J18 and J22 circuit breakers

CP BUS 4.07

Regulatory proposal 2021–2026

CitiPower

January 2020

Contents

1 Overview

Business	CitiPower
Title	J18 and J22 circuit breakers
Project ID	CP BUS 4.07 - J18 circuit breakers - Jan2020 - Public
Category	Replacement
Identified need	The identified need is to address the increasing risks to safety and reliability of supply associated with J18/J22 6.6/11kV circuit breakers within our network
Recommended option	Option four: replace existing oil-filled J18/J22 circuit breakers with modern vacuum circuit breakers at high-risk or consequence zone substations
Supporting models	• CP MOD 4.17 - J18 AP - Jan2020 - Public • CP MOD 4.18 - J18 AR - Jan2020 - Public • CP MOD 4.19 - J18 FB - Jan2020 - Public • CP MOD 4.20 - J18 FR - Jan2020 - Public • CP MOD 4.04 - J18 TK - Jan2020 - Public

This business case is focused on the management of J18 and J22 oil-filled circuit breakers. These assets have been installed on our network since the early 1960s, and are increasingly exposing our staff and communities to significant safety and reliability risks.

In line with industry practice, our preferred asset management approach is to replace J18 and J22 oil-filled circuit breakers at selected, high-consequence zone substations. This program will begin in 2020, and the forecast capital expenditure requirements in the 2021–2026 regulatory control period, for the preferred option, are shown in table 1.

Table 1 Expenditure forecasts for preferred option ($ million, 2021)

Expenditure forecast	2021/22	2022/23	2023/24	2024/25	2025/26	Total
Albert Park zone substation	-	-	-	0.8	0.8	1.6
Armadale zone substation	0.7	-	-	-	-	0.7
Fishermans Bend zone substation	0.9	0.9	-	-	-	1.7
Flinders/Ramsden zone substation	-	-	0.9	0.9	-	1.9
Toorak zone substation	-	0.6	0.6	-	-	1.2
Total	**1.5**	**1.4**	**1.5**	**1.8**	**0.8**	**7.1**

Source: CitiPower

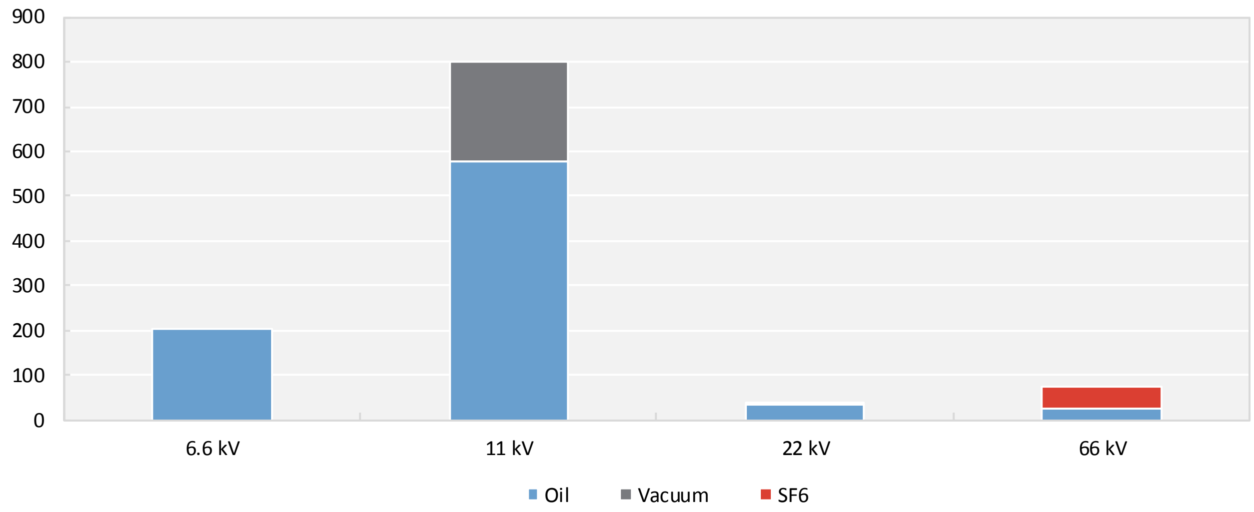
2 Background

The key role of zone substation switchgear in our network is to protect plant and personnel within the zone substation. Devices such as circuit breakers, automatic circuit reclosers, sectionalisers, and fuses can act to interrupt the fault current to protect the electrical plant, and avoid significant and sustained outages as a result of plant damage.

2.1 Asset population

We currently own and operate over 1,110 zone substation circuit breakers. These are primarily 11kV circuit breakers installed within indoor switchboards., and as shown in figure 1, the majority are oil type circuit breakers.

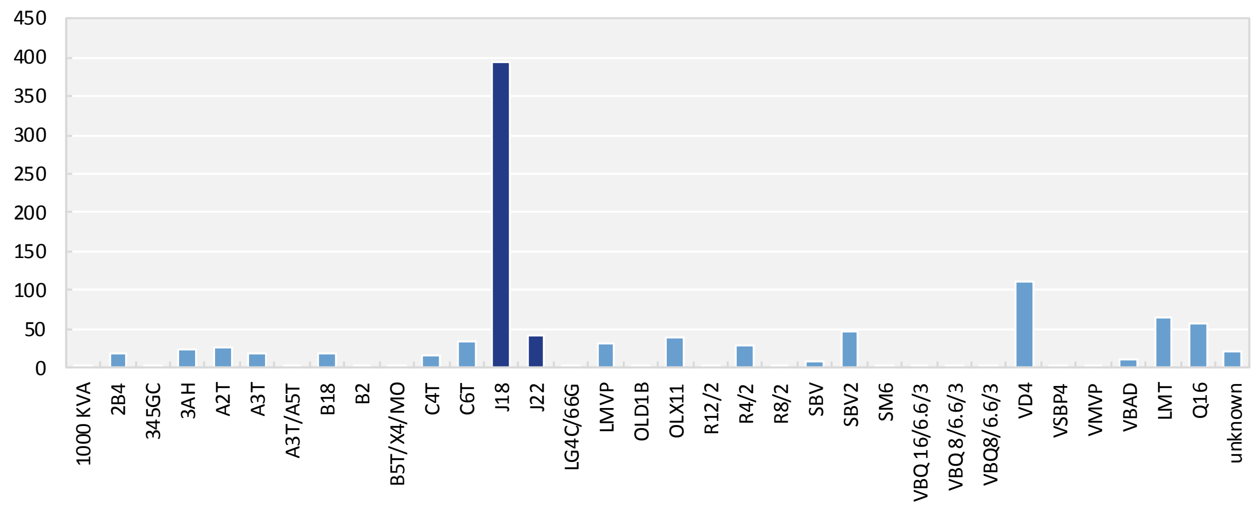
Figure 1 Existing circuit breaker volumes (by interruption medium)



Source: CitiPower

Further, as outlined in figure 2, the most common circuit breakers are J18 models, with J22 models also representing a material percentage of our population (i.e. in combination, over 39%).

Figure 2 Existing circuit breaker volumes (by model)



Source: CitiPower

2.2 Degradation and failure

The functional properties of the materials used within circuit breakers will degrade with age or with service. With certain ageing processes the physical, chemical, thermal, mechanical or electrical properties of the materials will change in a way that will influence the ability of the material to withstand electrical and mechanical stresses.

Other ageing processes are the result of a material being subjected to conditions that differ from those encountered in normal use, which can promote rapid ageing and degradation. Solid and liquid electrical insulation can be exposed to a wide variety of stresses that may cause the insulation to deteriorate over time and lead to failure. Chemical and environmental stresses such as the presence of water, contaminants and corrosive materials can lead directly to breakdown or accelerate the ageing process.

The typical ageing processes and failure mechanisms of some of the materials and components in circuit breakers are described in the following section.

2.2.1 Electrical degradation of solid insulation

The main mechanisms of failure of solid insulation are tracking, discharge erosion and thermal deterioration.

Tracking

Tracking is the formation of permanent carbonaceous paths or lines on the surface of an insulator caused by an electrical discharge. The partial discharge generally occurs due to contamination or degradation of the insulation surface, leading to uneven distribution of electrical stresses. Continued discharge will result in a discharge path and subsequent arc fault to earth.

Discharge erosion

Corona discharges occur when the electrical stress across voids within insulation material exceeds the discharge inception voltage for the particular medium filling the void. The discharge activity results in erosion of the walls of the void, which cause further increase in the stress. Continued discharge will result in a discharge path and subsequent arc fault to earth or between phases.

Thermal deterioration

Thermal instability results from a mechanism of dielectric loss that increases with temperature. The most important source for such loss is moisture absorbed by insulation which is under voltage stress. Moisture in insulation will respond to the electric field and convert electric energy into heat. If the rate of dielectric heating exceeds the rate of cooling by thermal transfer, then the temperature will increase until the insulation burns out or breaks down.

2.2.2 Ageing and degradation of metalwork and construction materials

The main factors leading to degradation and failure of metalwork and components are corrosion, overstressing and wear. Ageing and degradation of plated surfaces will occur as a result of corrosion, chemical erosion and mechanical stresses.

Fatigue and impact failures along with stress corrosion cracking have occurred to components in switchgear mechanisms. The parts of components which are prone to such failures are the areas where changes in shape produce high stress concentrations.

2.2.3 Degradation of insulating oil

In oil-filled switchgear, the oil is a primary means of insulation, but it also provides the environment in which the majority of the other components exist. Therefore, the condition of the oil is not only important in terms of its own insulating behaviour, but also in the way in which it influences the degradation of other components.

The moisture and acidity levels of the oil are particularly important when considering degradation of internal components. Significant oxidation of insulating oil normally requires elevated temperatures which would not be expected in distribution switchgear and therefore in normal circumstances oil recovered from switchgear would be expected to have a low acidity.

2.2.4 Oil circuit breaker failures

Failures in oil circuit breakers are not common on the CitiPower/Powercor network but, when they do occur, the results can be catastrophic. Tanks can rupture resulting in the ejection of burning oil and gas clouds, causing death or serious injury to persons and major damage to plant and buildings in the vicinity of the failed equipment. Investigation of accidents caused by circuit breaker failures has shown that failure usually occurs at, or shortly after, operation of the equipment. Thus, the way a circuit breaker is operated, its condition, and the circumstances existing in the system at the time of operation, to a large extent determine whether the equipment will safely perform its duty.

Equipment should not be used where its strength and capability may be exceeded, and it should be protected from excess current.

The main failure types associated with oil-filled circuit breakers are summarised in table 2.

Table 2 Failure mechanisms associated with oil-filled circuit breakers

Equipment component	Possible failure causes
Cable box	• Failure of solid or compound insulation
Circuit breaker trip coil	• Insufficient/excessive/incorrect lubrication • Secondary wiring/protection faults • Thermal/mechanical degradation
Bolted connections and contacts	• Corrosion • Mechanical ageing/wear
Internal insulation	• Mechanical damage • Moisture ingress
Insulating oil	• Loss of insulating properties • Particulate build-up from fault operations
Operating mechanism	• Maloperation • Mechanical ageing/wear
Bushings	• Mechanical damage • Loss of insulating properties
Instrument transformers	• Failure of solid or compound insulation • Moisture ingress
All locations	• Ageing under electric stresses • Pollution, moisture, ingress of dust, vermin etc • Over voltages

Source: CitiPower

2.3 Condition monitoring

The condition of oil-filed circuit breakers is monitored through a number of different processes, which are summarised below.

2.3.1 Substation inspection

On entry to the substation, the operator should check for evidence of:

- high temperature
- smell of smoke or overheating
- smell of ozone
- audible discharge.

Hand-held partial discharge detection equipment may also be used.

2.3.2 Circuit breaker inspection

The exterior of the circuit breakers can be visually examined for evidence of degradation in the form of:

- corrosion

- oil leaks
- compound leaks.

2.3.3 Diagnostic testing

A number of diagnostic tests can be used to assess the condition of the circuit breakers during an outage without a major strip down. Typically, the diagnostic tests include the following:

- internal visual examination
- trip timing/travel
- oil testing
- capacitance and loss angle
- thermovision.

For the reasons already noted, considerable emphasis is placed on the condition of the oil, with the following measurements commonly applied:

- moisture content
- electrical breakdown strength
- acidity
- particulate analysis.

2.3.4 Partial discharge testing

Partial discharge in insulation can take two forms, surface partial discharge and internal partial discharge. When surface partial discharge is present, tracking occurs across the surface of the insulation and is exacerbated by airborne contamination and moisture, leading to erosion of the insulation. Internal partial discharge occurs within the bulk of insulation materials and is caused by age, poor material quality or manufacturing defects. If discharge is allowed to continue unchecked, either mechanism will lead to failure of the insulation system under normal working stress, potentially resulting in catastrophic failure of the equipment.

A benchmark non-intrusive partial discharge survey is undertaken on all HV circuit breakers and cable boxes, employing both TEV (transient earth voltage) and ultrasonic methodologies. The results of the survey can be interpreted with reference to a database of previous results to provide interpretation of the findings and recommendations of further action required to address potential problems with deterioration of the insulation.

This exercise must be carried out by technical staff experienced in the use of non-intrusive measurement equipment and the interpretation of results.

3 Identified need

The identified need is to ensure our asset management approach in relation to oil-filled circuit breakers—particularly J18 and J22 type circuit breakers—minimises safety risks as far as reasonably practicable, and efficiently manages the reliability risks associated with unexpected asset failures.

As noted previously, J18 and J22 circuit breakers comprise almost 40% of our total circuit breaker population. These circuit breakers were commissioned during the period 1963–1973, across 22 zone substations. Although these circuit breakers have historically been reliable, the assets have now aged beyond their original design life (40 years) and are approaching their technical asset life (60 years).

The risks associated with oil-filled circuit breakers are discussed below, as well as the industry experience in proactively shifting away from these types of circuit breakers.

3.1 Risk and consequences of failure

It is well recognised that the probability of failure of J18 and J22 model circuit breakers will increase as the condition of the insulating materials break down over time. This deterioration increases as operating temperatures rise, increasing the risk of failure at times of peak load. Insulation tests on our network have shown evidence of degradation of the circuit breaker internal insulation, and equipment obsolescence means that it is not possible or cost effective to replace the degraded components.

While to date there has been one recent catastrophic failure of an oil-filled circuit breaker on our network (discussed in section 3.2), there is growing concern that this will increase in the coming years as our population exceeds its technical life and further degradation of the circuit breaker materials occur.

The consequences of failure for our large population of J18 and J22 circuit breakers include the following:

- oil-filled switchgear failure often results in the ignition of the oil and can result in a rupture of the switchgear oil chamber. This will result in the ejection of burning oil and gas clouds, with high potential to cause death or serious injury to persons, and major damage to adjacent plant and building, in the vicinity of the failure
- J18 and J22 circuit breakers were not designed to contain arc-faults, resulting in increased potential for catastrophic consequences
- leakage or expulsion of oil or insulating compound causing environmental damage and hazardous waste
- J18 and J22 circuit breakers contain asbestos lining in cable conduits, which was incorporated as an early form of fire protection. Damage to the asbestos as a result of equipment failure will result in increased risk to staff, longer clean-up or repair time, and high disposal costs.

3.2 Industry experience

The safety risks associated with J18 and J22 circuit breakers have been recognised by distributors in Australia and internationally. We discuss the industry shift away from these circuit breaker models below, including our own failure experience.

3.2.1 CitiPower

In 2016, the switchboard at our B zone substation suffered significant damage as a result of a disruptive failure of the B23 feeder circuit breaker. This circuit breaker was an oil-filled Email J18 model.

The failure of this J18 circuit breaker affected electricity supply to 1,200 customers and posed a significant safety risk to employees, with the resulting rise in pressure and subsequent explosion blowing open the doors in the switch room. The metal cladding on the switchboard suffered extensive damage, requiring two circuit breakers (B23 and B24) to be decommissioned and their loads transferred to spare feeder positions. Extensive clean up and repairs were also required to the no.4 bus and the switch room due to fire and heat damage.

An example of the damage incurred is shown in figure 3.

Figure 3 Extensive damage to B23 circuit breaker following a catastrophic failure

Source: CitiPower

Fortunately, in this failure event, no residual oil fire occurred. However, had any staff been in the substation at the time of failure they could have sustained serious injuries, or resulted in a fatality due to the explosion and hot gas and oil.

3.2.2 SA Power Networks

SA Power Networks (and its predecessor, ETSA) have previously experienced internal failures of a J18 circuit breaker at their Athol Park substation in 2010, and Thebarton zone substation in 2012:

- the Athol Park failure caused internal damage to the circuit breaker, with expulsion of oil from the vents. The circuit breaker and switchboard were repaired, but the failure resulted in 4,500 customers being disconnected for up to 2 hours
- the Thebarton J18 failure resulted in damage to all three phases and was attributed to poor oil condition due to fault operations between scheduled maintenance periods.

As a result of these failures, SA Power Networks made modifications to their maintenance practices and had a program of replacement which covered many of their oil-filled circuit breakers between 2011 and 2013.

A further internal failure of a J18 circuit breaker at Keswick substation in 2016 also resulted in the ejection of a large amount of oil. It was found that arc products had allowed the flashover near the interrupter, leading SA Power Networks to prioritise replacement of the circuit breakers at this substation.

3.2.3 Ausgrid

Ausgrid's asset management documents show that Westinghouse/Email HQ switchboards and their associated J18 and J22 oil circuit breakers have been prioritised for replacement for safety reasons since 2015.[1] Previous projects involved retrofit of bulk oil circuit breakers to extend the life of the switchboards.

3.2.4 Western Power

Western Power only have a small population of J18 units remaining, as they have been removing switchboards from the network for some time.[2]

3.2.5 Jemena

Jemena historically reported the failure of a J18 oil circuit breaker which resulted in a fire at their Flemington substation.[3]

Documentation published by Jemena indicated that maintenance of J18 circuit breakers has shown evidence of ongoing problems with circuit breaker mechanisms that have resulted in circuit breakers failing to close or operate correctly. Insulation testing using Dielectric Dissipation factor has indicated that degradation of the internal insulation has occurred; some circuit breakers show measurement results at a level considered to present an operational hazard due to the increased risk of insulation failure.[4]

The detected degradation has the potential to result in catastrophic damage to the switchboard and loss of supply to customers.

It is understood that Jemena is planning to remove these J18 circuit breakers from the network as part of an augmentation project.

3.2.6 Endeavour Energy

Based on published specification documents, it is clear that Endeavour Energy is retrofitting J18/J22 oil-filled circuit breakers with vacuum circuit breaker trucks.[5]

3.2.7 TasNetworks

TasNetworks have undertaken work to replace all oil-filled circuit breakers in zone substation sites with modern vacuum circuit breakers, with work completed in 2016.[6]

3.2.8 International industry experience

Broader international experience supports the view that oil-filled switchgear poses an increasing safety and reliability risk. For example:

- SP Energy Networks in the UK began a program of circuit breaker retrofitting during the DPCR5 (2010-2015) regulatory period and will continue during the current RIIO-ED1 (2015-2023) regulatory period. The bulk of the 10,000 primary circuit breaker population was installed during the 1950s, 1960s and 1970s, and a

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1 CP ATT116 - Ausgrid - Selected replacement projects - Jan2015 - Public

2 CP ATT115 - Western Power - Annual planning report - 2017 - Public

3 CP ATT114 - Jemena - East Preston conversion stage 5 - Nov2018 - Public

4 CP ATT117 - Jemena - Flemington network development - Jan2016 - Public

5 CP ATT118 - Endeavour Energy - 11kV vacuum CB - Feb2015 - Public

6 CP ATT119 - TasNet - Zone substations - Oct2015 - Public

combination of replacement, refurbishment and retrofit is being used to remove older and problematic bulk oil equipment from the network.[7]

- UK Power Networks began installing vacuum retrofit circuit breakers in 1995, with 14% of their grid and primary circuit breakers having retrofit circuit breakers installed. Retrofitting of problematic populations of bulk oil and vacuum circuit breakers is continuing in the current regulatory period and into the next period (RIIO ED2).[8]
- Electricity North West have increased their use of retrofit during the RIIO ED1 regulatory period in order to cost-effectively reduce the network risk associated with primary circuit breakers. The retrofit program considers the fixed portion condition in deciding whether to retrofit or replace the asset. Where the fixed portion is considered to place the operator in danger, the switchboard is replaced as a safety hazard.

[7] CP ATT120 - SPEN - 11kV substation plant strategy - Mar2014 - Public

[8] CP ATT121 - UKPN - 11kV Switchgear LPN, Asset stewardship - 2014 - Public

4 Options analysis

We considered several following options to address the identified need, as outlined below:

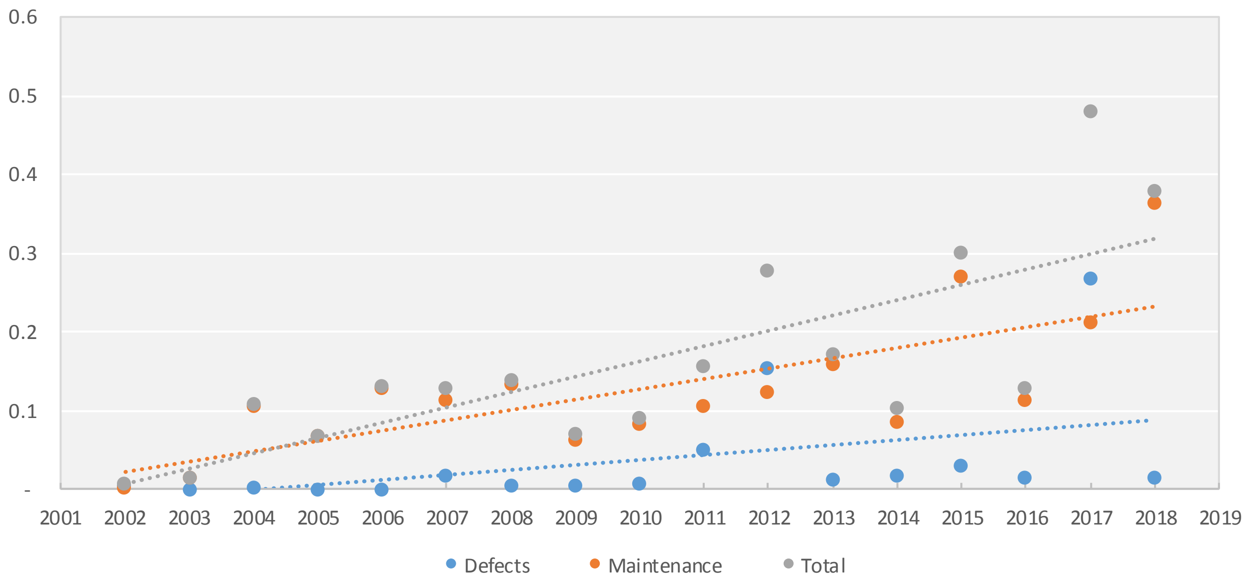
- option one: continue to maintain, rather than replace, J18 and J22 circuit breakers
- option two: replace J18 and J22 circuit breakers when the relevant zone substation switchboard is upgraded
- option three: replace the entire population of J18 and J22 circuit breakers
- option four: replace J18 and J22 circuit breakers at selected zone substations
- option five: adopt a non-network solution.

For the reasons discussed below, our preferred option is to only replace J18 and J22 circuit breakers at selected, high-consequence zone substations. Planning for this program has already begun, with replacement works at our Deepdene zone substation scheduled for completion by 2020/2021.

4.1 Option one: maintain status-quo

We currently manage the risk posed by oil-filled J18 and J22 switchgear through maintenance alone, without a proactive asset replacement program. As shown in figure 4, this has resulted in an increasing trend of maintenance and defect costs since 2008.

Figure 4 Defect and maintenance costs associated with J18 and J22 circuit breakers ($ million, nominal)



Source: CitiPower

Further, maintenance will not reverse the degradation that has already occurred within the circuit breaker population. As a consequence, the ongoing asset ageing and degradation will lead to an increasing risk of catastrophic failure. An increase in failures will likely result in interruptions to customer supply for extended periods of time.

Given the known safety risks associated with J18 and J22 oil-filled circuit breaker failures, continuing a maintenance-only approach is unlikely to be consistent with good asset management practice. That is, it will not minimise safety risks as far as reasonably practicable or efficiently manage the reliability risks associated with unexpected asset failures.

4.2 Option two: replace J18 and J22 circuit breakers during switchboard upgrades

Under this option, we would replace J18 and J22 circuit breakers as part of planned switchboard replacement projects. For example, as we replace the switchboard at our Collingwood zone substation (based on a risk monetisation assessment), we would remove all J18 and J22 circuit breakers on site.

This option will gradually address the risks associated with J18 and J22 circuit breakers, and therefore, is regarded as superior to option one. This option, however, will not address the remaining large population of J18 and J22 circuit breakers that are expected to continue to degrade. As noted in section 2.1, these circuit breaker models comprise almost 40% of our total oil-filled circuit breaker population.

As a consequence, linking J18 and J22 interventions to full switchboard replacements will not adequately address the remaining safety risks in accordance with our safety obligations. For this reason, this option only partially addresses the identified need.

4.3 Option three: replace the entire population of J18 and J22 circuit breakers

Option three involves establishing a program to replace all J18 and J22 circuit breakers on our network. This recognises that oil-filled circuit breakers create additional safety risks compared to modern vacuum circuit breakers. This option is consistent with other distributors, who have established programs to replace or retrofit oil-filled circuit breakers (as outlined in section 3.2).

Whilst a program to replace the entire population of J18 and J22 circuit breakers will minimise the associated safety risks, the costs of this program would be materially higher than alternative interventions.

4.4 Option four: targeted replacement program for J18 and J22 circuit breakers

This option involves developing a targeted replacement program for selected J18 and J22 circuit breakers at specific, high-risk and/or consequence zone substations. In effect, this option is a refinement to option three, as it determines the replacement program for the 2021–2026 regulatory period but stops short of committing to replacing the entire population of J18 and J22 circuit breakers.

In terms of the proposed works, this option would involve replacing the J18 and J22 oil-filled circuit breakers with modern, internal arc-rated, non-oil type circuit breakers which use vacuum or SF6 insulation. Unless testing identifies the need to replace the switchboard, the original switchboards would remain in-service and would be fully condition assessed as part of the retrofit process.

We consider this option best balances our obligation to minimise risk as far as reasonably practicable, without incurring costs that are grossly disproportionate.

As this is our preferred option, our risk monetisation assessment for this alternative is provided in section 5.

4.5 Option five: non-network

It is not possible to address the identified need using non-network options. The large population of aged circuit breakers, which are considered to pose a high safety and reliability risk, can only be addressed by managing the presence of these assets on our network.

5 Risk monetisation

This section explains our risk monetisation process and how it has been used to inform the timing of our J18 and J22 circuit breaker replacement program (consistent with our preferred option—option four). We have applied this risk monetisation assessment to a limited set of zone substations on our network, with capital works proposed at the following sites:

- Albert Park
- Armadale
- Fishermans Bend
- Flinders/Ramsden
- Toorak.

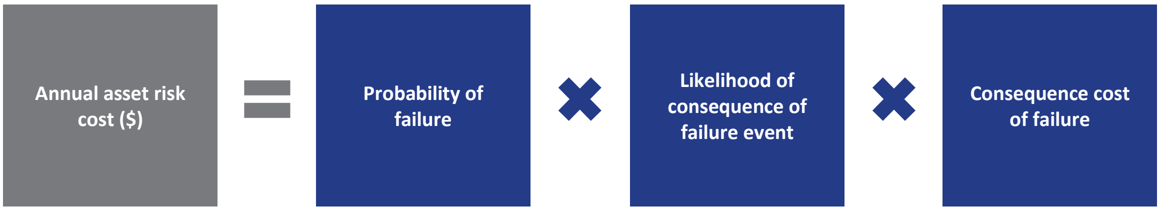
The zone substations where replacement works are proposed were identified based on the condition of the existing circuit breakers and the higher potential consequences of failure at these sites. This followed a qualitative review of all sites in our network with aged oil-filled circuit breakers.

The risk monetisation model for each of the proposed zone substations is attached with our regulatory proposal, and a summary of the key inputs for each zone substation are provided as appendices in this document.[9]

5.1 Overview of risk monetisation approach

We monetise risk when assessing investment decisions by first determining annual asset risk costs (as shown in figure 5). This approach is applied to all identified failure modes for an asset, and the sum of the annual asset risk cost for all of failure modes is compared to the annualised cost of the preferred option to determine the economic timing for any intervention. This approach is consistent with the AER's recent asset replacement guidance practice note.[10]

Figure 5 Calculation of annual asset-risk cost



Source: CitiPower

Our approach to risk monetisation employs CBRM to provide a robust methodology for the preparation and application of the required input information (i.e. the probability of failure, and the likelihood and consequence cost of failure).[11] CBRM enables us to use current asset information, engineering knowledge and practical experience to predict future asset condition, performance and risk for our assets. It is a comprehensive management methodology.

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9 CP MOD 4.17 - J18 AP - Jan2020 – Public; CP MOD 4.18 - J18 AR - Jan2020 – Public; CP MOD 4.19 - J18 FB - Jan2020 – Public; CP MOD 4.20 - J18 FR - Jan2020 – Public; CP MOD 4.04 - J18 TK - Jan2020 – Public.

10 CP ATT175: AER, *Industry practice application note: asset replacement planning*, January 2019.

11 The CBRM is a proprietary model developed by EA Technologies. The model is an ageing algorithm that takes into account a range of inputs to produce a health index for each asset in a range from zero to 10 (where zero is a new asset and 10 represents end of life). The health index provides a means of comparing similar assets in terms of their calculated probability of failure.

5.2 Probability of failure

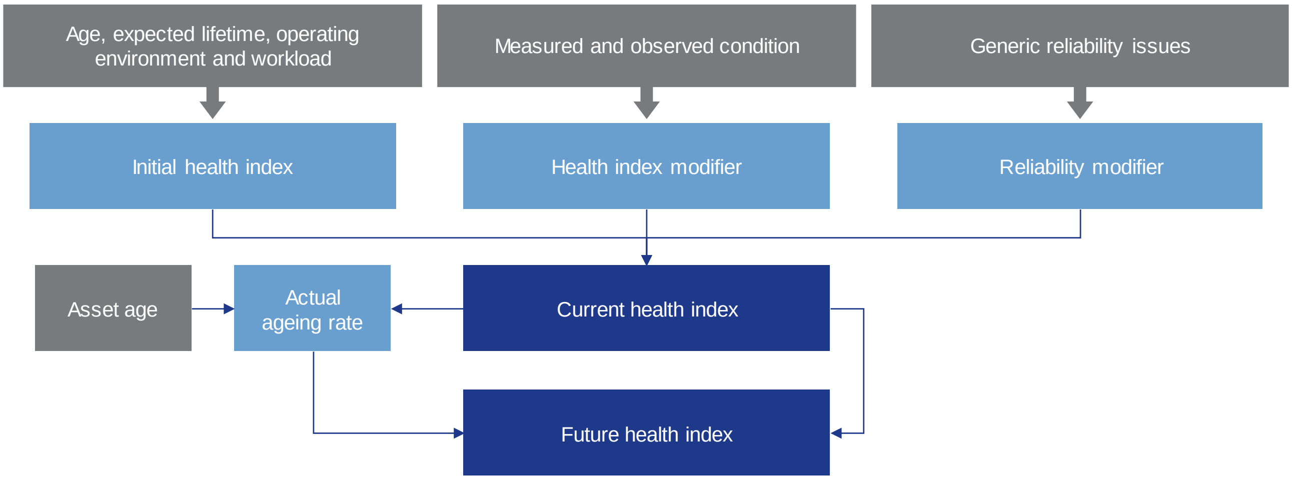
Asset performance is measured in terms of probability of failure and, for each asset category, is determined by matching the 'health index' profile with recent data on failure rates.

Health indices are derived for individual assets by combining information on age, environment, duty and specific condition information. These indices are projected forward to reflect the asset's ageing rate, which is dependent on its condition and operating environment.

5.2.1 Determination of health index

The detail of the health index formulation is different for each asset class, reflecting the asset-specific information and degradation processes. There is, however, a consistent approach to determining the health index for all asset classes as shown in figure 6.

Figure 6 Overview of health index determination



Source: EA Technology

An initial health index for our circuit breakers is calculated using knowledge and experience of the asset's performance and expected lifetime, taking account of factors such as original specification, manufacturer, operational experience and operating conditions (e.g. duty and location).

The initial health index is then adjusted by the health index modifier, which is based on the known condition of the asset. It includes information on condition that is gathered by inspecting the asset, together with information relating to asset defects and failures, and condition information obtained through diagnostic tests.

A reliability modifier can also be applied to modify the current health index to reflect generic issues affecting asset health and/or reliability associated with a manufacturer or model type, or a specific asset performance issue. It can also be used where a specific material or treatment has been applied to the asset. The reliability modifier should be used where there is evidence to show that a sub-group of assets has a materially different probability of failure compared to other assets with the same health index in that asset category.

The current health index, therefore, is derived by modifying the initial health index by the health index modifier and the reliability modifier, subject to upper and lower thresholds derived from the condition and reliability data. Information on the degradation of each asset is then used to 'age' the current health index and thus derive the future health index of each asset.

5.2.2 Determination of probability of failure

The probability of failure is determined by assessing the current condition of the asset and how it will continue to degrade over time. For circuit breakers, the condition related failure modes that have been derived by considering actual failure data are listed in table 3.

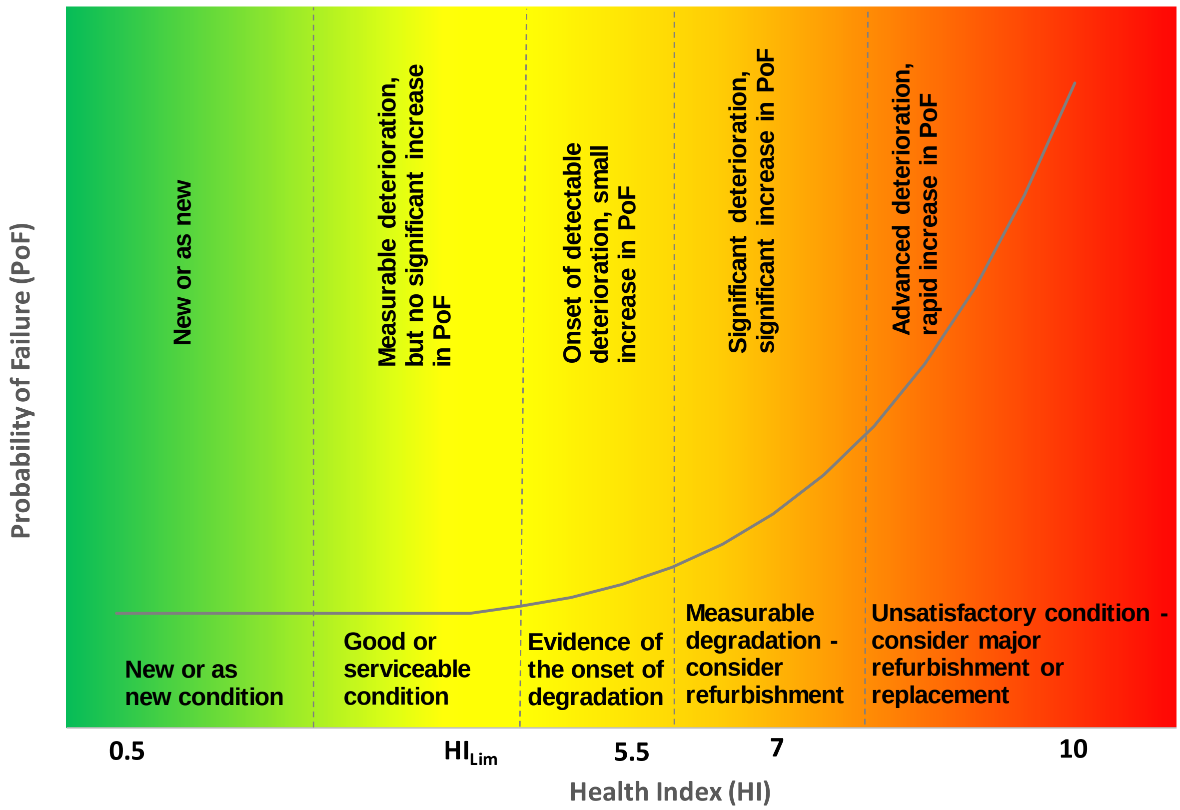
Table 3 Failure mode definitions for circuit breakers

Failure Mode	Description
Significant	Failure of any one circuit breaker that results in an outage
Major	Failure of a circuit breaker resulting in damage to adjacent circuit breakers and results in an outage

Source: CitiPower

The specific relationship between asset health index and probability of failure is determined by matching the health index profile with the recent failure rate for the asset category. This relationship is not linear. An asset can accommodate significant degradation with very little effect on the probability of failure. Conversely, once the degradation becomes significant or widespread, the risk of failure rapidly increases. The probability of failure of an asset is a function of its health index, as shown in figure 7.

Figure 7 Relationship between health index and probability of failure



Source: EA Technology

Mathematical modelling techniques carried out by EA Technology suggest that a cubic relationship (3rd order polynomial) is appropriate to define the health index and probability of failure relationship as follows:

$$PoF = k \cdot \left(1 + (HI \cdot c) + \frac{(HI \cdot c)^2}{2!} + \frac{(HI \cdot c)^3}{3!}\right) \qquad \text{Equation 1}$$

where:

PoF	=	probability of failure per annum
HI	=	health index
k & c	=	constants

The value of c fixes the relative values of the probability of failure for different health indices (i.e. the slope of the curve) and k determines the absolute value; both constants are calibration values.

Practical experience has indicated that this cubic relationship is appropriate for assets with higher health indices. However, at low values it has been found that even modest increases in probability of failure defined by the cubic relationship do not fit with actual experience. Therefore, it has become standard practice to adopt a hybrid relationship. Up to a limit value (HI_{Lim}), the probability of failure is set at a constant value; above HI_{Lim} the cubic relationship applies. Experience suggests that HI_{Lim} be set at 4; this is the value that has been used in our evaluation of the transformer replacement program.

Determination of c

The value of c in equation one can be determined by assigning the relative probability of failure values for two health index values (generally HI = 10 and $HI = HI_{Lim}$). Where reasonably complete information is available that directly relates to the critical degradation processes, there is a fairly high level of confidence in the health indices and, consequently, the relative PoF between the two assets is expected to be high. However, where health indices are predominantly derived from indirect condition related information, leading to a lower level of confidence in the health index, the relative PoF between the two assets is expected to be lower.

In practice, with the use of the hybrid HI / PoF relationship, the value of c is typically set to 1.086, which corresponds to a PoF for an asset with a health index of 10 that is ten times higher than the PoF of a new asset.

Determination of k

The value of k in equation one is determined on the basis of:

- the total observed number of functional failures per annum;
- the health index distribution for the asset category; and
- the volume of assets in the asset category.

The asset group can have a different curve shape and height for each failure mode if it is considered appropriate.

For each asset category, k is calculated as follows:

$$k \cdot \sum_{i=1}^{n} \left(1 + HI_i \cdot c + \frac{(HI_i \cdot c)^2}{2!} + \frac{(HI_i \cdot c)^3}{3!}\right) = (\text{Average no. of failures per annum})_I \qquad \text{Equation 2}$$

where:

n	=	the number of assets in asset category I
HI_i	=	Health index of asset i

The total experienced failure rate for each failure type is allocated across the asset population based on each asset's health index. Each asset will have a calculated probability for minor, significant and major failures.

Having calculated the health index for each asset, the projected ageing curve can be determined. This projected ageing rate is used to determine the future health index in each year and the resulting probability of failure value for each year.

5.3 Consequences of failure

Our risk monetisation approach identifies four consequence categories that capture the potential impact on electricity customers of asset failures relating to circuit breakers. Table 4 shows these risk categories and the associated consequences, each of which can be quantified in dollar terms.

Table 4 Consequence of failure categories and inputs

Consequence category	Consequence inputs
Network performance	• Unserved energy
Safety	• Minor injuries • Serious injuries • Fatality
Financial	• Repair and replacement costs (operating and capital expenditure) • Fire brigade attendance
Environmental impact	• Fire starts • Volume of waste produced • Level of disturbance

Source: CitiPower

The calculation of the consequence of failure in our CBRM uses the same failure modes as the probability of failure. For each of these consequence categories, any actual consequences of failure are considered and used to produce a reference cost of failure, which represents the 'typical' impact of a failure based on historical data.

Each of the consequence categories are discussed in further detail below.

5.3.1 Network performance: consequence cost and likelihood

The expected average unserved energy costs are based on the energy at risk, the time at risk, and the value of customer reliability (**VCR**) per megawatt hour. The time at risk reflects that taken to transfer capacity to adjacent zone substations and restore supply. A weighted average of the 50th and 10th percentile expected unserved energy estimates is calculated by applying weightings of 70% and 30% (respectively).

The likelihood of consequence is set to 100% on the basis that when a particular failure type occurs it is known to have a particular consequence. For example, as the definition of a significant or a major failure is a failure that results in an outage, and the consequences are determined using actual values of load and capacity, then the likelihood of the consequence occurring must be set to 100%. By definition, these failure modes could not occur without causing loss of the asset and some consequences must occur if there is a significant asset failure.

5.3.2 Safety: consequence cost and likelihood

The safety consequences of failure represent the quantification of the societal value of preventing an accident, serious injury or fatality. The safety consequence for each failure is derived from the reference safety cost of failure used in the CBRM, modified by the probability of a safety consequence occurring.

The safety consequences are estimated with reference to minor, serious and fatal injuries by applying a dollar value that reflects the seriousness of the incident. A 'disproportionate factor' is also applied, which recognises that serious and fatal injuries should be avoided even if the costs of doing so outweigh the actuarial value of the loss incurred.

The safety consequence represents the risk that the asset presents to the workforce and public by its characteristics and particular situation. The safety consequence incorporates a measure of the likelihood that someone would be in the vicinity of the asset at the time of failure. The assessment of the safety consequence recognises that staff may be present for routine activities or in response to alarms from monitoring or protection equipment prior to the asset failure.

The value of the safety consequence of asset failure takes into account the likelihood that a failure of each type would result in injury or death. As the likelihood of the consequence is included in defining the value of consequence, the likelihood of consequence value is set at 100% (otherwise the likelihood of consequence would be double-counted in calculating the expected safety risk).

5.3.3 Financial: consequence cost and likelihood

The financial consequence of circuit breaker failure is the cost of repair or replacement to return the network to its pre-fault state. As the financial consequences are based on repair or replacement costs, and the failure modes are defined as the need to repair or to replace one or more assets, the likelihood of the defined consequence occurring is 100%.

A separate operating expenditure impact is also modelled for the cost of fire brigade attendance.

Replacement costs

The replacement costs for a circuit breaker are based on recent, observed replacement works on our network. For a major circuit breaker failure, it is assumed the failed circuit breaker will need replacing, as well as the circuit breakers immediately adjacent to the failure (i.e. three circuit breakers in total). For a significant failure, only the failed circuit breaker replacement value is included.

The replacement cost for an asset under failure conditions is assumed within the model to be the same as the planned asset replacement unit cost.

5.3.4 Environmental: consequence cost and likelihood

The environmental consequences of failure represent the quantification of the potential environmental impacts of failure for each specified failure mode. For each asset, the environmental consequence is derived from the reference environmental cost of failure used in the CBRM, modified by an asset-specific environmental consequence modifier.

A failure has a single outcome and will have 100% likelihood of consequence.

5.4 Investment evaluation methodology

The methodologies described above allow the asset probability of failure and consequence of failure values in current and future years to be determined, and used to project the asset risk over the regulatory period and beyond. The optimal timing for asset intervention, therefore, is based on a comparison of the asset risk and the annualised cost of the preferred option.

We also model alternative scenarios to provide sensitivity analysis for key assumptions.

Based on our risk monetisation assessments, the forecast capital expenditure requirements in the 2021–2026 regulatory control period are shown in table 5. Further site specific details are provided in the following appendices and attached risk monetisation models.[12]

Table 5 Expenditure forecasts for preferred option ($ million, 2021)

Expenditure forecast	2021/22	2022/23	2023/24	2024/25	2025/26	Total
Albert Park zone substation	-	-	-	0.8	0.8	1.6
Armadale zone substation	0.7	-	-	-	-	0.7
Fishermans Bend zone substation	0.9	0.9	-	-	-	1.7
Flinders/Ramsden zone substation	-	-	0.9	0.9	-	1.9
Toorak zone substation	-	0.6	0.6	-	-	1.2
Total	**1.5**	**1.4**	**1.5**	**1.8**	**0.8**	**7.1**

Source: CitiPower

12 CP MOD 4.17 - J18 AP - Jan2020 – Public; CP MOD 4.18 - J18 AR - Jan2020 – Public; CP MOD 4.19 - J18 FB - Jan2020 – Public; CP MOD 4.20 - J18 FR - Jan2020 – Public; CP MOD 4.04 - J18 TK - Jan2020 – Public.

A Albert Park

Our Albert Park (**AP**) zone substation is supplied by the Fishermans Bend terminal station, and comprises 21 J18/J22 circuit breakers.

A.1 Probability of failure

The total probability of any circuit breaker failing at our AP zone substation is shown in table A.1.

Table A.1 Probability of failure values (%)

Failure mode	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Major	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.7
Significant	24.1	25.9	27.7	29.8	32.0	34.4	36.9	39.7	42.7	45.9	49.5	53.3

Source: CitiPower

A.2 Consequences of failure

A summary of the consequence of failure for each failure mode, for circuit breakers at our AP zone substation, is set out in tables A.2 and A.3.

Table A.2 Major failure risk: consequence of failure ($ million, 2021)

Description	Total risk value	Likelihood of consequence	Cost of consequence
Expected average unserved energy	1.62	100%	1.62
Safety consequence	0.01	100%	0.01
Cost of replacement assets	0.23	100%	0.23
Environmental consequence	0.01	100%	0.01
Fire brigade attendance	0.05	100%	0.05

Source: CitiPower

Table A.3 Significant failure risk: consequence of failure ($ million, 2021)

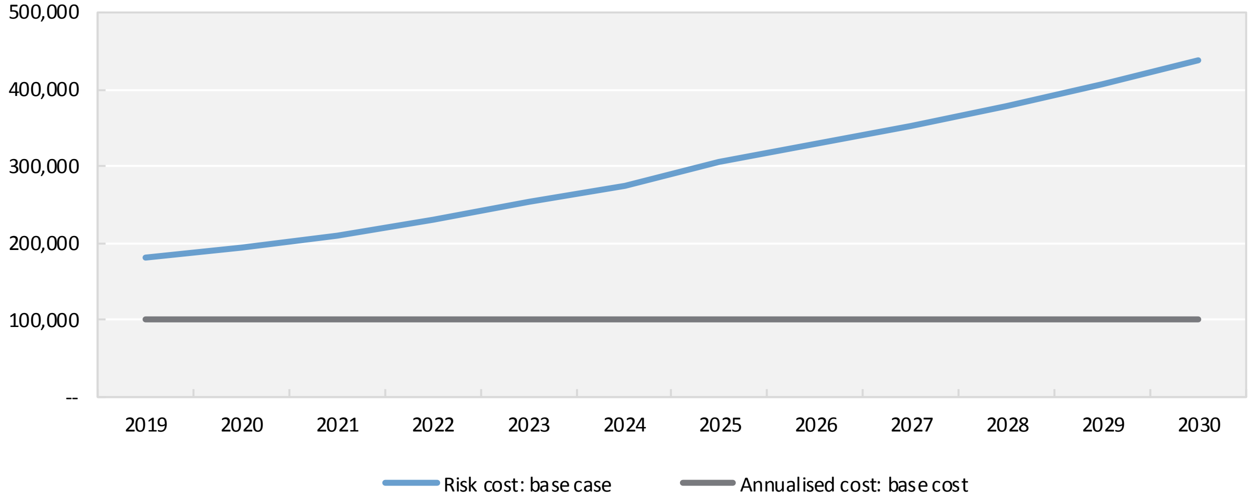
Description	Total risk value	Likelihood of consequence	Cost of consequence
Expected average unserved energy	0.54	100%	0.54
Safety consequence	0.00	100%	0.00
Cost of replacement assets	0.08	100%	0.08
Environmental consequence	0.00	100%	0.00
Fire brigade attendance	0.05	100%	0.05

Source: CitiPower

A.3 Optimal timing of asset replacement

The optimal timing of asset replacement is based on a comparison of the asset risk and the annualised cost of the preferred option. As shown in figure A.1, the annual asset risk cost is already higher than the annualised replacement cost.

Figure A.1 AP circuit breakers: comparison of asset risk and annualised cost for base case ($2021)



Source: CitiPower

B Armadale

Our Armadale (**AR**) zone substation is supplied by the Richmond terminal station, and comprises 17 J18/J22 circuit breakers.

B.1 Probability of failure

The total probability of any circuit breaker failing at our AR zone substation is shown in table B.1.

Table B.1 Probability of failure values (%)

Failure mode	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Major	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.4
Significant	15.0	16.0	17.2	18.4	19.7	21.2	22.7	24.4	26.2	28.2	30.3	32.6

Source: CitiPower

B.2 Consequences of failure

A summary of the consequence of failure for each failure mode, for circuit breakers at our AR zone substation, is set out in tables B.2 and B.3.

Table B.2 Major failure risk: consequence of failure ($ million, 2021)

Description	Total risk value	Likelihood of consequence	Cost of consequence
Expected average unserved energy	0.80	100%	0.80
Safety consequence	0.01	100%	0.01
Cost of replacement assets	0.23	100%	0.23
Environmental consequence	0.01	100%	0.01
Fire brigade attendance	0.05	100%	0.05

Source: CitiPower

Table B.3 Significant failure risk: consequence of failure ($ million, 2021)

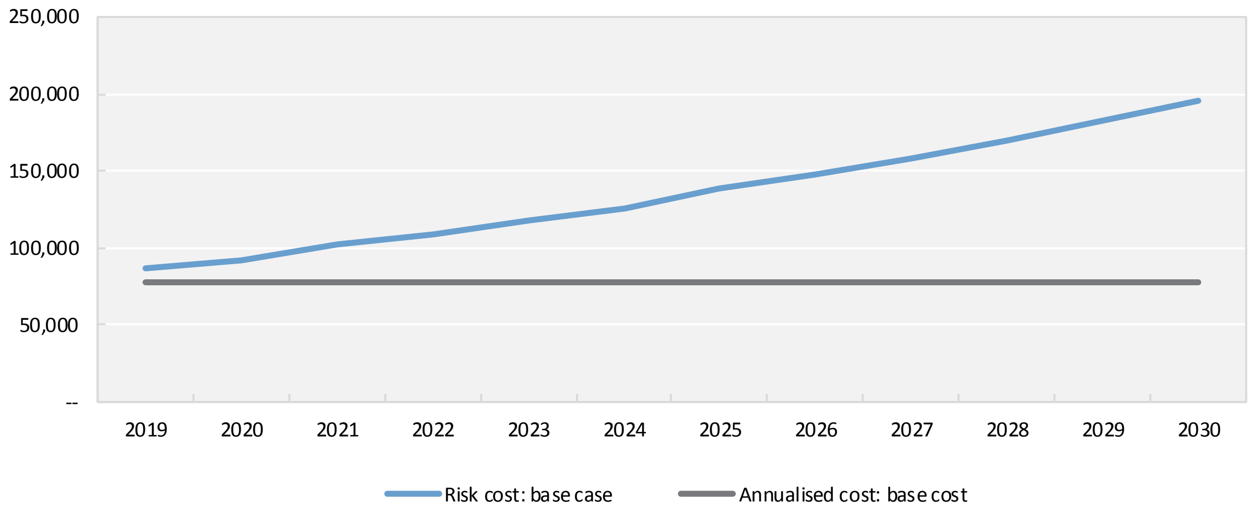
Description	Total risk value	Likelihood of consequence	Cost of consequence
Expected average unserved energy	0.40	100%	0.40
Safety consequence	0.00	100%	0.00
Cost of replacement assets	0.08	100%	0.08
Environmental consequence	0.00	100%	0.00
Fire brigade attendance	0.05	100%	0.05

Source: CitiPower

B.3 Optimal timing of asset replacement

The optimal timing of asset replacement is based on a comparison of the asset risk and the annualised cost of the preferred option. As shown in figure B.1, the annual asset risk cost is already higher than the annualised replacement cost.

Figure B.1 AR circuit breakers: comparison of asset risk and annualised cost for base case ($2021)



Source: CitiPower

C Fishermans Bend

Our Fishermans Bend (**FB**) zone substation is supplied by the Fishermans Bend terminal station, and comprises 22 J18/J22 circuit breakers.

C.1 Probability of failure

The total probability of any circuit breaker failing at our FB zone substation is shown in table C.1.

Table C.1 Probability of failure values (%)

Failure mode	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Major	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.8
Significant	18.2	20.1	22.4	24.9	27.7	30.8	34.4	38.4	42.9	48.0	53.7	60.2

Source: CitiPower

C.2 Consequences of failure

A summary of the consequence of failure for each failure mode, for circuit breakers at our FB zone substation, is set out in tables C.2 and C.3.

Table C.2 Major failure risk: consequence of failure ($ million, 2021)

Description	Total risk value	Likelihood of consequence	Cost of consequence
Expected average unserved energy	1.35	100%	1.35
Safety consequence	0.01	100%	0.01
Cost of replacement assets	0.23	100%	0.23
Environmental consequence	0.01	100%	0.01
Fire brigade attendance	0.05	100%	0.05

Source: CitiPower

Table C.3 Significant failure risk: consequence of failure ($ million, 2021)

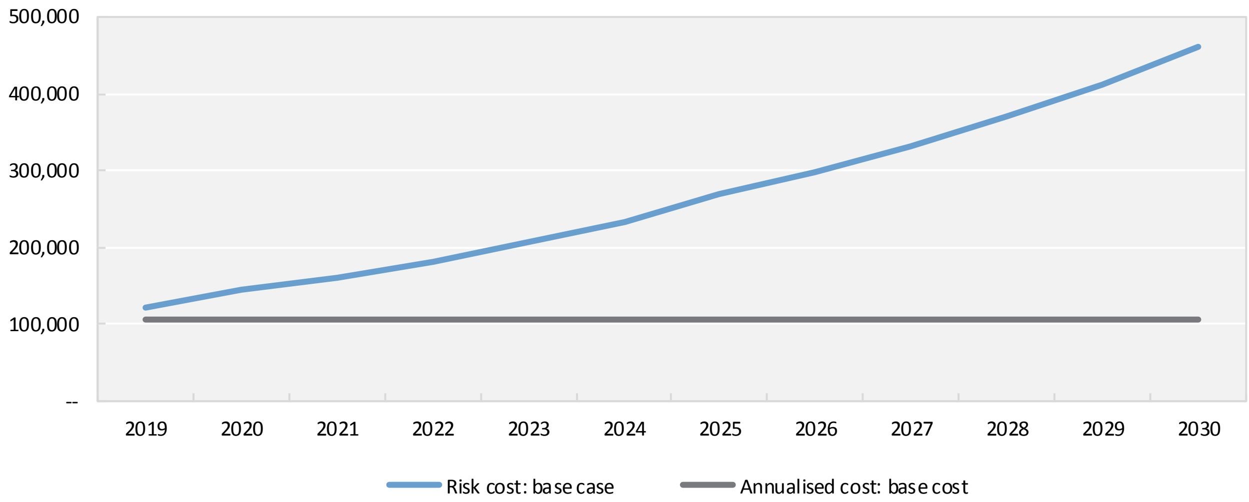
Description	Total risk value	Likelihood of consequence	Cost of consequence
Expected average unserved energy	0.45	100%	0.45
Safety consequence	0.00	100%	0.00
Cost of replacement assets	0.08	100%	0.08
Environmental consequence	0.00	100%	0.00
Fire brigade attendance	0.05	100%	0.05

Source: CitiPower

C.3 Optimal timing of asset replacement

The optimal timing of asset replacement is based on a comparison of the asset risk and the annualised cost of the preferred option. As shown in figure C.1, the annual asset risk cost is already higher than the annualised replacement cost.

Figure C.1 FB circuit breakers: comparison of asset risk and annualised cost for base case ($2021)



Source: CitiPower

D Flinders/Ramsden

Our Flinders/Ramsden (**FR**) zone substation is supplied by the Richmond terminal station, and comprises 30 OLX/J22 circuit breakers.

D.1 Probability of failure

The total probability of any circuit breaker failing at our FR zone substation is shown in table D.1.

Table D.1 Probability of failure values (%)

Failure mode	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Major	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.6
Significant	18.3	18.3	18.7	20.6	22.7	25.0	27.6	30.6	33.8	37.4	41.5	46.1

Source: CitiPower

D.2 Consequences of failure

A summary of the consequence of failure for each failure mode, for circuit breakers at our FR zone substation, is set out in tables D.2 and D.3.

Table D.2 Major failure risk: consequence of failure ($ million, 2021)

Description	Total risk value	Likelihood of consequence	Cost of consequence
Expected average unserved energy	2.12	100%	2.12
Safety consequence	0.01	100%	0.01
Cost of replacement assets	0.19	100%	0.19
Environmental consequence	0.01	100%	0.01
Fire brigade attendance	0.05	100%	0.05

Source: CitiPower

Table D.3 Significant failure risk: consequence of failure ($ million, 2021)

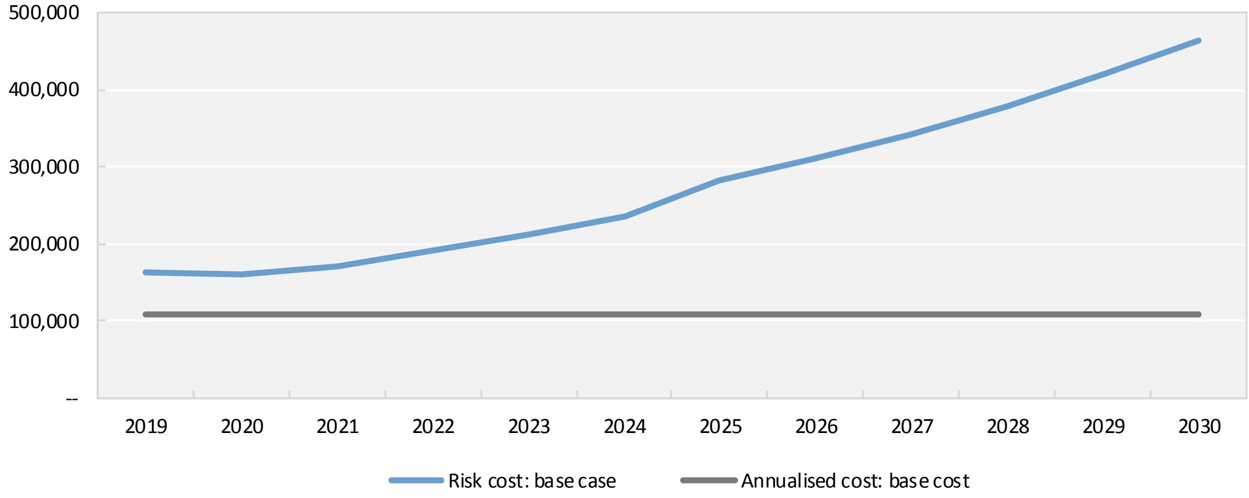
Description	Total risk value	Likelihood of consequence	Cost of consequence
Expected average unserved energy	0.71	100%	0.71
Safety consequence	0.00	100%	0.00
Cost of replacement assets	0.06	100%	0.06
Environmental consequence	0.00	100%	0.00
Fire brigade attendance	0.05	100%	0.05

Source: CitiPower

D.3 Optimal timing of asset replacement

The optimal timing of asset replacement is based on a comparison of the asset risk and the annualised cost of the preferred option. As shown in figure D.1, the annual asset risk cost is already higher than the annualised replacement cost.

Figure D.1 FR circuit breakers: comparison of asset risk and annualised cost for base case ($2021)



Source: CitiPower

E Toorak

Our Toorak (**TK**) zone substation is supplied by the Richmond terminal station, and comprises 15 J18/J22 circuit breakers.

E.1 Probability of failure

The total probability of any circuit breaker failing at our TK zone substation is shown in table E.1.

Table E.1 Probability of failure values (%)

Failure mode	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Major	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
Significant	11.0	11.8	12.7	13.7	14.7	15.9	17.2	18.5	20.0	21.7	23.4	25.4

Source: CitiPower

E.2 Consequences of failure

A summary of the consequence of failure for each failure mode, for circuit breakers at our TK zone substation, is set out in tables E.2 and E.3.

Table E.2 Major failure risk: consequence of failure ($ million, 2021)

Description	Total risk value	Likelihood of consequence	Cost of consequence
Expected average unserved energy	1.45	100%	1.45
Safety consequence	0.01	100%	0.01
Cost of replacement assets	0.23	100%	0.23
Environmental consequence	0.01	100%	0.01
Fire brigade attendance	0.05	100%	0.05

Source: CitiPower

Table E.3 Significant failure risk: consequence of failure ($ million, 2021)

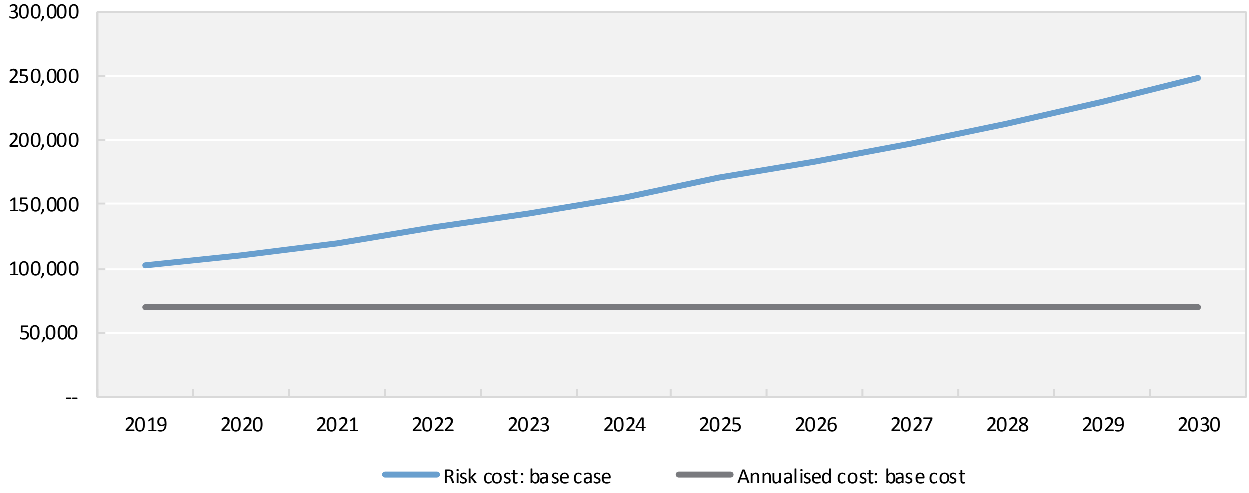
Description	Total risk value	Likelihood of consequence	Cost of consequence
Expected average unserved energy	0.72	100%	0.72
Safety consequence	0.00	100%	0.00
Cost of replacement assets	0.08	100%	0.08
Environmental consequence	0.00	100%	0.00
Fire brigade attendance	0.05	100%	0.05

Source: CitiPower

E.3 Optimal timing of asset replacement

The optimal timing of asset replacement is based on a comparison of the asset risk and the annualised cost of the preferred option. As shown in figure E.1, the annual asset risk cost is already higher than the annualised replacement cost.

Figure E.1 TK circuit breakers: comparison of asset risk and annualised cost for base case ($2021)



Source: CitiPower