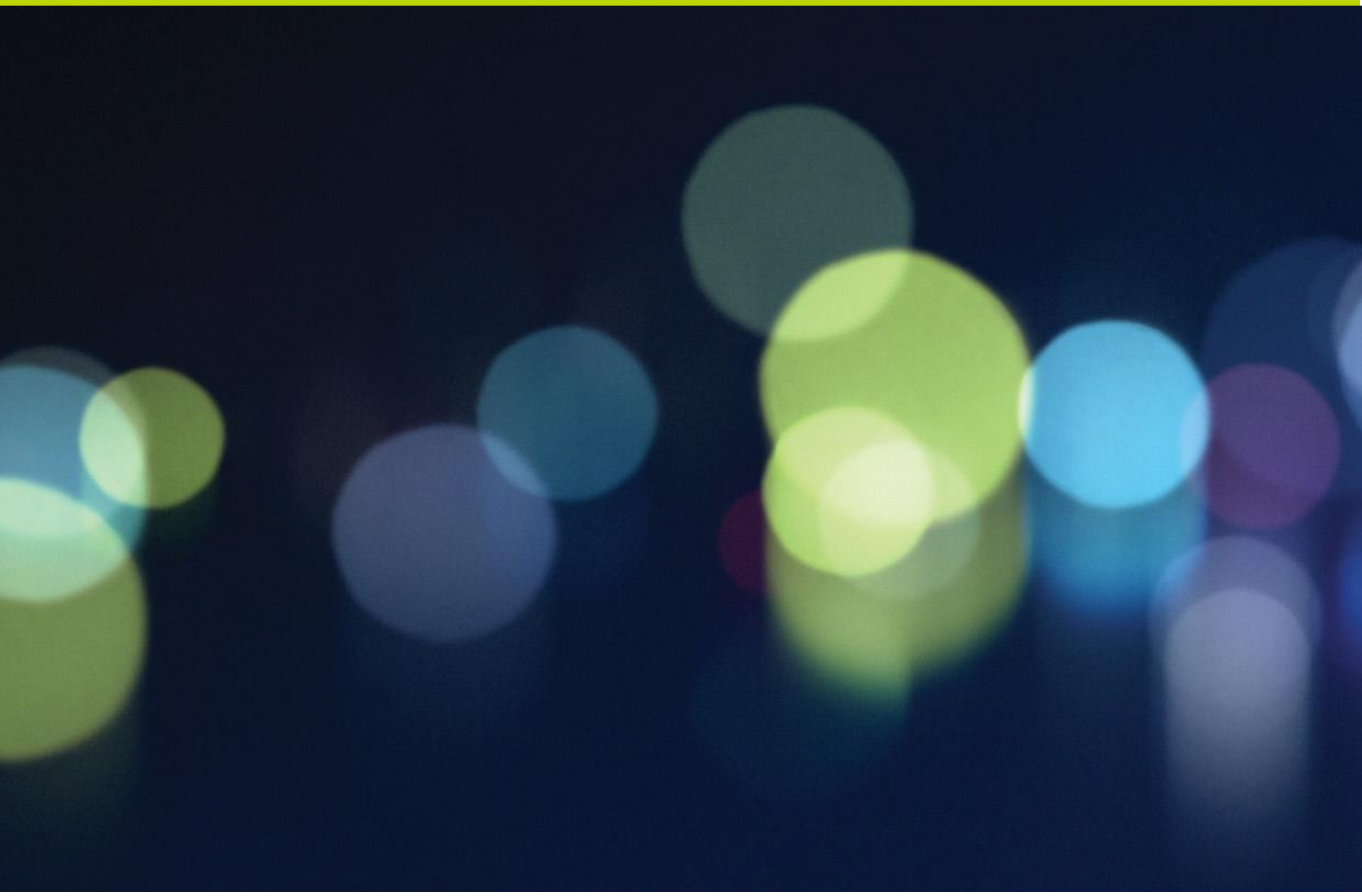
Power Transformers Asset Class Plan

Substation Assets

November 2022



Endeavour Energy

Version control

Version	Date	Comments
1.0	Nov 2022	Initial Release

Contents

1. Executive Summary

The purpose of this document is to outline the asset management practices for the asset class Power Transformers and define a 10-year strategic plan for the class based on the risk the asset's present risk and the cost of replacement and refurbishment options.

The asset class currently includes power transformers that are in service in zone and transmission substations and customer substations throughout the network.

Power transformers are used to transform electricity from one voltage to usually a lower voltage to allow for its distribution through the sub-transmission and distribution networks and to customers.

The failure of a power transformer in service has direct financial consequences and may lead to reliability consequences. Generally, there are nil material safety, bushfire or environmental consequences of a failure. The population of power transformers is aging and therefore the risks associated them are increasing. Accordingly, a 10-year strategy has been developed for power transformers to manage those risks. The forecasted risk, strategy cost breakdown, and performance metrics are outlined below.

Risk Forecast

The consequences of failure of power transformers in service are quantified in monetary terms and coupled with statistical modelling to determine the optimal level of investment to manage the risk.

As these assets age, the risk associated with their failure in service (the baseline risk) also increases. The baseline risk and the expected level of residual risk as an outcome of the proposed management strategy for these assets over the next 10 years is illustrated in Figure 10 – Risk forecast.

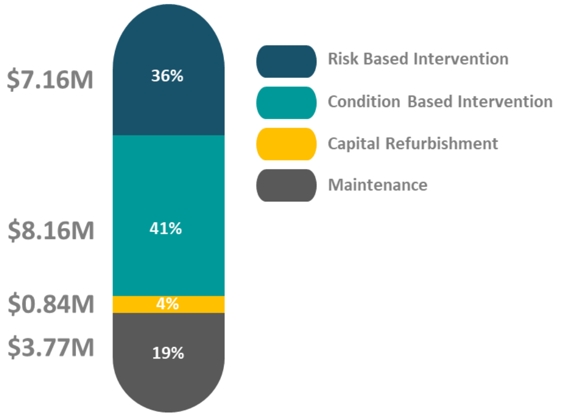
Strategy and Cost

Generally power transformers are installed with an N-1 level of supply security and their failure in service does not lead to a loss of supply to customers. As a result of this, economic modelling generally favours running transformers to functional failure[1] and replacing them from the essential spares pool. However, there are limited situations where the risk of failure of multiple transformers simultaneously increases the reliability risk to a level that provides value from planned risk-based replacement. Therefore, the strategy adopted to address the risk associated with power transformers is a balance between reactive condition-based replacements in response to functional (or condition-based) failures and planned risk-based replacement.

This strategy represents a departure from the previous approach which was focussed on planned risk-based replacement. However, the current regime of routine preventative maintenance and condition-based maintenance, supplemented with mid-life refurbishment for selected transformers, is continued under the proposed strategy.

[1] This also includes "condition-based" replacement where transformers are scheduled for replacement in a reactive manner based on test results indicating that a functional failure of the transformer is imminent. Condition based replacement avoids the financial risk costs associated with a functional failure.

Figure 1 – Forecast asset investment



The total cost of this strategy (in $ real FY23) for the 2025 - 2029 period is $7.16 million for planned risk-based capital replacements, $8.16 million for possible reactive condition-based replacements, $0.84 million for capital refurbishment works and $3.77 million for maintenance, as shown in Figure 1.

Key Performance Indicators

The performance objectives for the power transformer asset class and the current status of each of those objectives is shown in

Table **1** below.

Based on the 10-year strategy proposed in this asset class plan, the reliability performance indicator is expected to remain steady as the fleet of aged power transformers which are experiencing secondary system failures, are gradually replaced with new transformers with associated infant mortality and commissioning error issues. The safety indicator is currently compliant and is expected to remain compliant. The environmental indicator is compliant and is expected to remain compliant.

Table 1 - Power transformer performance indicators

Performance category	Objective	Status
Reliability	Reduce the number of unplanned outages associated with secondary system failures followed by failure of automated change-over to the alternate transformer supply	●
Safety	Maintain the current low level of safety incidents	●
Environmental	Maintain the current low level of safety incidents	●
Financial - CAPEX	Capital investment in the asset class to be monitored against forecasts with a view to building an accurate REPEX model for the next regulatory submission	●
Financial - OPEX	Annual maintenance costs for the class on a per unit basis to not increase	●

2. Overview

2.1 Purpose

The purpose of this document is to outline the asset management practices for the asset class Power Transformers and define a 10-year strategic plan for the class based on the risk the asset's present risk and the cost of replacement and refurbishment options.

The 10-year plan seeks to use current knowledge of the asset in the context of the whole electrical network to establish Key Performance Indicators (KPI) to assist in understanding and monitoring the ongoing performance of the asset class. The adopted levels of service for power transformers are based on risk/benefit trade-offs versus cost of investment options, legislative requirements, customer expectations and strategic goals set by Endeavour Energy.

This document is intended to function as part of the "Performance Monitoring and Review Process" as established in the Asset Management System (AMS) outlined in 0 of this report. The document plays a key role in:

- Providing line of sight between the company's performance objectives and investments proposed for the power transformer asset class;
- Monitoring of the performance of the asset class against the set of performance indicators (KPI's);
- Establishing a link between the performance of individual power transformers and the performance of the asset class as a whole;
- Communication of the risks presented by the asset class and cost (as indicated by the volume of asset replacements initiated by functional failures, condition-based replacements and risk-based replacements).

This document will highlight and discuss historical trends and future forecasts of risk and cost for a replacement strategy based on a mix of the following asset replacement approaches:

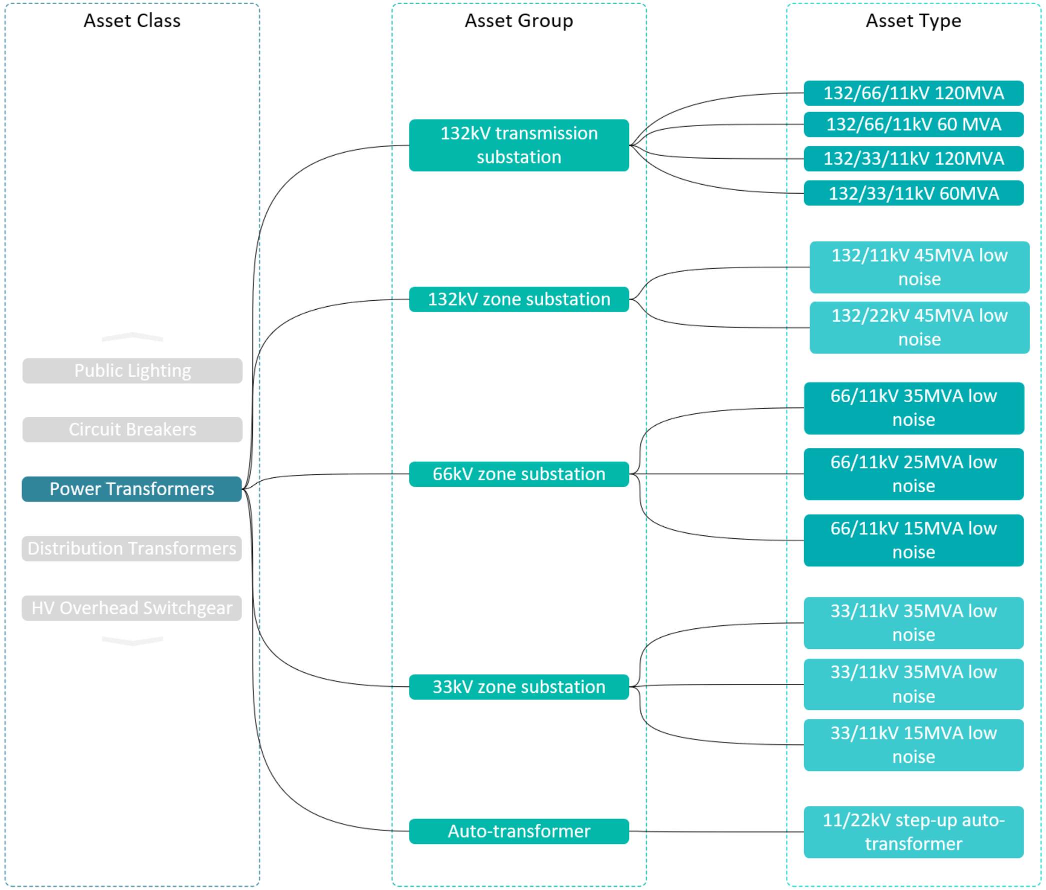
- Risk-based asset replacements (e.g. planned proactive replacements based on risk/cost justification);
- Condition-based asset replacements (e.g. replacements triggered by failure of the asset to meet applicable performance or condition standards. Usually identified during inspection and/or maintenance works);
- Functional asset failures (e.g. assets replaced after failure whilst in service).

The forecast "outcome" risk projections throughout this document are based on an optimal mix of the above investment approaches as well as the continuation of the existing maintenance strategies. The "baseline" risks outlined throughout this document represent the risk trend which is expected to be experienced in the absence of any planned proactive asset replacement strategy or program.

2.3 Scope

This report covers all power transformers owned by Endeavour Energy with primary voltages of 132kV, 66kV and 33kV which are installed in zone and transmission substations and customer substations. The scope also includes 11/22kV step-up auto transformers located in zone substations but excludes auto transformers located in distribution feeders outside of the bounds of a zone substation. Power transformers kept as essential spares are excluded from scope of this plan but their role in the strategy for managing power transformer risks is noted. Amongst the older transformers in service, there is a wide range of capacities. However, there are now standardised capacities which are shown in Figure 2 below.

Figure 2 – Assets included in the power transformers asset class plan



3. Asset Portfolio

3.1 Asset Function

The purpose of power transformers is to transform electricity from one voltage to another (usually lower) voltage to allow for its distribution through the sub-transmission and distribution networks and to customers.

Power transformers include "on-load" tap-changers which are used to regulate the voltage levels in the sub-transmission and distribution networks whilst the transformer is in service and carrying load.

The objective of the class of power transformers is to contribute to achieving the required standards of safety, reliability and quality of the electricity supply.

The role and minimum performance measures for power transformers is underpinned by Company Policy 9.2.5 - *Network Asset Design*. This policy states:

"The sub-transmission and distribution network assets will be designed so that they can be operated and maintained safely and within design parameters under normal and foreseeable abnormal situations. The designs of network assets and systems will be simple and robust and must be able to be protected by industry standard protection systems and managed using industry standard management practices."

The ratings requirements for power transformers are specified in Company Policy 9.2.10 – *Network Asset ratings* and in Substation Design Instruction (SDI) 501 – *Subtransmission Network and Zone Substation Configuration*.

The breakdown of risks that are attributed to this asset class are shown in section 0 to illustrate performance measures and key drivers.

3.2 Asset Population

Endeavour Energy currently has a fleet of 451 individual power transformers in service at voltages of 132kV, 66kV, 33kV and a further six 11/22kV step-up auto-transformers in service in zone substations.

The power transformers and their tap-changers utilise copper conductor for their windings and connections. The windings and connections are insulated with kraft paper immersed in insulating oil.

Table 2 below shows the breakdown of the fleet of individual power transformers by voltage and capacity.

Table 2 – Power transformer fleet summary

Primary voltage	Nameplate capacity (MVA)						Total
	120	60	45	35	25	<=15	
132	36	42	54	2	1	0	**135**
66				34	17	14	**65**
33				43	139	69	**251**
11/22 auto					2	4	**6**
Total	**36**	**42**	**54**	**79**	**159**	**87**	**457**

The current fleet of power transformers has been installed progressively as the network has expanded and been renewed over the last 60 or so years. Figure 3 shows the current age profile of the fleet of in-service power transformers.

Figure 3 – Power transformer age profile

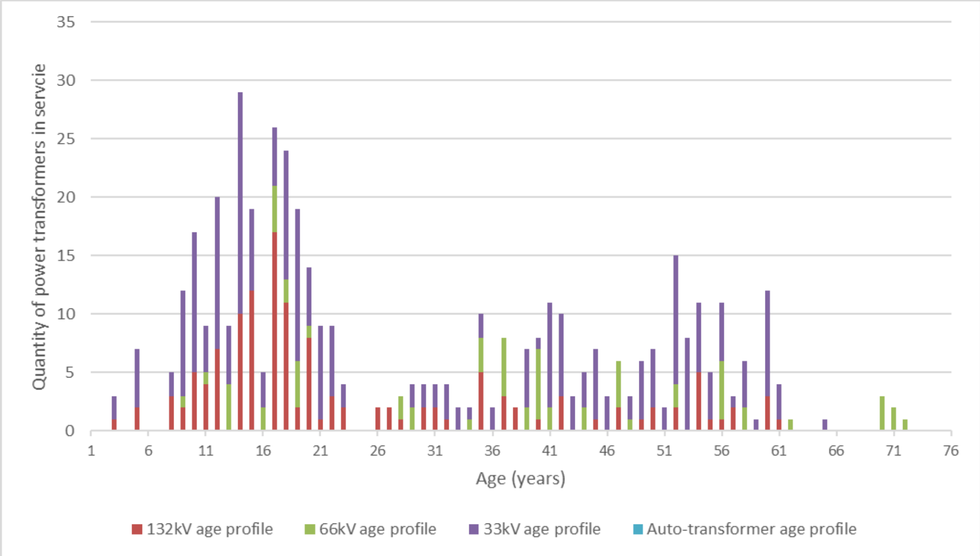
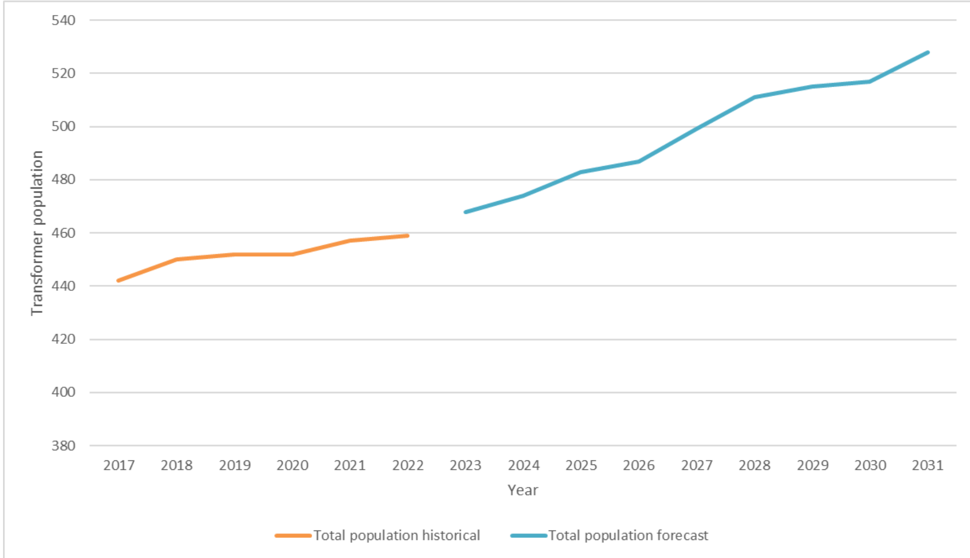


Figure 4 - Volume of power transformers in the network



The total number of assets in the network has increased over the past 10 years as additional zone and transmission substations have been added to the network to meet customer demand and, to a lesser extent, as older substations have been augmented with an additional transformer.

Looking forward, the trend of network expansion is expected to continue for a further 10 years or so in line with forecasts of new zone and transmission substation developments in new release areas.   shows the past trend of volume of installed power transformers and the forecast looking forward.

4. Asset Performance

This section quantifies the risks associated with power transformer failures and performance measures applicable to the asset class. The weighting for different risk categories indicates the areas of focus for managing the maintenance, life cycle and intervention options for this asset class. These are further broken down into performance measures that enable the relationships to be drawn between risk and the asset performance.

The consequences of failure of power transformers and the proportion of the total risk presented by each is summarised as shown in

Table 3. This risk profile is an average across the fleet of power transformers. The largest risk for this asset class is associated with reliability impacts.

Table 3 – Consequences of failure

Risk Category	Range of consequences	Risk Contribution (%)
Reliability	- Loss of supply to customers and unserved energy only in single transformer substations; - In substations with multiple transformers, unserved energy occurs only if: ○ Multiple transformers fail simultaneously; ○ Supply redundancy is not available due to maintenance or other assets not being available; ○ Failure of protection or automation schemes, particularly the failure to change-over to the alternate transformer; ○ Demand is above the firm capacity of the transformers.	58
Financial	- Clean up of the failure, investigation and reporting, replacement of the failed asset(s) in a reactive manner (providing the service of the asset is still required – which is generally the case).	42
Safety	- Nil material risk[2]	0
Bushfire	- Nil material risk – failures are invariably contained within the switchyard.	0
Environmental	- Nil material risk – any oil which escapes a transformer failure will be collected in the bund and not cause environmental damage. - An explosive failure of a power transformer (which would release smoke and fumes and possibly polluted run-off fire-fighting water) may result in environmental pollution for a short-term period of time. However, given that no fines or monetised value is placed on this type of risk, and that this failure mode is extremely rare and has not occurred in Endeavour Energy's network, the environmental CoF is considered not to be material.	0
Total		**100**

[2] Transformer failure modes can include an explosive failure followed by an oil fire. These have occurred in 330kV transformers but rarely in lower voltages and none within Endeavour Energy's fleet. This probability could be factored into a functional non-repairable (end of life) failure of power transformer but the CoF due to this will not be material, and therefore, for this first pass, it has been excluded. Likewise, a bushing failure is likely to expel shards of porcelain which has safety implications for workers in the switchyard near the transformer at the time. This failure mode resulted in material safety consequences for oil circuit breakers. However, a bushing failure generally represents a repairable failure for the transformer as a whole that alone does not signify the end of the life transformer and therefore its impacts have not been included as a CoF for this initial version of the plan.

Table 4 below summarises the asset performance service level and objectives across the fleet of power transformers.

Table 4 – Asset performance service levels

Performance Category	Objective	Performance Measure	Asset Type	Current Performance	Performance Target	Status	Trend
Asset Utilisation[3]	Optimise the load factor of power transformers			TBC			
	Maximum demand versus capacity			TBC			
Safety	Maintain current low level of safety incidents from end-of-life power transformer failures	5-year rolling average of total incidents	All	0.0	Maintain low number safety incidents	●	—
Reliability	Manage a modest increase in unserved energy as a direct result of end-of-life power transformer failures	5-year rolling average of unplanned outages	All	0.0	Monitor	●	—
Financial	Monitor the financial impacts of power transformer failures	% of forecast risk-based and reactive investment to the model forecast	All	TBC	—	—	—
	Maintain annual maintenance costs for the asset class in line with the population	5-year rolling average of maintenance costs	All	0.76	Maintain	●	—
Resilience	Monitor the number of instances of customers impacted during unplanned outages during extreme weather conditions	Average number of customers losing supply due to power transformer incidents during extreme weather conditions	All	0	Monitor	—	—

[3] The performance of power transformers in this category is a function of the arrangement of the network and the network planning decisions associated with that and the standardisation of replacement transformer ratings. These functions are covered by design and planning standards. The development of these is not within the remit of the Investment Planning team and therefore asset utilisation is not an effective measure of the performance of power transformers from an asset class plan perspective.

4.1 Asset Utilisation

4.1.1. Objective

To monitor and understand asset utilisation across each asset type and network wide to inform topology standards and maximise the utilisation of the existing asset base.

4.1.2. Performance

TBC

4.1.3. Gap

TBC

4.1.4. Response

TBC

4.2 Safety

4.2.1. Objective

Monitor and maintain safety risk across the asset base over the forthcoming regulatory control period (FY25 - FY29).

4.2.2. Performance

Safety incidents are categorised by severity and include general hazards, near misses, minor injuries, major injuries, and fatalities.

During the past 10 years there have been four safety incidents recorded in the Mysafe database against in-service power transformers. All incidents were classified as "general hazards" and involved oil spills. Three incidents involved minor defects in the power transformers which were subsequently repaired and the transformers continued in service. One incident involved the Dundas ZS transformer No. 2 which was subsequently assessed as conditionally failed and then retired. There were nil safety incidents in near miss or injury categories.

Accordingly, the current asset management strategy is expected to continue this same level of safety performance across the fleet of assets.

Table 5 – Asset safety performance

Performance Category	Objective	Performance Measure	Asset Type	Current Performance	Performance Target	Status	Trend
Safety	Maintain the current low number of incidents (excluding general hazards)	5-year rolling average of total incidents (excluding general hazards)	All	0.0	Maintain in line with forecasts	●	—

4.2.3. Gap

Nil current gap. Safety impacts are currently not material, and this is forecast to continue based on the proposed strategy.

4.2.4. Response

Safety risk will continue to be monitored and the risk modelling will be reviewed to improve future forecasts if any changes are observed.

4.3 Reliability

4.3.1. Objective

Maintain the level of network reliability risk and number of outages due to unassisted failures of power transformers at a balanced position between risk and investment value.

4.3.2. Performance

The reliability performance of the fleet of power transformers over the last decade has not been particularly good. However, all instances of loss of supply to customers appear to have been the result of a combination of a secondary system failure causing the transformer trip coinciding with either the lack of availability of the alternate transformer or the failure of the automated change-over to the alternate transformer supply. Each of these incidents have been investigated by Secondary Systems and are being managed as secondary systems asset management and/or capital works project management issues.

There have been nil instances of unserved energy resulting from the unassisted failure of a power transformer over this same period. However, the current risk-based strategy includes the allowance for an increasing number of power transformers to fail in service and associated with this is the increasing likelihood of incidents of unserved energy occurring as shown in Figure 5 below.

Figure 5 – Reliability risk forecast

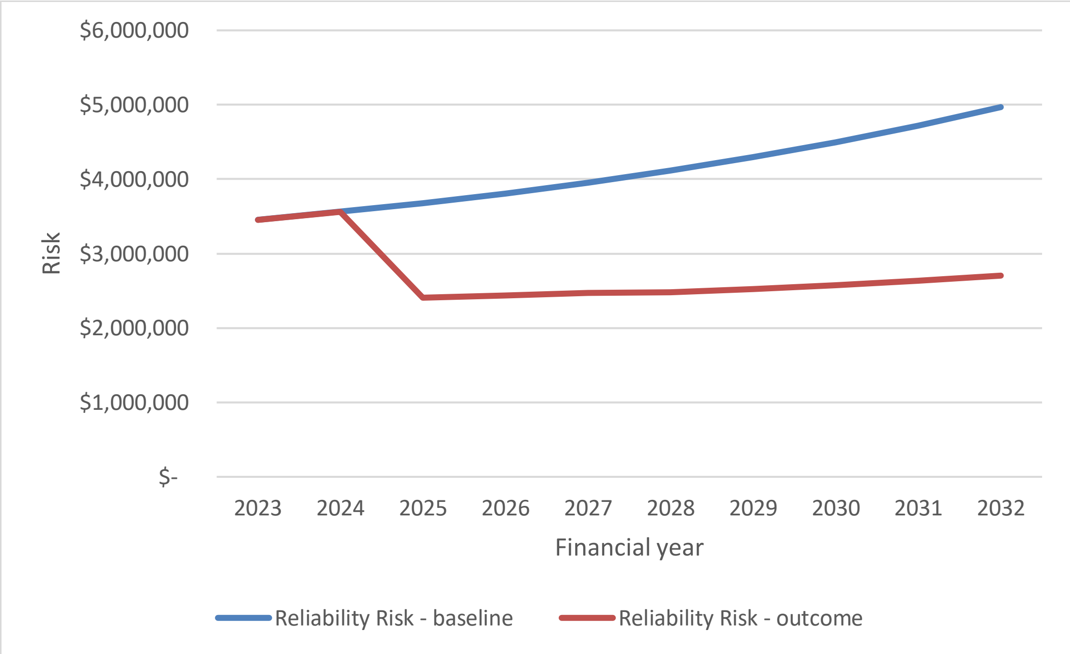


Table 6 – Asset reliability performance

Performance Category	Objective	Performance Measure	Asset Type	Current Performance	Performance Target	Status	Trend
Reliability	Maintain a modest increase in the number of unplanned outages associated with functional failures	5-year rolling average of unplanned outages	All	0.0	Increase in line with forecasts	●	—

4.3.3. Gap

No Gaps are currently identified in the reliability risk associated with power transformers.

4.3.4. Response

The proposed asset management strategy indicates a modest increase in the reliability risk profile. Continued monitoring of this metric will be performed to ensure that the strategy overall provides the optimum value balance between investment and risk.

4.4 Network Resilience

4.4.1. Objective

To monitor the reliability performance of power transformers during extreme weather conditions to ensure that the current strategy has struck the optimum value balance between investment and performance for the asset class.

4.4.2. Performance

In the last 10 years there have been nil incidences of loss of supply to customers being caused by the unassisted failure of the power transformer primary asset. However, the proposed strategy forecasts an increase in reliability risk. This metric needs to be monitored to ensure that the balance being achieved between investment and reliability is appropriate and that power transformers are available to support the network in supplying our customers during the most adverse weather conditions.

Table 7 – Asset resilience performance

Performance Category	Objective	Performance Measure	Asset Type	Current Performance	Performance Target	Status	Trend
Resilience	Monitor the number of instances of customers impacted during unplanned outages during extreme weather conditions	Average number of customers losing supply due to power transformer incidents during extreme weather conditions	Total	0.0	monitor	●	—

4.4.3. Gap

No Gaps are currently identified in the resilience/reliability risk associated with power transformers

4.4.4. Response

Monitor the reliability metric to ensure that the strategy overall provides the optimum value balance between investment and risk.

4.5 Bushfire

4.5.1. Objective

Not applicable to this asset class.

4.6 Financial

4.6.1. Objective

To align the capital investment forecast for power transformers with the AER REPEX model and to monitor the financial impacts of unassisted failures of power transformers to test the veracity of the financial risk estimations for the asset class.

4.6.2. Performance

In the last 10 years there have been only two incidences of unassisted failures of power transformers which have led to the transformer being retired. The financial loss in each case has been low. However, the proposed strategy forecasts an increase in failures in service/reactive condition-based replacements. Failures in-service carry increased financial risks which are largely avoided by a condition-based replacement approach. This metric needs to be monitored to test the accuracy of the failure risk estimations and to ensure that the balance between investment and financial risk is optimum.

Furthermore, maintenance costs for power transformers appear to have decreased over the past 10 years. This trend is to be monitored and also those assets with particularly high maintenance costs including the costs associated with addressing oil leaks. Figure 6 below shows the forecast trend in financial risk over the next 10 years.

Figure 6 – Financial risk forecast

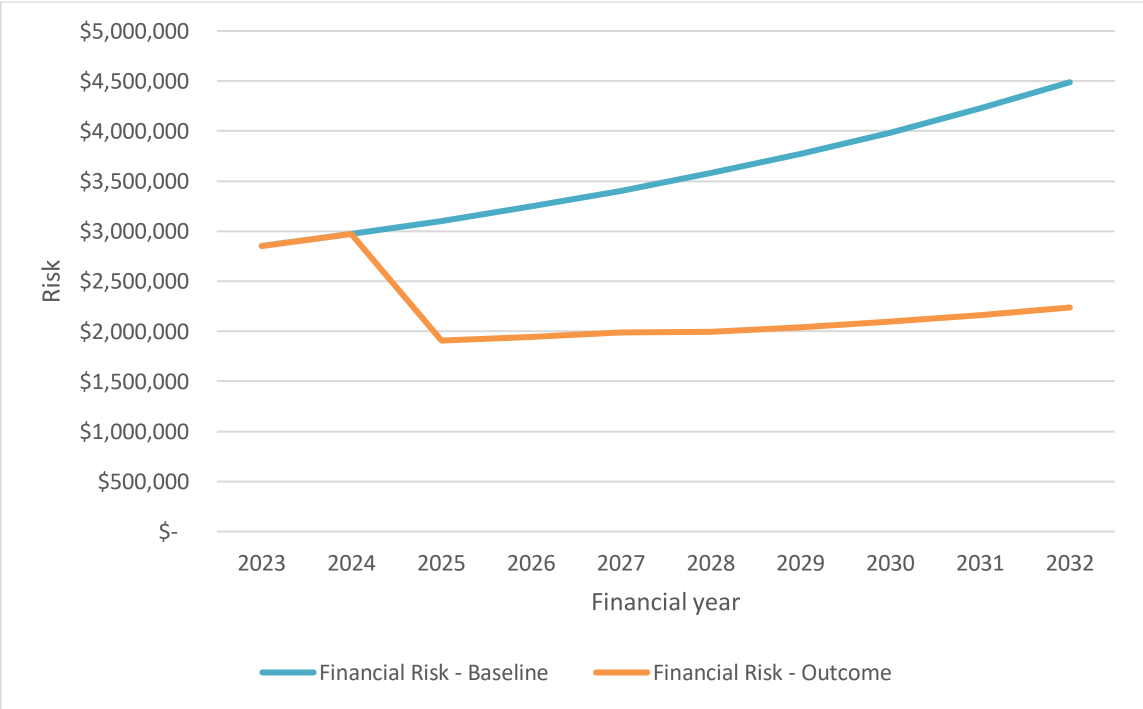


Table 8 – Asset financial risk performance

Performance Category	Objective	Performance Measure	Asset Type	Current Performance	Performance Target	Status	Trend
Financial	Monitor the financial impacts of power transformer failures	% of forecast risk-based and reactive investment to FY25-29 REPEX model forecast	All	TBC	-	—	—
	Maintain annual maintenance costs for the asset class in line with the population	5-year rolling average of maintenance costs	All	0.76	Maintain	●	—

4.6.3. Gap

No Gaps are currently identified in the financial risk considerations associated with power transformers

4.6.4. Response

Monitor the reactive replacement volumes and the realisation of financial risk to test the veracity of the financial risk value model and ensure that the strategy overall provides the optimum value balance between investment and risk.

4.7 Environmental

4.7.1. Objective

To monitor the quantity and rate of change associated with oil leaks from power transformers, to support the company's Net Zero Emissions and Sustainability Linked Loan targets.

4.7.2. Performance

In the past 10 years there have been no recorded environmental impacts associated with power transformer failures and therefore this risk is not included in the investment value assessment. However, this metric should be monitored to test the veracity of the environmental risk model applied to this asset class, particularly if the rate of unassisted failure of power transformers in service should increase over the forthcoming regulatory control period as forecast.

4.7.3. Gap

No Gaps are currently identified in the environmental risk considerations associated with power transformers

4.7.4. Response

Monitor the failure rates and any associated environmental impacts (or near misses) to test the veracity of the environmental risk value model being applied.

5. Asset Lifecycle

This section discusses power transformers throughout the asset lifecycle and brings to light key factors that currently (or may in the future) impact the asset class performance.

5.1 Acquisition

The types of power transformers installed on the network has varied little over time. All units consist of paper insulated copper windings around laminated steel cores in insulating oil and housed in a steel tank. On-load tap-changers are installed on the high-voltage windings and are either in-tank or bolt-on designs. Transformers designed after 1980 are designed and manufactured to closer tolerances than the earlier units but utilise essentially the same technology.

The current technical criteria for this asset class are defined in Equipment Technical Specifications (ETS) as listed in Section 8.1.

5.2 Operations

Power transformers are specified with appropriate capacity ratings, voltage and short-circuit ratings to fulfil their role of transforming electricity supply from one voltage to another in transmission and zone substations and customer substations throughout the network.

In recent years the tapping range of power transformers has been revised in response to the changing direction of power flows through the network due to the increasing volume of distributed energy resources (principally roof-top solar panels) being installed.

Otherwise, there are currently no known operational issues associated with the asset class of power transformers.

SDI 501 *Subtransmission Network and Zone Substation Configuration* outlines both standard operating ratings which power transformers need to be designed to withstand as well as the standards configuration of new substations.

5.3 Maintenance

An overview of the current maintenance activities being performed on power transformers is summarised below. These maintenance activities result in the current asset performance (e.g. risk and number of unassisted/conditional asset failures). The currently proposed asset renewal strategy is not expected to make a material change to the risk profile of the asset class or to the existing maintenance strategy or procedures. The maintenance strategy for power transformers includes:

- Routine inspections and preventative maintenance on the power transformer and it's tap-changer, including essential spares transformers;
- Condition based and post fault maintenance interventions; and
- Maintenance and management of a fleet of essential spare transformers

5.3.1. Inspections & Preventative Maintenance

Routine inspections and preventative maintenance includes:

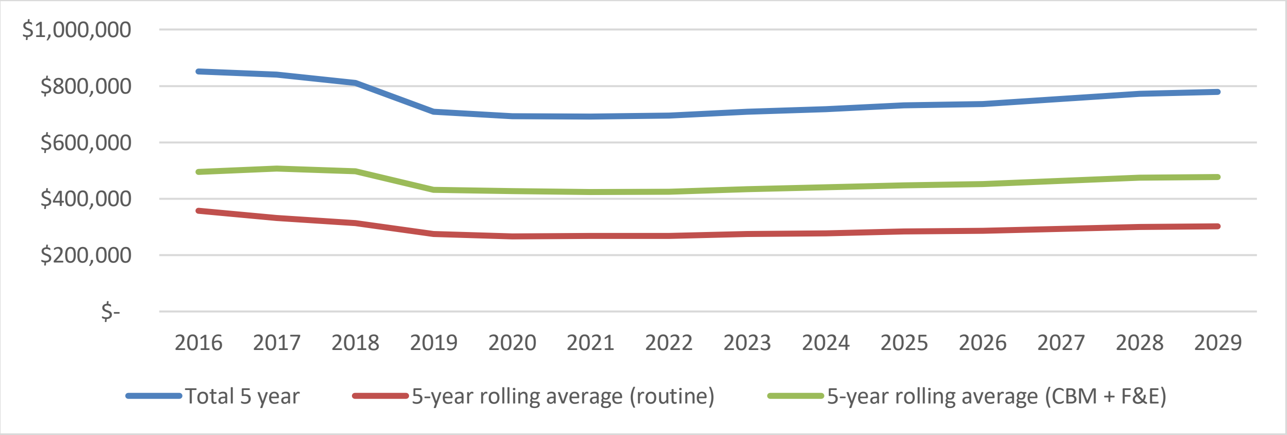
- Visual inspection and operational checks of fans and pumps;
- Oil tests – including oil quality, dissolved gas and furan tests;
- Major maintenance - including insulation resistance and polarisation, DDF and winding capacitance, bushing tests and operational test of protection systems.
- Tap-changer major maintenance – including signature tests, clean and dress contacts and overhaul of the motor box.

The intervals for routine power transformer maintenance can be found in SMI 100 *Minimum requirements for maintenance of transmission and zone substation equipment.*

Details for each transformer based on primary voltage and for tap-changers are found in the substation maintenance instructions shown in 8.1 below.

The historical average annual maintenance costs, including routine inspections and preventative maintenance, as well as condition based and post fault maintenance interventions on a five-year rolling average basis is shown in Figure 7 below. This trend is expected to continue over the next 10 years with a slight increase commensurate with the growing population of transformers.

Figure 7 – Historical and forecast maintenance costs



5.3.2. Essential Spares

The requirement for an essential spare's strategy is governed by the criticality of the equipment's function in the network and is dependent on the lead time for acquisition.

The number and type of essential spares carried will be probabilistically assessed for each of the major categories of assets based on their distribution and experience of their:

- failure rates;
- modes of failure;
- population;
- criticality in the network;
- lead time for the spares; and
- cost of the spares.

Based on the above, the minimum acceptable service level for spares holdings will be such that a minimum 99% service level can be achieved for each of the major asset classes.

Essential spares are to be suitably stored in readily accessible locations and maintained in good working order so that they can be easily identified and ready for service when required.

Endeavour Energy's procurement and logistics section is responsible for the on-going sourcing strategy of power transformers and bushings including its supply chain security.

Power transformers are critical to the operation of the network and have a long lead time for acquisition, and therefore an essential spares strategy has been developed to ensure that a supply of complete power transformers as well as major components such as bushings are available for use in emergency situations.

The spare transformers are stored in bunded areas at Mount Druitt and Springhill transmission substations and temporarily at other locations and are maintained to a similar standard as the in-service transformers to ensure that they are in good working order when required for service.

Details of the essential spares holding requirements for power transformers and their bushings is provided in Company Procedure GAM1096 – *Essential Spares Holdings and Mobile Response Solutions.*

It is noted that there are some shortcomings in the current holdings of both transformer and transformer bushing essential spares which requires further assessment and investment in inventory. This is particularly important given the current strategy of risk-based and reactive replacement which is likely to see an increased volume of failures in service than has been experienced in the past.

5.4 Disposal

Power transformers no longer required in the network are to be disposed of in accordance with Company Procedure GSU 0006 – *Disposal of Surplus Goods and Equipment*, Company Procedure GSU 012 - *Selection and Approval of a Disposal Method* and Environmental Guidelines, EMS 0007 *Waste Management* and EMS 0017 *Oil Management.*

6. Intervention Options

A range of options have been considered as possible intervention options to address the risk presented by power transformers whilst providing the maximum benefit to participants in the electricity market. These options are initially considered at an asset type/class level to determine if they are technically feasible and/or practical. Intervention options which are likely to be credible are then considered at an asset level to determine the most appropriate option for each individual asset.

Table 9 – Intervention options

Intervention Type	Option	Assessment of effectiveness	Credibility
Non-Network Based	-	Due to the substantial load that each power transformer carries on a continual basis, there are no non-network solutions which can credibly replace their functionality[4].	Not a credible Solution
Condition Based	Additional maintenance to extend the life of the existing asset	Maintenance procedures are able to ensure an otherwise sound power transformer asset reaches its full life potential. Mid-life refurbishment including drying out the paper insulation on the windings, refurbishing or replacing the insulating oil and repairing seals and refurbishing or replacing ancillary equipment is an option for extending the life of power transformer. This option is considered for all power transformers proposed for risk-based replacement. However, there is a limited time frame in the mid-life period of a transformer for which this approach is financially sound and therefore, it is not generally credible solution for assets identified for risk-based replacement in the latter stages of their life when the probability of failure is elevated.	An option to be considered but not a credible solution in isolation
Risk Based	Reduce the load on the asset through network reconfiguration, network automation or demand management	The risk of failure can in some circumstances be influenced by the load on the transformer. Likewise, the life of a power transformer is influenced by the load that it carries over its lifetime. However, the loading on each substation and hence the transformers has been balanced around the network and transferring load from one substation to another to prolong the life of one power transformer will generally result in a shortening of the life of a transformer elsewhere, effectively cancelling the benefit. Transfer of load on a temporary basis is carried out to address emergency situation but in itself is unlikely to provide a credible alternative to the risk-based replacement of power transformer nearing the end of its life. In some instances, demand on a substation may have reduced to the point where a power transformer at end of life can be retired without being replaced. This option is considered on a case-by-case basis.	Not a credible solution

[4] This conclusion applies to like-for-like replacement with a standardised capacity modern equivalent transformer. When augmentation of the capacity of the host substation is required, there may be credible non-network solutions to fulfil this need. However, consideration of the requirements to undertake the regulatory investment test, distribution (RIT-D) is also a factor in determining whether non-network solutions need to be pursued further for any particular asset and/or program of asset replacements.

Further, the conclusion that non-network approaches cannot provide credible solutions for the like-for-like replacement of power transformers is based on the outcome of the RIT-D process carried out for the replacement of Marayong Zone Substation and for the replacement of the 11kV busbars at Sussex Inlet Zone Substation, both of which included either power transformer like-for-like replacement or network elements (the busbars at Sussex Inlet) which perform the same network capacity functionality as power transformers and which received nil proposals from the non-network market.

Intervention Type	Option	Assessment of effectiveness	Credibility
		Further, as noted above, power transformers are integral to the supply to their substations which are required to carry load for the foreseeable future. There are no practicable non-network solutions for replacing a zone or transmission substation and therefore on their own, there are no credible non-network options for replacing the functionality of a power transformer.	
	Implementing operational controls such as limiting access, remote switching protocols etc	These controls are in place to limit the safety risks presented by this equipment to workers. However, the principal risk that drives the need for intervention is reliability and financial loss, which cannot be affected by practicable controls.	Controls only safety risk for workers
	A combination of options together or staged to maintain option value and reduce the consumer's long-term service cost	Replacement of power transformers is generally the only credible option but mid-life refurbishment and retirement without replacement may in limited cases be credible and are therefore also considered on a case by case basis.	Feasible Option

6.1 Non-Network Based Interventions

No non-network based interventions have been identified as credible for replacing the primary function of this asset class, the transformation of power from one voltage level to another.

6.2 Condition Based Interventions

The inspections and preventative maintenance programs outlined in 5.3 Asset Maintenance result in identification of conditional failure defects which require repair to avoid the asset deteriorating to a functional failure. Defects are directly linked to an asset's failure mode(s) and are prioritised based on a qualitative assessment of the likelihood the defect will result in a functional failure.

Endeavour Energy determines what constitutes a defect based on Failure Modes Effects and Criticality Analysis (FMECA). FMECA is an analytical process that is derived from an assessment of an asset's ability to sustain technical function and purpose and relies on information relating to failure modes, their probability and consequences of failure. FMECA establishes a condition-based approach to asset maintenance that enables a risk-based determination of the maintenance requirements for assets.

Substation Maintenance Instruction SMI 124 – *Maintenance data entry and defect prioritisation* provides detail on standard job numbers what is to be recorded as a defect, the required actions, and the corresponding priority for each failure mode. It is noted that this standard refers to the now superseded Ellipse database and therefore needs to be replaced with similar instructions based on the current use of SAP.

Table 10 below provides an overview of the most common standard job numbers used to address condition defects and also functional failures associated with power transformers and the average annual costs associated with each of these.

Table 10 – Condition based interventions

Defect – standard job number	Standard job description	Average Annual Costs ($)
1TRCBM	Transmission Defect – CBM (Addressing condition defects)	202,446
1TRDFE	Transmission Defect – F&E (Addressing functional failures)	190,546
1FAULT	For storms and major events or can be used when another standard job is not suitable	29,461
(blank)	Not correctly recorded – but are generally 1TRCBM defects	19,144
PCFEAS	P&C – F&E, Assist Trans Subs (Investigate alarms and protection system operations)	8,692
2OILTX	Top up of oil (This job number has only been used since 2021)	1,192

In the past five years, one power transformer (Minto ZS 66kV transformer No. 1), experienced a tap-changer fault, which, after investigation and assessment of the options, resulted in the reactive condition-based replacement of the transformer. A further transformer (Dundas ZS 66kV transformer No. 2), was retired from service due to tap-changer condition indicating imminent failure and after assessment of the options, was not replaced. All other condition-based interventions have resulted in repairs to the assets followed by a return to service.

The common repairable defects have been tap-changer repairs and low oil levels/oil leaks. The most common repairable functional failures are associated with oil leaks and protection operations, many of which are faults with the protection systems rather than with the transformer itself. No particular issues stand out as requiring particular attention apart from the mal-operation of protection systems, which has been discussed above in 4.3.2 and is being addressed through the Protection systems asset class.

6.3 Risk Based Interventions

6.3.1. Intervention value assessment

The initial assessment of the value of a risk-based intervention for power transformer assumes that the asset will be retired and then replaced with a modern equivalent transformer of standardised capacity.

Each asset is assessed for its probability of failure and consequences of failure and the benefits of deferring the risk associated with failure by replacement with a new asset. The present value of the benefits are compared with the present value of the costs of the intervention to provide a net present value (NPV). Assets are identified for replacement intervention in the year when the NPV of the proposed intervention is positive and reaches its maximum value. Intervention NPV characteristics which are negative but increase to converge with zero over time indicate (based on currently available data and understanding of the asset), that the asset should never be proactively replaced but should be operated to failure, to provide the maximum value.

In the future, it may prove that the cost of retaining the asset in service, (due to repeated repairable failures for instance) will alter the cost of ownership model and favour a risk-based intervention before the end-of-life failure of the asset.

A further caveat on the run-to-failure approach is that Endeavour Energy has a prudent philosophy of not knowingly allowing assets to fail in service if there is data available that indicates imminent failure. In the case of power transformers, which are tested routinely, eventually test data (such as winding paper degree of polymerisation, oil quality and/or dissolved gas results) will become available indicating imminent failure. At this point the transformer would be retired and assessed for replacement. This would be considered as a reactive condition-based intervention.

Transformers identified for risk-based replacement within the period of interest (the forthcoming regulatory period) are then checked against the continued need for the service provided by the asset. The credibility of reducing the risk presented by the asset by carrying out refurbishment works and hence deferring its replacement need is also tested.

Interventions that pass each of these tests are put forward for optimisation in the portfolio of investments.

6.3.2 Calculation of intervention value where there is redundancy

In zone and transmission substations there is generally a level of redundancy built into the power transformer capacity such that the loss of one transformer will not result in the loss of supply from the substation. On this basis, the reliability risk associated with the functional failure of these assets is essentially nil. As the reliability risk is the key driver for planned risk-based replacement, generally the cost-benefit model will favour a run-to-failure approach for these assets. However, in practise there are a number of factors which impact the reliability performance of redundant systems, and particularly that of power transformers within the same substation:

- There is a probability that the alternate supply element will be out of service either for maintenance or due to a fault elsewhere in the network. (The standardised value of the likelihood of this occurring is 1%)[5]; and
- There is a probability that the alternate supply element will fail at the same time as the asset in question or whilst the initial asset that failed is being investigated, repaired or replaced. This is particularly a risk for pairs of aged power transformers whereby the event which triggers the failure of one of the transformers may also trigger the failure of the other, or the failure of one may trigger the failure of the other due to increased demands on the remaining asset.

The method used for estimating the reliability risk of power transformers is summarised in the Table 11 below. The second column shows the likelihood of the reliability impact occurring (LoC) while columns three – six show the proportion of the maximum cost of consequence (CoC) which is modelled as occurring based on the number of power transformers installed in the substation. The consequence is unserved energy the full value of which equals the substation maximum demand (MW) * load factor (% of maximum demand) * VCR ($/MWh) * outage duration (hr).

It is assuming that in the single transformer there is nil redundancy (besides secondary voltage network switching) and in each other substation there is a single transformer redundant which notionally provides an N-1 level of supply security.

Table 11 – Power transformer reliability risk assessment

Reliability risk element	LoC (%)	CoC (% of maximum value of unserved energy)			
		Single transformer substation (no redundant transformer)	Two transformer substation	Three transformer substation	Four transformer substation
1. Principal failure impact	100	100	0	0	0

[5] The probability of two assets being failed simultaneously can be calculated from multiplying together the Annual PoF x Outage duration (hours)/Hours pa for each asset together. This will typically give a likelihood of around 1 $x10^{-6}$ or less, which is not material. The 1% value takes into account a range of other factors including maintenance windows, failures of auto-changeover systems etc and is a generally accepted value. Notwithstanding this, a 1% LoC also yields values of reliability risk which do not have a material impact on the cost-benefit equation.

Reliability risk element	LoC (%)	CoC (% of maximum value of unserved energy)			
		Single transformer substation (no redundant transformer)	Two transformer substation	Three transformer substation	Four transformer substation
2. Redundant elements not being available	1	N/A	100	50	33
3. Simultaneous failure of a redundant element	PoF of the redundant element * constant	N/A	100	50	33

The third reliability risk element, simultaneous failure of redundant element, has a material impact on both the reliability risk CoF as well as the financial risk CoF[6]. As this is an estimated value without a substantive basis in historical data, a constant is included to allow the effect to be adjusted to achieve outcomes which appear to be reasonable and give consistent results across the asset class.

Where multiple transformers in a substation are of similar age and condition, they will be identified by the cost-benefit value assessment for replacement at the same time. The rule applied in this case is to schedule the transformer whose replacement gives the highest value for planned risk-based replacement and then to defer the second unit for reassessment prior to the next regulatory control period.

Given two transformers of advanced age, each with similar health scores, once one is replaced, the likelihood of the simultaneous failure reduces significantly and therefore the assessment being re-run for the next RCP may not recommend the risk-based replacement of the remaining aged transformer.

6.3.3 Risk of systems attached to the primary asset

Power transformers are closely integrated with protection and control systems and are supported by auxiliary systems. The majority of power transformers have protection systems which monitor overcurrent and earth fault currents, differential current flows, oil surge between the main tank and conservator and between the tap-changer and its conservator (if fitted) and gas emissions from the oil. Control systems manage voltage regulation, cooling modes and automatic change-over to the redundant transformer after a failure. The capacity of the power transformer is also dependant on the correct functioning of its auxiliary cooling systems.

The associated protection and control and auxiliary systems can have a significant influence on the reliability of the primary asset. The strategy for managing these systems is that the associated protection and control systems are modelled and managed as secondary systems but the auxiliary systems (cooling fans, oil pumps in the case of power transformers) are modelled as part of the primary asset.

Note that auxiliary power supplies in zone and transmission substations have their own asset class and are therefore modelled as their own individual systems, including auxiliary transformer, cabling and switchboard(s).

[6] The financial risk is increased by the probability of having two transformers fail and their replacement needing to be funded.

7. Forecasts

7.1 Cost

The risked based replacement program has identified five assets within this asset class whose replacement reaches their maximum value in the upcoming regulatory control period. The earliest year for intervention is FY25 and all of the power transformers identified for risk-based intervention fall in that year. Further, the shape of their NPV characteristics, (which are decreasing significantly year on year), indicate that the optimum time for their replacement is prior to FY25. This has resulted in a peak in investment costs in FY25 as indicated in the expenditure profiles, however the labour resource constraints will likely see this peak flattened out over the regulatory period.

This asset class plan identifies a further two assets that, based on current assessment, are expected to reach their maximum NPV in the following FY30 – FY34 regulatory control period. It is noted that a further four power transformers are currently being assessed for possible reactive condition-based intervention based on defects of ongoing significant oil leaks and bushing failures. This is an area of ongoing investigation.

Table 12 - Power transformer potential investment forecast

Asset name	Equipment number	Asset type (standardised replacement asset)	Asset age (years, in 2023)	Investment driver	Proposed action	Proposed risk-based investment
South Wollongong ZS, 33kV, No. 2	175127	33/11kV 25MVA	56	NPV maximum	Replace FY25 – 29	1.63
Warilla ZS, 33kV, No. 2	175138	33/11kV 15MVA	61	NPV maximum	Replace FY25 – 29	1.30
Unanderra ZS, 33kV, No. 1	175130	33/11kV 15MVA	60	NPV maximum	Replace FY25 – 29	1.30
Wombarra ZS, 33kV, No. 1	175074	33/11kV 15MVA	61	NPV maximum	Replace FY25 – 29	1.30
Port Central ZS, 33kV, No. 2	175124	33/11kV 25MVA	54	NPV maximum	Replace FY25 – 29	1.63
Total						**7.16**
Sussex Inlet ZS, 33kV, No. 2	175102	33/11kV 15MVA	52	NPV maximum	Assess for risk-based replacement FY34	1.30
Hartley Vale ZS, 66kV, No. 1	183190	66/11kV 15MVA	71	NPV maximum	Assess for risk-based replacement FY34	1.30
Total						**2.60**
Quakers Hill ZS, 132kV, No. 1	183860	132/33/11kV 60MVA	56	Sustained and severe oil leaks	Assess for condition-based replacement	2.98
Bossley Park ZS, 33kV, No. 2	18812	33/11kV 35MVA	41	Sustained and severe oil leaks	Assess for condition-based replacement	2.29
Moss Vale ZS, 33kV, No. 2	175119	33/11kV 25MVA	45	Sustained and severe oil leaks	Assess for condition-based replacement	1.63
West Liverpool TS, 132kV, No. 2	184986	132/33/11kV 120MVA	50	Failed 33kV bushing – replacement not available	Assess for condition-based replacement	3.94
Total						**10.84**

Figure 8 below shows the historical capital expenditure on power transformers and the forecast for the next few years and the forthcoming regulatory period. It includes planned risk-based and reactive condition-based investment as documented in the case for investment for the FY25-29 regulatory control period - *Power transformer risk-based value assessment CFI FY25.* Over the next 5 years, inspection and maintenance expenditure is expected to be stable and track the population trend as shown in Figure 9 below.

Figure 8 – Historical and forecast capital Investment

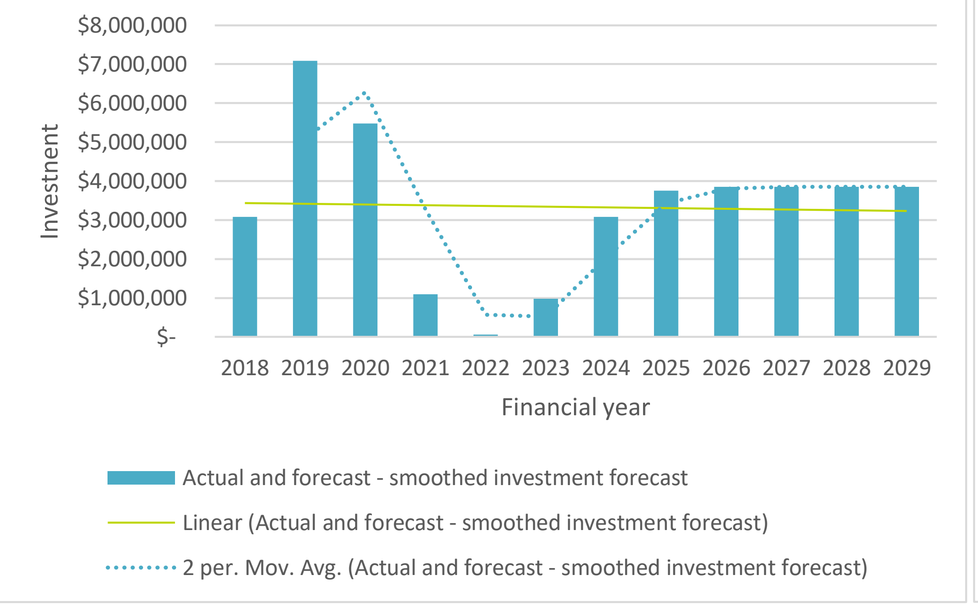
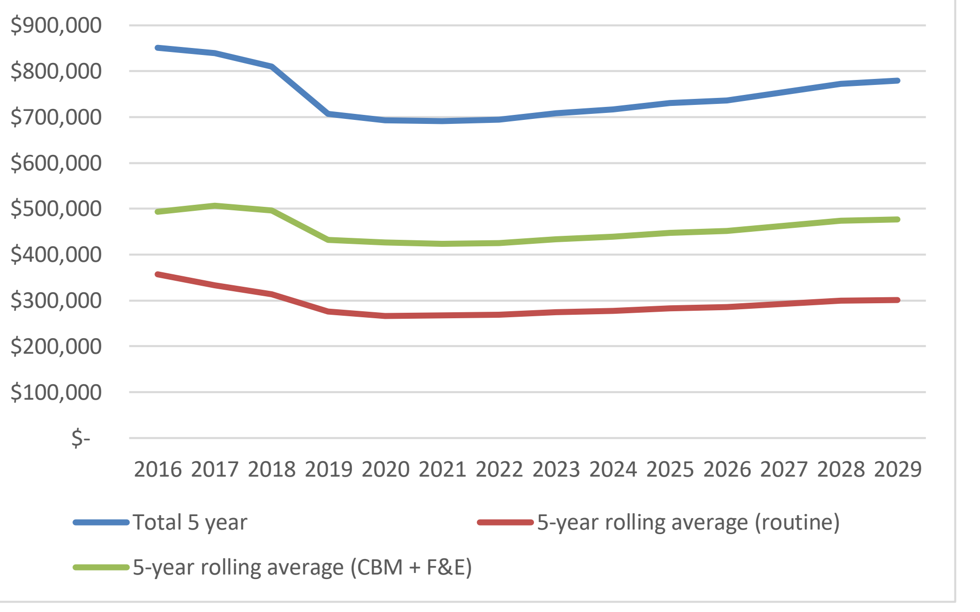


Figure 9 – Historical and forecast maintenance expenditure

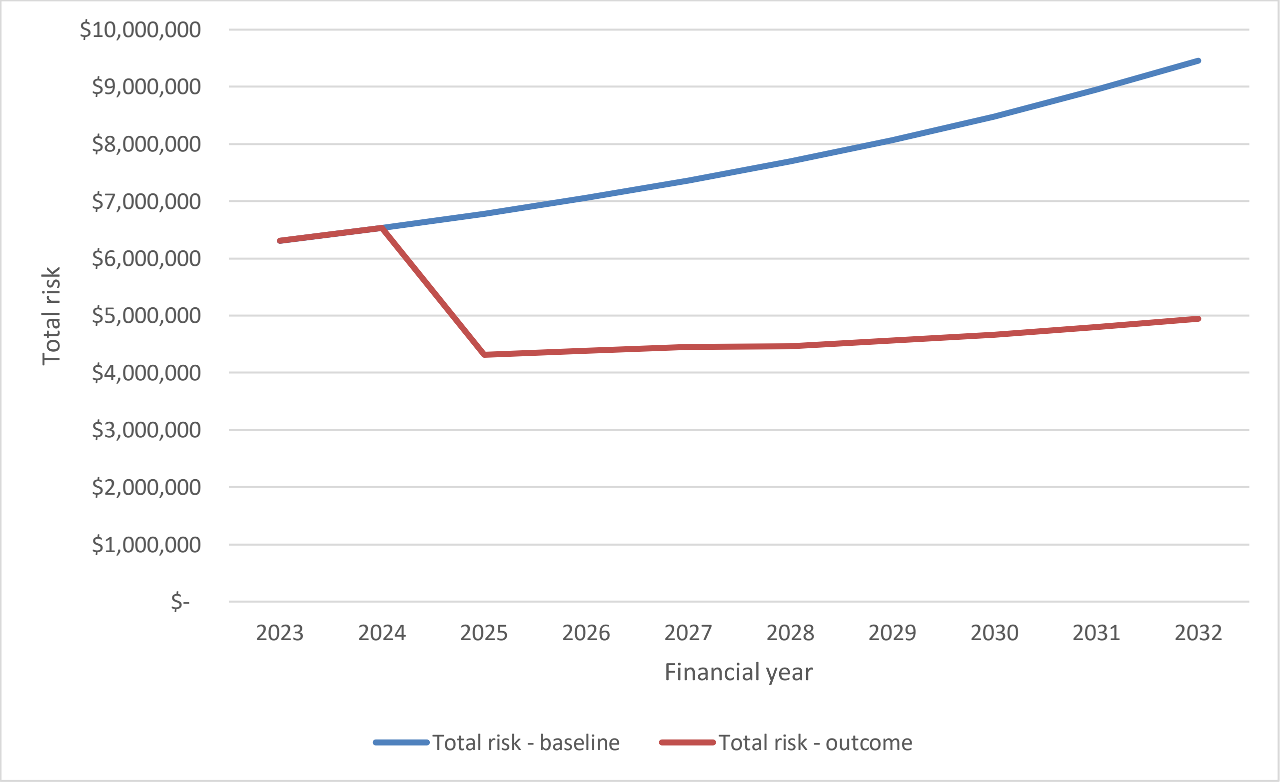


7.3 Risk

Network risk associated with power transformers has been calculated as per the current value framework. The risk in this asset class is comprised of Reliability (58%) and Financial (42%). Safety, bushfire, environmental and compliance risks are currently not material and are therefore not modelled. Later iterations of the value model may develop the safety and environmental risks further and also integrate the ongoing maintenance costs (particularly those associated with oil leaks), into the cost of ownership factor to ensure that this element of the life cycle costs of power transformers influences the investment decisions with an appropriate weight.

The baseline risk (no intervention) associated with this asset class is projected to increase by 19% from $6.8 million to 8.1 million over the regulatory control period if no action is taken. The outcome risk based on the proposed intervention profile with the risk-based investment concentrated in FY25. However, in practise, the investment and associated risk deferral benefit is likely to be spread more evenly across the regulatory period as shown in Figure 8 above. Figure 10 below shows the baseline and outcome risk as forecast.

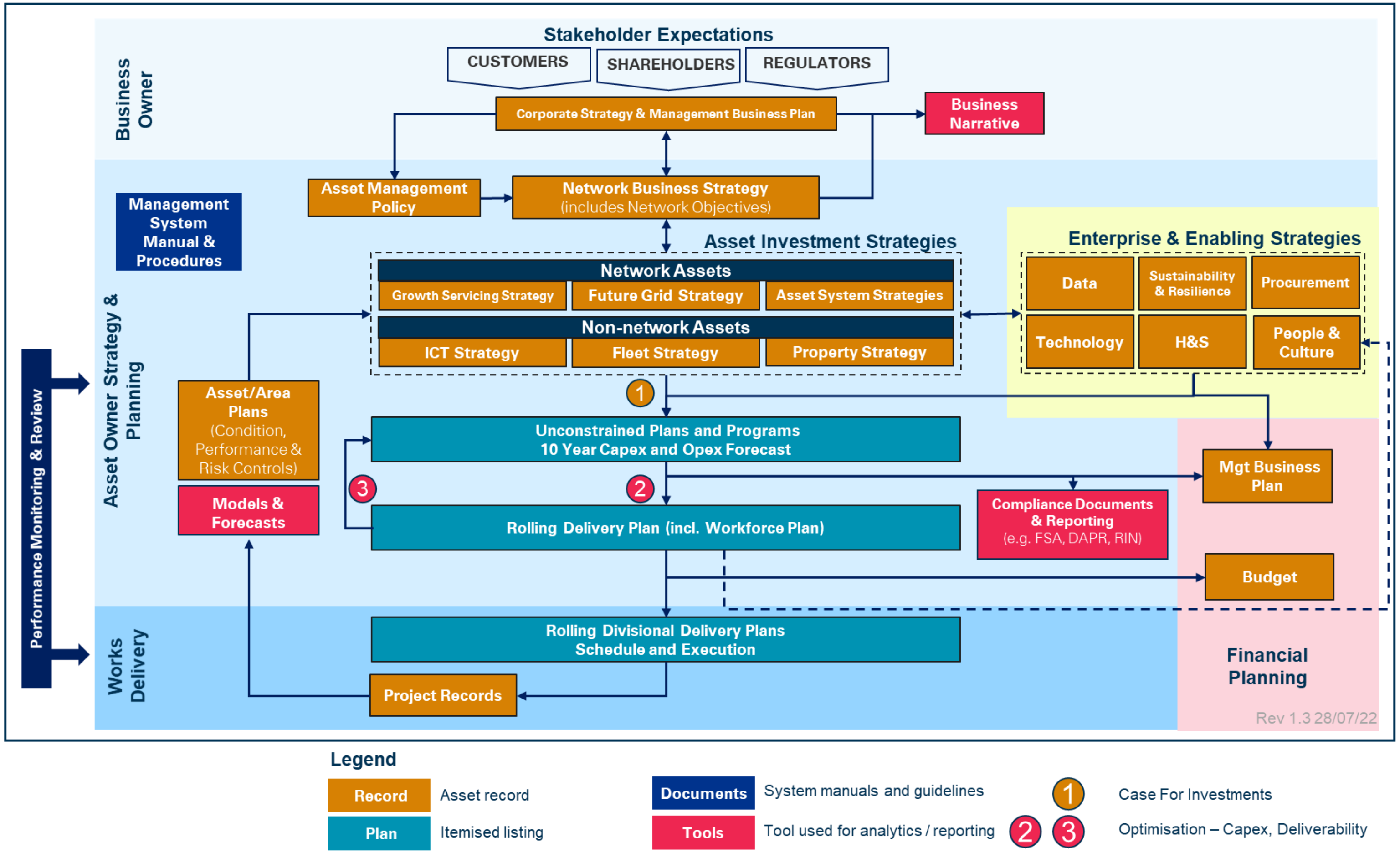
Figure 10 – Risk forecast



8. Asset Management Systems

This section identifies the strategies, practices and guidelines supporting the management of this asset class. A detailed description of Endeavour Energy's asset management system and its constituent parts is available in the Asset Management System Manual and the Asset Management System Guidelines

The relationship between this document and the other artefacts within Endeavour Energy's asset management system is illustrated below:



8.2 Standards, Guidelines & Policies

Endeavour Energy's asset management practises are governed and guided by numerous legislative requirements, guidelines, and industry best practises throughout Australia and Internationally. Endeavour Energy's manuals, procedures and workplace policies are all underpinned by these key documents as documented in 'GQY 1190 *Policy and Procedure Framework'* and in Figure 11 below. Legislation, regulations, and high-level Australian Standards applicable to HV network operations are detailed in the Endeavour Energy Asset Management System.

Endeavour Energy has developed the following documentation to specifically guide the life-cycle management of HV power transformers:

Figure 11 – Approved power transformer life cycle management documentation

Company Policies

9.1.6 Approved Materials List
9.1.7 Commissioning network Electrical Assets
9.1.9 Network Technical Compliance
9.2.1 Network Planning
9.2.2 Network Protection
9.2.5 Network Asset Design
9.7.1 Network Asset Construction
9.8.3 Network Operations
9.9.1 Network Asset Maintenance
9.9.2 Essential Spares

Approved Specifications

ETS 0005 15MVA, 25MVA and 35MVA power transformers
ETS 0006 45MVA, 60MVA and 120MVA power transformers
ETS 0010 Mineral insulating oil
ETS 0023 11/22kV 20MVA power transformers
ETS 0028 66/11kV 5MVA and 10MVA power transformers
ETS 0029 Regenerated mineral insulating oil
ETS 0030 15MVA 132/11kV power transformers
ETS 0032 Natural ester insulating oil

Design Instructions

SDI 501 Substation network and zone substation configuration
SDI 505 Minimum design & construction requirements for transmission & zone substations & switching stations
SDI 540 Transformer oil containment

Construction & Commissioning Standards

SDI 535 Site testing and pre-commissioning

Maintenance & Operations Standards

SMI 100 Minimum requirements for maintenance of transmission and zone substation equipment
SMI 115 Oil separators and bunds
SMI 119 Transmission and zone substation data asset structure and nameplate details (superseded?)
SMI 121 Storage and handling of insulating oil
SMI 124 Maintenance data entry and defect prioritisation (superseded?)
SMI 151 On load tap changers and tap changer motor boxes
SMI 155 Power, auto and regulating transformers
SMI 156 Breathers
SMI 161 Condition assessment of assets using health index

Disposal procedures

GSU 0006 Disposal of surplus goods and equipment
GSU 012 Selection and approval of a disposal method
EMS 0007 Waste management
EMS 0017 Oil management

8.3 Asset Management Tools

Endeavour Energy uses a range of database and geographical information system related tools to aid in the management of power transformer assets. Key tools used are shown in Table 13 below.

Table 13 – Asset management tools

Tools	Current Purpose	Future Purpose
Ellipse Database	Used for historical (2010 - 2021) asset nameplate details, routine maintenance scheduling, defect workorder recording and management	Superseded by SAP
SAP	Used for recent (2021 - current) asset nameplate details, routine maintenance scheduling, defect workorder recording and management	To be used as the primary data source for: • Asset characteristics; • Financials; • Safety – safety incidents are to be categorised by asset class, asset type, and severity; • Bushfire – bushfire incidents are to be categorised by asset class, asset type, and severity; and • Environmental – environmental incidents such as oil leaks and spills are to be captured and categorised by asset class, asset type, and severity.
ADMS	Not currently used	To be used as the primary data source for: • Reliability – reliability incidents are to be categorised by asset class, asset type, and include SAIDI and SAIFI contributions. • Resilience – Benefits from network automation to be quantified • Utilisation – switching events are to be categorised by asset class and asset type.
OMS	Used for historic (2012 - 2021) asset related reliability incidents	Superseded by ADMS
FireStart	Used for historic (2005 - 2021) asset related firestart incidents	Superseded by SAP
MySafe	Used for historic (2012 - 2021) asset related safety incidents	Superseded by SAP

9. Further actions

Areas for further investigation and development of this asset class plan are summarised in Table 14 below.

Table 14 – Further actions

Focus area	Action
CNAIM model implementation	Collection of additional data to further populate the default inputs, particularly for external asset condition and oil leaks, tap-changer and bushing inputs. Consider adoption/adaptation of the CNAIM model for consequences of failure.
Status of essential spares	Investigate the status of the power transformer essential spares, both full transformers and also bushings – and the impact of that strategy on the transformer investment strategy and reactive condition-based investment forecast.
Value model for single-transformer substation	Develop a reliability risk value model for single-transformer customer substations (eg Visy Paper substation) and adjust applicable VCR to reflect the value the customer places on reliability.
Environmental cost of ownership	Whilst environmental risks associated with asset failure are not material, the risk cost of ownership due to ongoing oil leaks needs to be integrated in the value model.
Safety and environmental risk costs	Whilst not being material, for completeness the safety and environmental risk costs associated with failure should be integrated in to the in the value model.

10. Appendices

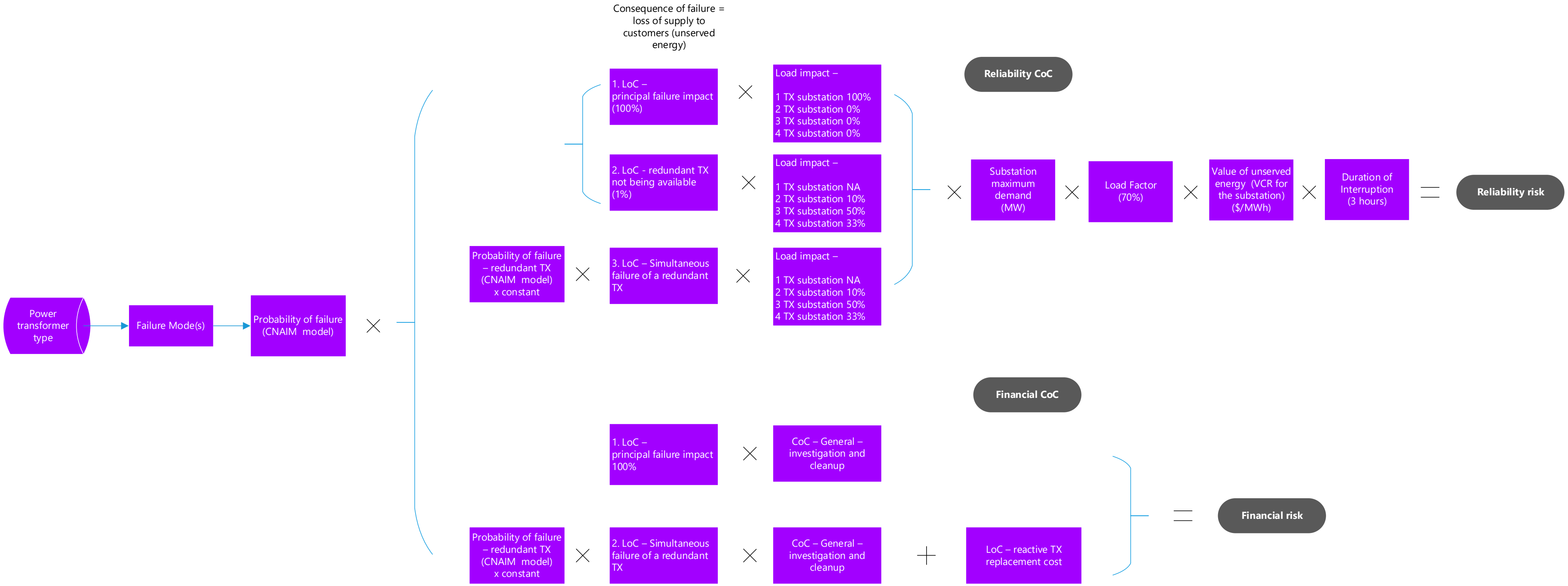
Appendix A – Risk mitigation flowchart

Appendix B – Probability of failure parameters

Appendix C – Consequences of failure

Appendix D – Additional asset information

Appendix A – Risk mitigation flow chart



Appendix B - Probability of failure parameters

The failure probability for an end-of-life functional failure is developed using the CNAIM methodology. A summary of the key inputs to the CNAIM model are shown in the tables below.

Probability of failure parameters – CNAIM methodology

CNAIM model inputs and variables	Value	Description/justification	Source/assumptions
Basic transformer data	Various	Transformer equipment number, capacity and voltage, type, in-service date	Ellipse
Transformer classification	Specific to transformer type	Translation of EE’s transformer types to CNAIM standard categories	Transformer PoF model lookup tables
Health Score New	0.5	Constant starting point health score collar. (Health scores range from 0.5 to 10 in the model)	Assigned by the CNAIM model
Health score at Normal Expected Life	5.5	The health score when the Normal Expected Life is reached	Assigned by the CNAIM model
Normal Expected Life	50 – 60 years specific to the transformer category	Standard values based on the voltage and era of manufacture (pre or post 1980). The age at which significant deterioration in the transformer’s condition is first observed. CNAIM assigned health score of 5.5	Assigned by the CNAIM model
Location factor (distance from the coast)	Geographic information for each transformer. Ranges from 0.9 – 1.35	The distance of the transformer from corrosive environment of the coast line. Used to adjust the Expected Life of each transformer.	ESRI geographic database and GIS database
Duty factor	Specific to transformer location in the network. Ranges from 0.9 – 1.4	Values for the range of standard transformer categories and locations in the network as input variables for the CNAIM model which adjust the Expected Life of each transformer.	Transformer PoF model lookup tables. Default value of 1 generally applied to all power transformers with N-1 arrangement
Expected Life	Varies	The Normal Expected Life divided by the Duty Factor and the Location factor	Calculated by the CNAIM model
Initial Aging Rate ($\beta 1$)	Varies	Constant that allows the health score at a future age to be forecast based on the health scores and expected life values	Calculated by the CNAIM model
Initial Health Score	Varies	A function of the age of the transformer, the Initial Aging Rate and the Health Score New	Calculated by the CNAIM model
Health Score Modifiers	Specific to each transformer	A range of inputs which modify the health score for each transformer. Specific to each transformer and evaluated using maximum and multiple increment technique The inputs include:	Input via spreadsheet based on observed condition. Ranges set by the CNAIM Model.
		Observed condition - in particular oil leaks and corrosion of tank, radiators and tap-changer, bushing condition, tap-changer condition	Not currently populated but needs to be populated to capture significant oil leaks and tank corrosion issues

CNAIM model inputs and variables	Value	Description/justification	Source/assumptions
		Measured condition including temperature readings, partial discharge results	Not currently used. Potential to include paper degree of polymerisation results here
		Oil test results including moisture, acidity and breakdown strength	Test results from spreadsheets on shared drive G:\Oildata. Ranges set by the CNAIM model.
		Oil dissolved gas analysis results	Test results from spreadsheets on shared drive G:\Oildata. Ranges set by the CNAIM model.
		FFA test – Furfuraldehyde in oil test results	Not currently used. Potential to include to complement paper degree of polymerisation tests
		Reliability modifier – includes refurbishment and oil replacement history. Values range from 0.6 – 1.5. Generally default value of 1.0 has been used. 0.8 applied to North Wollongong ZS PX to reflect the likely improvement made by refurbishment works carried out in 2012	Not generally used. Potential to include to adjust expected life of specific transformers. Assumption that refurbishment of PX at North Wollongong in 2012 will have an impact on the current PoF
Current Health Score	Varies	Health score for each transformer based on the Initial Health Score and the Health Score Modifiers	Calculated by the CNAIM model
Forecast Aging Rate ($\beta 2$)	Varies	Constant that allows the health score at a future age to be forecast based on the health score as modified and age	Calculated by the CNAIM model
Aging Reduction Factor	Varies	A factor which slows down the aging rate of older assets. Applied on the basis that older assets have proven their level of reliability and longevity. A function of health score and age.	Calculated by the CNAIM model
Future Health Score	Varies	The forecast health score at a particular age in the future. Based on the transformer Current Health Score, Forecast Aging Rate and Aging Reduction Factor. This data is calculated for each transformer in one year increments for input into the Copperleaf Predictive Analytics application	Calculated by the CNAIM model
Probability of Failure	Varies	The PoF at any age for each transformer based on the health score. Input into the Copperleaf Predictive Analytics application	Calculated by the CNAIM model
Interventions	Various	Logging assets which are already approved for replacement (for exclusion from the general PoF modelling). Also includes values for the reliability factor where appropriate.	
CoF inputs	Various	Spreadsheet which contains the input information such as Basic financial CoF, replacement costs etc	Estimation and cost estimate data
Substation VCR values	Specific to each substation	Value of customer reliability for an occasional short-term outage calculated for each substation based on customer mix and standard VCR values provided by the AER	Network Planning Manager – published VCR values for each substation (Endeavour Energy specific VCRs.xlsx 20220524)

Appendix C - Consequence of failure

Reliability risk inputs

Parameter	Value	Description/justification	Source/assumptions
Loss of supply to customers - LoC	1% generally 100% for single transformer substation	1% generalised likelihood of loss of load when N-1 supply security is available	RisCAT - 1% likelihood the alternate supply path will not be available due to maintenance, or failure.
Load impacted	Specific to each substation	The summer maximum demand of the substation at 50% probability of exceedance	2022 Summer Maximum Demand data (note – an improvement would be to assess both summer and winter peaks and take an average for this assessment)
Load factor	70%	Load assumed to be lost is 70% of the summer maximum demand value for the supplied substation(s)	Generalised load factor developed by Protection Manager based on a study of network faults.
VCR	Specific to each substation/switching station	Value of customer reliability for an occasional short-term outage	Specific values for each substation/switching station calculated by Network Planning based on values published by the AER
Power factor	0.95	Worst case value – to scale demand from MVA to MW for application of VCR	A minimum value which reduces the value of potential unserved energy. Generally zone substation power factor is 0.98 or better
Duration of interruption	3 hours	3 hours assumed interruption until alternate arrangements are made for supply through switching the network	A generalised value based on a range of outages of transmission assets. Assumes off-loading to reinstate supply through a combination of SCADA and manual switching of disconnectors on site and distribution switches in the field as appropriate
Coincidental failure factor	8	Utilises the PoF of other transformers in the same substation to assess the likelihood of having a simultaneous failure of the second transformer (either due to the same through-fault stresses, or due to the fault in one TX stressing the other TX) The highest PoF of the other TXs is taken at the end of the RCP and a constant applied to it to give a reasonable and consistent likelihood of two failures. The consequence is loss of 100% of supply in two transformer substations and 50% in three-transformer substations. This factor also adds the costs of replacing the second transformer to the Financial risk value of the transformer in question.	This factor has a material impact on the value model results and can shift transformers from run-to-failure to risk-based replacement. The constant applied is based on an estimation to give a realistic volume of risk-based replacements which aligns with the Repex model and SME expectations. The base value of 8 applied gives reasonable looking results which will be tested against the reactive investment demands leading up to and through the RCP.

Financial risk inputs

Parameter	Value	Description/justification	Source/assumptions
Financial general - CoC	$40,000	Switching to restore supply/supply security, clean-up, any temporary diversion works, investigation, additional removal and disposal of the failed transformer over and above what is included in a planned replacement	Estimate, based on typical clean-up and investigation costs
Financial general - LoC	100%	Likelihood of general financial risks being realised on failure	
Financial – coincidental failure	PoF	This value is a function of the PoF of other transformers in the same substation and considers the costs of replacing a second transformer in a reactive manner if that unit should fail at the same time as the first unit (due to being of the same age and condition as the unit being assessed). Note that the cost of replacing the principal transformer is **not** included in the financial risk cost as it is added in to the cost benefit equation by Predictive Analytics.	As for the Coincidental failure factor
Reactive replacement costs	Varies	Reactive replacement costs generally equal planned replacement costs	Estimate based on experience of past transformer failures. A replacement transformer is provided free of charge from the Essential Spares store and then the spare unit is replaced and the costs of the replacement charged to the failed transformer replacement project.

Appendix D – Additional Asset Information

Asset risks

Power transformers are complex electro-mechanical devices with a wide range of failure modes. Power transformers are also supported by protection and control systems which themselves introduce further failure modes.

Conditional failures generally have no immediate consequences but indicate impending *functional* failure, which will impede the power transformer from carrying out its required function.

Table 15 and Table 16 below summarise the condition and functional failure modes of a typical power transformer, possible effects to those failures and the range of responses to the failures.

Response to conditional failures (Failure modes and effects)

Due to the complex nature of power transformers, conditional failures can take a wide range of forms. Table 15 below summarises the responses to a typical range of conditional failures

Table 15 – Conditional failure summary

Conditional failure/defect	Typical cause	Comments	Typical response
Low insulation resistance	Deterioration of the insulating oil due to heat, moisture and gas discharge	May be repairable	• Dry and refurbish the oil • Mid-life refurbishment including drying the windings
Poor winding resistance signature	Worn tap-changer contacts	May be repairable	• Maintain tap-changer contacts
Low paper DP	Paper deteriorating towards end of due to heat, and moisture and acidity of the insulating oil	Usually signals the end of the transformer's life	• Signals impending end of life failure of the transformer
High moisture content	Water penetrating the transformer tank through leaking seals and faulty breathers	May be repairable	• Dry and refurbish the oil • Mid-life refurbishment including drying the windings
Poor oil dissolved gas results	Over-heating windings, discharge in the windings or tap-changer, arcing in the tap-changer	May be repairable	• Dry and refurbish the oil • Mid-life refurbishment including drying the windings • Maintain tap-changer contacts and leads, barrier boards etc

Conditional failure/defect	Typical cause	Comments	Typical response
Bushing dielectric loss-angle	Break down of insulation, usually due to moisture ingress	Can deteriorate to explosive failure of the bushing. This may be a repairable failure for transformers with spare bushings available. Where replacement bushings are not available, this contributes to the consideration for condition-based replacement.	• Replace bushing; or • Consider for replacement
Leakage of insulating oil	Leaking seals caused by age and exposure to the weather and/or poor quality manufacturing and/or failure of seals over time	Some seals can be replaced but main tank seals may require a major refurbishment. Significant leaks from main tank seals is a factor which drives consideration for condition-based replacement in older transformers.	• Repair leaks/replace seals • Consideration for replacement
Corrosion of radiator fins	Caused by age and exposure to the weather and/or poor quality manufacturing	May possibly be repairable to some extent or radiators may be replaceable. But in an old transformer it is generally a factor contributing to the consideration for condition-based replacement	• Replace radiator(s) • Consideration for replacement
Corrosion of main tank	Caused by age and exposure to the weather and/or poor quality manufacturing	May be repairable to some extent if managed before the corrosion becomes extensive or severe. In an old transformer it is generally a factor contributing to the consideration for condition-based replacement	• Repair • Consideration for replacement
Cooling system failure	Failure of fan(s), oil pump(s), failure of secondary control systems	Generally repairable. In an old transformer it may be a factor which contributes to the consideration for condition-based replacement	• Repair

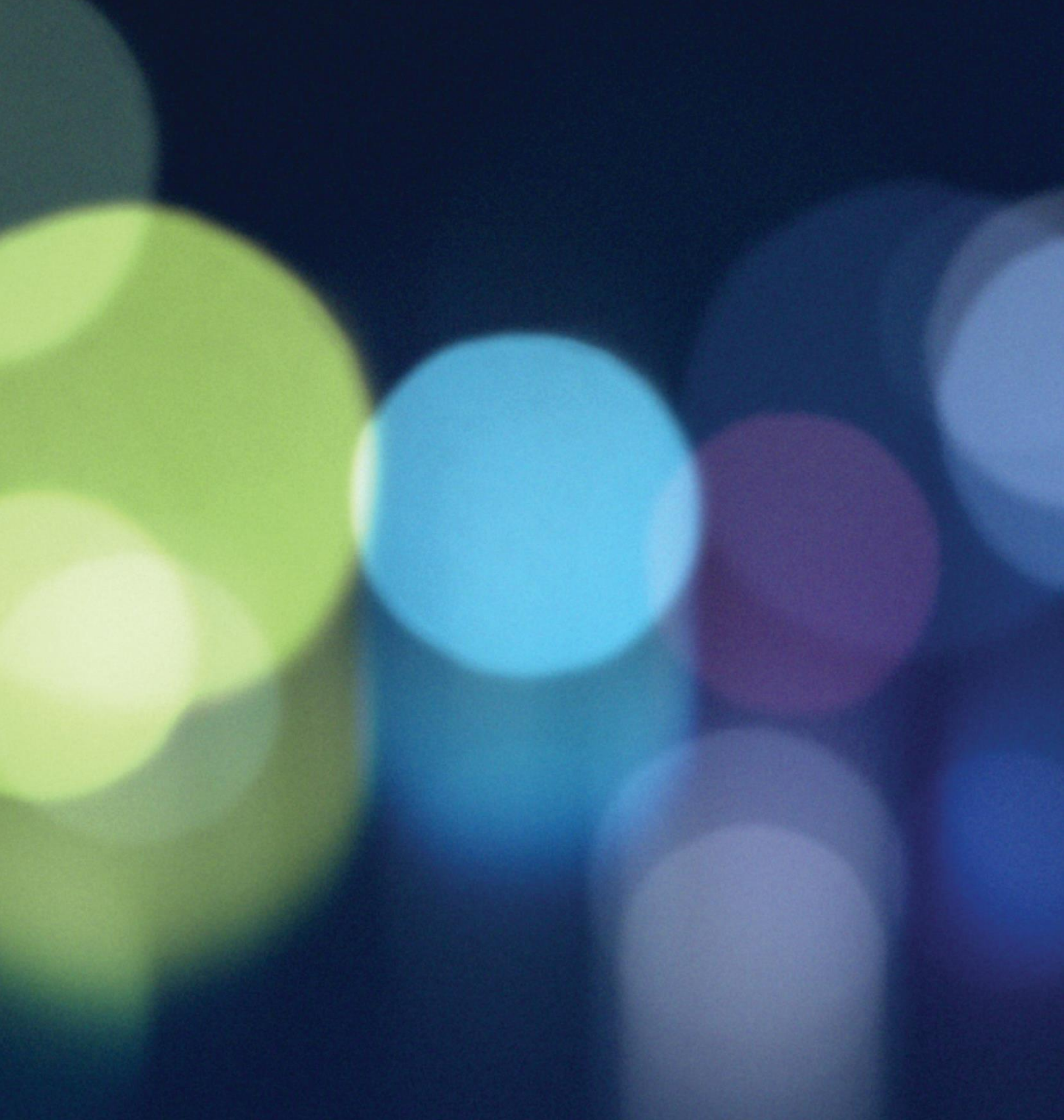
Response to functional failures (Failure modes and effects)

Functional failures of power transformers will all result in the transformer being switched out of service by the transformer's protection system. Table 16 below summarises the possible consequences of and responses to, a typical range of functional failures.

Table 16 – Failure summary

Failure mode	Typical cause	Type of failure	Consequences of failure (CoF)	Typical response to the failure
Protection trip – genuine fault	• Hot winding • Hot oil • Gas bubble in oil • Oil surge • Winding insulation break-down • Tap-changer insulation break-down • Tap-changer mechanical failure • Bushing failure	Functional failure	• Transformer will be isolated • Possible unserved energy depending on substation topology and the correct operation of the automatic transformer change-over functions	• Investigate and assess for repair or replacement • Winding and tap-changer failures may be repairable in younger transformers but will generally signal the end of life of an older transformer • Bushings are generally replaceable providing spares are available

Failure mode	Typical cause	Type of failure	Consequences of failure (CoF)	Typical response to the failure
Protection system mal-operation	• Hot winding • Hot oil • Gas bubble in oil • Oil surge	Functional failure in effect	• Transformer will be isolated • Possible unserved energy depending on substation topology and the correct operation of the automatic transformer change-over functions	• Investigate and return transformer to service



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