# Economics of Replacing IGBTs on Murraylink

APA | November, 2022

# DISCLAIMER

This report was commissioned by APA. The objective of the report is to assess the underlying economics of replacing insulated-gate bipolar transistors (IGBTs) on Murraylink.

The analysis and information provided in this report is derived in part from information provided by a range of parties other than Oakley Greenwood (OGW). OGW explicitly disclaims liability for any errors or omissions in that information, or any other aspect of the validity of that information. We also disclaim liability for the use of any information in this report by any party for any purpose other than the intended purpose.

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## Summary Background and Conclusions

In December 2020, the sole provider (Hitachi) advised APA that the Gen 2 Insulated Gate Bipolar Transistors (IGBT) positions that are used for Murraylink would no longer be produced.

Based on current failure rates, APA's existing stock of spares would only support the continued operation of Murraylink for another ~6 years.

APA engaged Oakley Greenwood (OGW) to analyse the short and long term options to determine the optimal economic approach to resolving the IGBT obsolescence issue.

In summary, our analysis of the incremental market benefits of making one or more capital investments to ensure Murraylink can continue to operate are that:

- Upgrading phase-by-phase using new Gen3 IGBT technology (made by Hitachi) is likely to:
  - Deliver net benefits to the market, with the incremental market benefits associated with continuing to maintain Murraylink's operation exceeding the incremental capital costs associated with the upgrade in almost all scenarios modelled; and
  - Deliver the best results in NPV terms, as compared to the other technology solutions modelled.
- This outcome is not materially influenced by either the:
  - WACC assumed; or
  - Threshold number of spares that, once breached, activate a capital solution being adopted in the model.
- It is not worth pursuing the new, multi-level converter (MMC) technological solution, whose primary benefit over the Gen3 IGBT solution is that it delivers incremental efficiency improvements.

These results, further background to the project, and our approach to undertaking the modelling are explained in further detail below.

## Background

Murraylink is a high-voltage, direct current (HVDC) transmission line that connects the power transmission networks at Red Cliffs (in Victoria) and Berri (in South Australia).

Murraylink became operational in 2002 and had an original design life of 40 years. Murraylink uses ABB's (now Hitachi) older Generation 2 Insulated Gate Bipolar Transistors[1] ('Gen 2 IGBTs') in a three-level Voltage Source Converter (VSC) technology, with 972 IGBTs per phase and a total of 2,916 IGBTs in each converter station[2].

In December 2020, the sole provider (Hitachi) advised APA that the Gen 2 IGBT positions used for Murraylink would no longer be produced, and that Murraylink would only have access to a portion of the IGBT positions in stock.

1 IGBTs are a solid state switchable transistor and are the main component used to convert AC to DC and DC back to AC.

2 Murraylink consists of one converter station at each end, consisting of three single-phase legs.

The current failure rate is around 24 per annum. The total available spares (Hitachi stock allocation plus APA's site stock) is estimated to be around 165, which, based on current failure rates, would support the current operation for another ~6 years.

### Capex Solutions Modelled

APA separately engaged Amplitude Consultants Pty Ltd (Amplitude) to undertake the necessary preliminary investigations into the technical feasibility of options for continued operation of Murraylink. In doing so, Amplitude have considered the reliability of the existing units, the costs to replace the valves and associated equipment and the technical (relating to improvements in efficiency) and commercial benefits (multiple competitive vendors available) of upgrading to the newer modular multi-level converter (MMC) VSC technology.

The three key infrastructure options considered were:

- **Option 1: Replace existing 'Gen 2 IGBTs' with 'Gen 3 IGBTs', by replacing individual phases:** This option involves completely replacing a single-phase with newer generation IGBT positions ('Gen 3 IGBTs') to free up some of the existing 'Gen 2 IGBTs' for spares to be used elsewhere. The newer generation IGBTs are not electrically or physically directly compatible with Gen 2 IGBTs, hence why only the replacement of an entire phase is feasible, however the existing cooling, protection and control systems are reusable.
- **Option 2: Replace one converter station with MMC valves to generate spare 'Gen 2 IGBTs' for use in the other converter station:** This option requires a complete converter station (3 phases) to be upgraded with MMC valves. This option would involve one end of Murraylink operating with new, slightly more efficient, MMC technology, whilst the other end operates with VSC technology (Gen 2 or Gen 3). As this involves a completely different switching configuration and topology, it requires a change in infrastructure and balance of plant.
- **Option 3: Replace both converter stations with new MMC valves:** This option involves replacing both converter stations (3 phases at each end) with new, more efficient, MMC technology. Any spare 'Gen 2 IGBTs' generated could potentially be sold to another transmission company that operates similar technology.

The following tables sets out the capex solutions that were modelled, their costs, the number of spares created and the number of days Murraylink would not be available to the market because of an outage.

Table 1: Capex solutions modelled

| Capex Solution | Costs^ | Spares Created | Planned Outages |
|---|---|---|---|
| GEN2 IGBT to GEN 3 IGBT (per phase) | ~$20.5m | 900 | 70 days |
| Upgrade one converter station to VSC MMC | ~$42.2m | 3000 | 150 days |
| Upgrade both converter stations to VSC MMC | ~$82.5m | 6000^^ | 150 days |

^Raw costs, as per Amplitude, plus 15% overhead. ^^ This is designed to in effect, remove the sparing issue, as this is a new technology.

In addition to the engineering options, theoretically, APA may also be able to either:

- Purchase spare IGBTs from another authority that utilises similar technology (such as the Cross-Sound Cable Company[3] in the USA), or
- Sell spare IGBTs that might be created from any of the previously mentioned technology solutions, to that authority.

We have only assessed the feasibility of these options at a high level in this report.

### OGW's Modelling Approach

APA engaged OGW to analyse the short and long term options to determine the optimal economic approach to resolving the IGBT obsolescence issue.

A summary of our modelling approach is as follows:

- We engaged our Partner, Endgame Economics, to undertake a "with" and "without" Murraylink wholesale market model run using PLEXOS, with the difference in aggregated regional half hourly dispatch cost outcomes under each run transferred to an NPV (Excel) model;
- That NPV Model randomly combines one of 15 potential failure curves for IGBTs with one of three potential CAPEX solutions to create a "scenario", of which 40 (scenarios) are run at any given time in the model (with the model being run multiple times to generate the results that are presented in this report);
- For each scenario in the model, we have:
  - A starting stock of spares (which is the same across all scenarios - ~165 – based on our analysis of information provided by APA)
  - A forecast stock of spares for each year of the model, which is driven by:
    - the starting stock of spares (above),
    - *less* the number of assumed IGBT failures in that year (which depends on the randomly selected failure curve assigned to that scenario), and
    - *plus* the additional stock of spares that are created *if* a CAPEX solution is assumed to be built under that scenario.
- CAPEX solutions are automatically activated in the model in the year after the stock of spares reduces below 50.
- Different CAPEX solutions:
  - Create different amounts of spares;
  - Impose a different capital cost against that scenario; and
  - Impose a different outage cost against that scenario.
- The outage is assumed to be planned, with perfect foresight, hence the impact on the market (which is what is included in the NPV analysis, based on the difference between the "with" and "without" Murraylink dispatch costs from the PLEXOS runs) is based on the minimum impact over 70 /150 consecutive days in the year the CAPEX solution occurs in the model.

3 Cross-Sound Cable is a submarine power cable between New Haven, Connecticut and Shoreham, on Long Island, in New York, United States.

- If, after the initial capex solution occurs, the stock of spares breaches the 50 spare threshold again, then another CAPEX solution (of the same type) occurs.
- The marginal economic cost of not undertaking any capex solution is calculated for each scenario, based on the difference between the "with" and "without" Murraylink PLEXOS outcomes, for the duration of Murraylink not being available from the first failure (until 2042 – which is the end of forecast time horizon in the NPV model)

Overall, for each of the scenarios modelled, the final NPV result reflects:

- The costs that must be incurred to maintain Murraylink in operation under that scenario, which includes:
  - The cost of the CAPEX solution that is required to maintain Murraylink under that scenario; *plus*
  - The cost to the market of the planned outage(s) that is required to implement that CAPEX solution.
- The benefits resulting from maintaining Murraylink's operation under that scenario, which includes:
  - The cost to the market if Murraylink were not available (i.e., the difference between the "with" and "without" Murraylink wholesale dispatch costs), from the year Murraylink was first unavailable under that scenario through to 2042, which is the end of the modelling horizon; and
  - The impact on overall dispatch costs if Murraylink was not available, and an outage on the Heywood interconnector occurred in the 'at risk' June / July period (when renewable droughts tend to occur)[4].

### OGW's Conclusions

Our conclusions are as follows:

- Upgrading phase-by-phase delivers a positive NPV and is likely to deliver the best results in NPV terms. This outcome is not materially influenced by either the WACC assumed, or the threshold number of spares that, once breached, activate a capital solution being adopted in the model;
- The NPV of this type of solution declines, the more failures there are and hence, the more single-phase upgrades that are required.
- Based on the different model runs contained in this report, to make upgrading a single converter station the preferred option would require[5]:
  - 5 single-phase upgrades (Run1)
  - 6 single-phase upgrades (Run 2)
  - 5 single-phase upgrades (Run 3)
- The failure rates associated with these are:

4 This aspect of the modelling is discussed in more detail in the body of the report.

5 It is important to note that this doesn't account for the different failure curves that may have been ascribed to different capex solutions in those runs.

  - 20% per annum (Run 1)
  - 33% per annum (Run 2)
  - 20% and 33% per annum (Run 3)
- However, removing the randomness of the failure rates, and looking at the specific results of different scenarios with the same failure rates indicates that at a 20% per annum increase would require 5 single-phase upgrades and two single converter station upgrades, and:
  - Despite the raw CAPEX being lower for upgrading a single converter station twice, the NPV over 20 years is similar to undertaking 5 single-phase upgrades; and
  - This occurs because an upgrade of a single-phase "buys" around 9 years between upgrades in the earlier part of the evaluation period (when failures are growing off a low existing base), with this timing an important influence on NPV outcomes.
- The timing of the initial capex solution is 2027 under most scenarios. However, applying a lower threshold (than the 50 spares that we have assumed in our base modelling) would:
  - Lead to replacement occurring later in the modelling horizon (~2029); however
  - Lead to there being a greater risk of having to adopt an unplanned (instead of planned) replacement.
- Future capex (beyond the first upgrade) is significantly impacted by what future failure rates are assumed, which, at this stage is inherently uncertain. In saying this:
  - Whilst the model can give an idea of the timing and number, as time goes by, better empirical information will become available upon which to base decisions; and
  - A possible approach to quantifying likely failure rates of the future spares is to undertake accelerated life testing under high temperature, voltage, and environmental conditions. This is commonly used for IGBTs that are used in Electric Vehicles and other power electronic components.
- Murraylink's willingness to pay for spares from Cross Sound is likely to be in the order of $20k to $25k per IGBT, however, based on feedback from APA, this solution is considered to have a very low probability of success; and
- Upgrading both converter stations is a poor solution when measured in pure NPV terms. To breakeven with the best option (single-phase upgrade), it would require APA to sell spare IGBTs to Cross Sound at around the following price and volume levels:
  - 6000 spares @ ~$7k per spare; 3000 spares @ $14.1k per spare; 1500 spares @ $28.3k per spare[6].
  - At this stage we have no insight as to Cross Sounds' potential willingness to pay (WTP), or just as importantly, the number of spares it might be willing to purchase at any price point.

6 This reflects the outputs of one model run, however the results for the other model runs relatively similar.

# 1. Background and objective

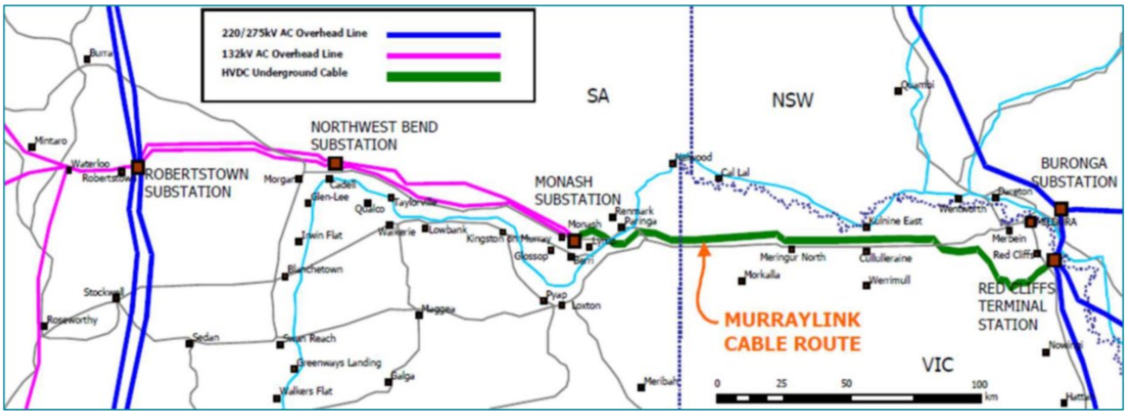
## 1.1. Background to Murraylink

Murraylink is a high-voltage, direct current (HVDC) transmission line that connects the power transmission networks at Red Cliffs (in Victoria) and Berri (in South Australia).

The facility, which was constructed 20 years ago, consists of converter stations at Red Cliffs and Berri, the direct current (DC) cables connecting the two converter stations and the alternating current (AC) cables connecting each converter station to nearby AC substations (Red Cliffs Terminal Station in Victoria and Monash Substation in South Australia).

Murraylink utilises three-level voltage source converter (VSC) technology. The DC cables are buried underground and are approximately 180 km in length.

Figure 1: Murraylink HVDC link




Source: APA

The Australian Energy Market Operator (AEMO) determines the power transmission through Murraylink as a part of their central dispatch process considering the limitations on the power systems in South Australia and Victoria. APA Group (APA) manages and operates Murraylink on behalf of Energy Infrastructure Investments (EII).

The key parameters of Murraylink are:

- Bi-directional, with a maximum power flow of 220 MW with current losses of 8.5%;
- Maximum reactive power generation between +140 MVAr and -150 MVAr at each end;
- AC connection voltage of 220 kV at Red Cliffs and 132 kV at Berri; and
- DC voltage of ±150 kV.

## 1.2. Overview of Issue

Murraylink became operational in 2002 and had an original design life of 40 years. Murraylink uses ABB's (now Hitachi) older Generation 2 Insulated Gate Bipolar Transistors[7] ('Gen 2 IGBTs') in a three-level Voltage Source Converter (VSC) technology, with 972 IGBTs per phase and a total of 2,916 IGBTs in each converter station[8].

In December 2020, the sole provider (Hitachi) advised APA that the Gen 2 IGBT positions used for Murraylink would no longer be produced, and that Murraylink would only have access to a portion of the IGBT positions in stock.

The current failure rate is around 24 per annum. The total available spares (Hitachi stock allocation plus APA's site stock) is estimated to be around 165, which, based on current failure rates, would support the current operation for another ~6 years.

Amplitude Consultants Pty Ltd (Amplitude) were engaged to undertake the necessary preliminary investigations into the technical feasibility of options for continued operation of Murraylink. In doing so, Amplitude have considered the reliability of the existing units, the costs to replace the valves and associated equipment and the technical and engineering benefits (which primarily relate to improved efficiency) of upgrading to the newer modular multi-level converter (MMC) VSC technology.

## 1.3. Objective

APA has engaged OGW to analyse the short and long term options to determine the optimal economic approach to resolving the IGBT obsolescence issue.

## 1.4. Structure of Report

The remaining sections of this report are structured as follows:

- Section 2 describes the options we have modelled;
- Section 3 outlines the approach we have adopted;
- Section 4 outlines the key results of our analysis; and
- Section 5 contains our conclusions.

7 IGBTs are a solid state switchable transistor and are the main component used to convert AC to DC and DC back to AC.

8 Murraylink consists of one converter station at each end, consisting of three single-phase legs.

# 2. Options modelled

The three key infrastructure options modelled are:

- **Option 1: Replace existing 'Gen 2 IGBTs' with 'Gen 3 IGBTs', by replacing individual phases:** This option involves completely replacing a single-phase with newer generation IGBT positions ('Gen 3 IGBTs') to free up some of the existing 'Gen 2 IGBTs' for spares to be used elsewhere. The newer generation IGBTs are not electrically or physically directly compatible with Gen 2 IGBTs, hence why only the replacement of an entire phase is feasible, however the existing cooling, protection and control systems are reusable.
- **Option 2: Replace one converter station with MMC valves to generate spare 'Gen 2 IGBTs' for use in the other converter station:** This option requires a complete converter station (3 phases) to be upgraded with MMC valves. This option would involve one end of Murraylink operating with new, slightly more efficient, MMC technology, whilst the other end operates with VSC technology (Gen 2 or Gen 3). As this involves a completely different switching configuration and topology, it requires a change in infrastructure and balance of plant.
- **Option 3: Replace both converter stations with new MMC valves:** This option involves replacing both converter stations (3 phases at each end) with new, more efficient, MMC technology. Any spare 'Gen 2 IGBTs' generated could potentially be sold to another transmission company that operates similar technology.

The following figure provides more detail regarding these solutions.

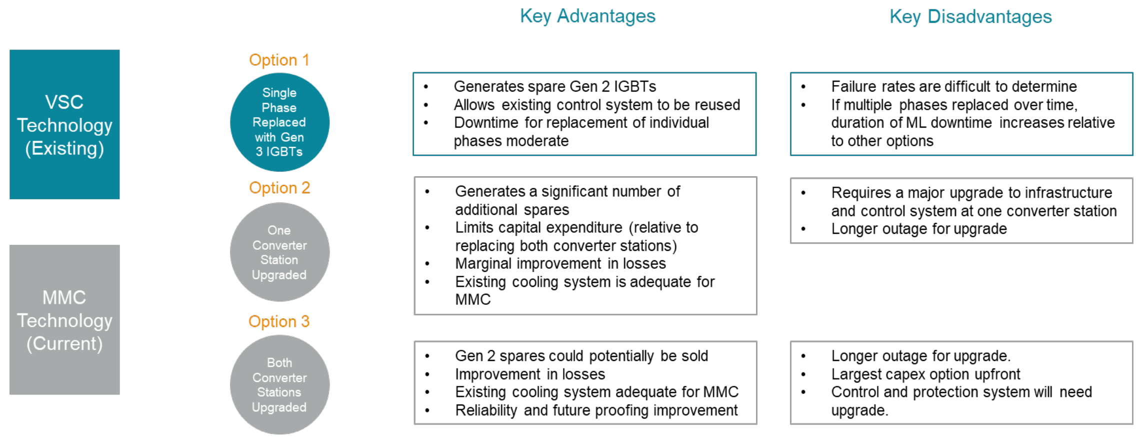
Table 2: Infrastructure options considered by Amplitude

| Parameter | Option 1: Replace Gen 2 IGBTs with Gen 3 IGBTs | Option 2: Replace one converter station with new MMC valves | Option 3: Replace both converter stations with new MMC valves |
|---|---|---|---|
| **Infrastructure** | Reuses most of the existing building infrastructure. Control system and protection system replaced in 2020. | Need to replace all phases, new clean room valve halls, possibly new control and protection systems with different suppliers for one converter station. | Need to replace all phases, new clean room valve halls, possibly new control and protection systems with different suppliers for one converter station. |
| **System Losses** | BAU (8.5% total) | Minor benefit of 1% improvement (7.5% in total) | 2% improvement (6.5% in total) |
| **Service Life** | Replacement of one phase will free up ~900 Gen 2 IGBTs for use as spares on other phases.<br>Operational life of Gen 2 IGBTs as spares is unknown and may need another phase conversion at a later date. | It would free up ~3000 spares, which can be used to support the other converter station. | Operational life to at least existing design life. Potential to extend further. |
| **Outage requirements** | 10 weeks (per phase) | 5 months (all phases) | 5 months (all phases) |
| **Direct Capex** | $17.8m per phase | $36.7m | $71.8m |

Source: OGW, based on information from Amplitude, *Murraylink Valve Replacement, Project Options Assessment*, 17 June 2022.

The following figure summarises the advantages and disadvantages of each of the three infrastructure options.

Figure 2: Key advantages and disadvantages of the three infrastructure options




Source: OGW

In addition to the engineering options, theoretically, APA may also be able to either:

- Purchase spare IGBTs from another authority that utilises similar technology (such as the Cross-Sound Cable Company[9] in the USA), or
- Sell spare IGBTs that might be created from any of the previously mentioned technology solutions, to that authority.

Based on information that we have gleaned from our discussions with APA regarding their approaches to the Cross-Sound Cable Company, this option is, at this stage, considered quite speculative. As such, our presentation of this option in this report is framed in the context of:

- How much APA might be willing to pay for Gen 2 IGBT's from the Cross Sound Cable Company, based on APA's opportunity cost; and
- How much APA would need to be able to sell IGBT's to the Cross Sound Cable Company in order for a particular engineering solution to deliver net benefits (relative to other potential solutions).

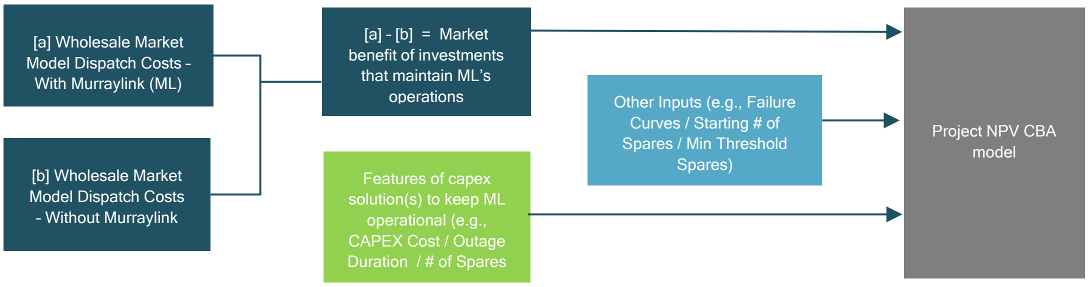
[9] Cross-Sound Cable is a submarine power cable between New Haven, Connecticut and Shoreham, on Long Island, in New York, United States.

# 3. Overview of our approach

## 3.1. Summary of approach

Our overall approach to undertaking this modelling is represented in the following diagram.

Figure 3: Overview of our approach




Source: OGW

## 3.2. Wholesale market modelling

The wholesale market modelling was performed by OGW's sub-contractor, EndGame Economics, using PLEXOS.

All wholesale modelling scenarios were based on AEMO's Final 2022 Integrated System Plan (ISP)[10] input assumptions.

The market modelling did not endogenously generate the level of generation capacity required and hence investment requirements, rather the investment outlook was based on the results of the 2022 ISP Step Change scenario[11]. Therefore, they were exogenous inputs in the dispatch model[12]. For generation, this includes both the forecast entry and retirement, whilst future interconnector upgrades were based on the final 2022 ISP optimal development path.

To understand the benefits or costs Murraylink contributes to the wholesale market, the total NEM-wide generation dispatch cost in each half hour was generated for 'with' and 'without' Murraylink scenarios, over a 20-year time horizon (to 2042). The difference in the two dispatch costs is the benefit (or cost) of not having Murraylink operational.

10 All inputs were sourced from AEMO's final 2022 ISP, which has been developed with extensive consultation with the industry. Stakeholders considered Step Change to be the most likely scenario during the development of the 2022 ISP. The following inputs from the selected ISP scenario were used in the market modelling: Operational demand forecast including peak and energy targets; Fuel prices including coal, gas and distillate; and plant technical and operational characteristics.

11 The 2022 ISP assumes Newport Power Station's retirement in 2037. The Step Change case doesn't present any new build replacement capacity in the Generation Outlook to replace this retirement. For the purposes of our modelling Newport remains operational to prevent USE as the model is not trying to resolve for new build capacity. This represents a conservative case for the Murraylink modelling as this step change in supply is not being transferred to other capacity or interconnectors.

12 Whilst the modelling did not explicitly model changes in investment outcomes under various Murraylink options, we note that prior to 2030, new VRE investment will be largely driven by state-based renewable schemes. Given the relatively small size of Murraylink (approx. 220 MW maximum transfer capacity), its impact on new generation entry decisions will likely be secondary compared to the state-based renewable schemes. As such, we do not believe this simplification compromises the results in any material way.

The following scenarios have been modelled:

- *With* Murraylink being operational (BaU) for the Step Change case; and
- *Without* Murraylink being operational for the Step Change case.

For the avoidance of doubt, we choose not to test the impact of the different technologies on market outcomes, as the efficiency improvements of 1% and 2% (associated with upgrading one or both converter stations with the new MMC technology respectively) was deemed to be immaterial, in the context of the modelling outcomes and given the inherent accuracy associated with this form of market modelling.

In addition to the above modelling runs, we ran another parallel set of model runs:

- *With* Murraylink being operational and a Heywood Outage during an "at-risk period"[13] between 10 June and 24 July (inclusive) every year for the Step Change case; and
- *Without* Murraylink being operational and a Heywood Outage during an "at-risk period" between 10 June and 24 July (inclusive) every year for the Step Change case.

Without Murraylink, there will be less interconnection between South Australia and the rest of the NEM, and more expensive local generation resources will be required more often to meet demand. The market benefit of the *with* Murraylink options were based on the difference in total NEM dispatch cost when compared to the *without* Murraylink options.

## 3.3. Features of the Capex Solutions that allow Murraylink to continue to operate

The following tables sets out the capex solutions that were modelled, their costs, the number of spares created and the number of days Murraylink would not be available to the market because of an outage.

Table 3: Capex solutions modelled

| Capex Solution | Costs^ | Spares Created | Planned Outages |
|---|---|---|---|
| GEN2 IGBT to GEN 3 IGBT (per phase) | ~$20.5m | 900 | 70 days |
| Upgrade one converter station to VSC MMC | ~$42.2m | 3000 | 150 days |
| Upgrade both converter stations to VSC MMC | ~$82.5m | 6000^^ | 150 days |

^Raw costs, as per Amplitude, plus 15% overhead. ^^ This is designed to in effect, remove the sparing issue, as this is a new technology.

## 3.4. Key Inputs

The following subsections summarise the other key inputs contained in the model.

### 3.4.1. Failure curves

APA has advised us that historic IGBT failure rates have been ~24 per annum on average. Our modelling assumes that this is the 'BAU' failure rate (curve).

13 This is likely the worst period (1.5 month) in terms of VRE droughts in the southern states based on our experience.

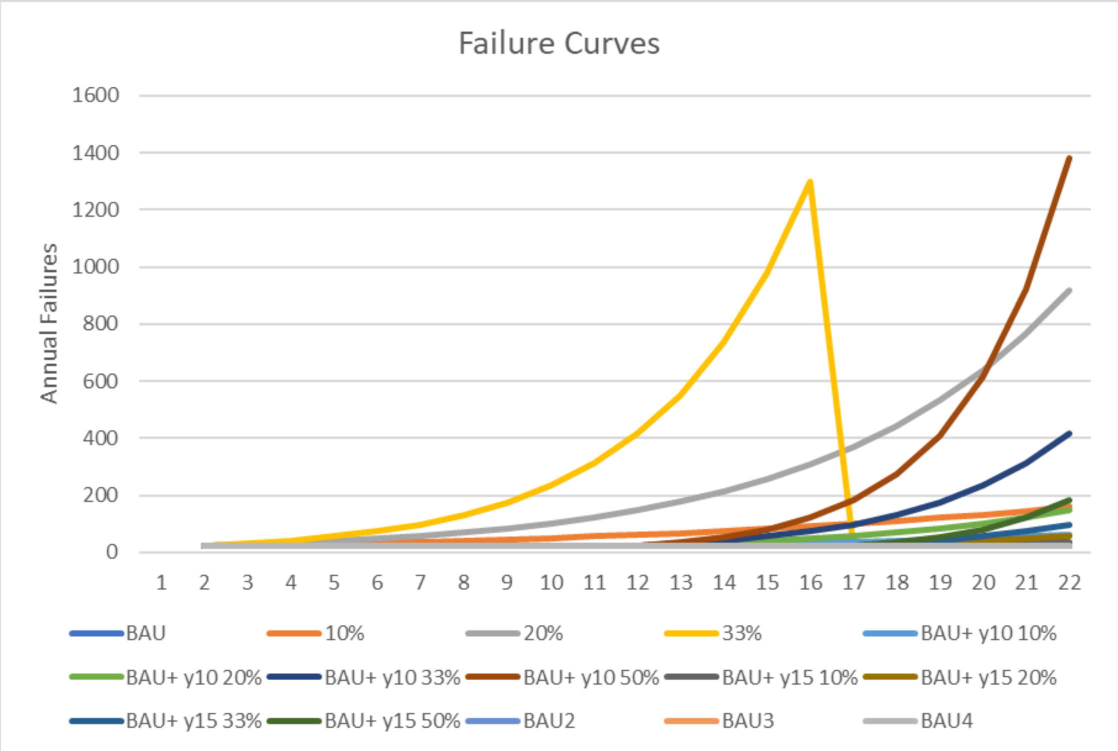
That said, given the age and service life of the *in situ* IGBTs, it is possible that this annual failure rate may increase in the future. However, no detailed historic failure data is available to determine the Weibull distribution and provide quantifiable failure probabilities[14]. As such, we have relied on information contained in the Amplitude report[15] to posit potential increases in these failure rates, grouped as follows:

- Accelerated failure at different rates have been derived from the Amplitude report, and have been applied over the full 20 year modelling period;
- BAU failure rates have been combined with accelerated failure rates (derived from the Amplitude report) from year 10 onwards; and
- BAU failure rates have been combined with accelerated failure rates (derived from the Amplitude report) from year 15 onwards.

In some of the cases the cumulative number of failures lead to results whereby the number of failures exceeds the number of *in situ* Gen 2 IGBTs. In these situations, OGW has assumed that once the cumulative failure rate exceeds approximately 5000, all of the *in situ* IGBTs have been replaced, leading to the annual failure rate returning to the BAU of 24 per annum.

OGW's 15 failure curve scenarios are presented in figure below.

Figure 4: Failure curves modelled




Source: OGW, noting that multiple BaU scenarios have been included in the modelling, the effect of which is to increase the probability that the BaU failure curve is randomly selected in the model.

14 Component failure rates fit to a bathtub curve with high rates initially, reaching a lower steady state rate, and then an increased failure rate towards the end of life of the component.

15 Amplitude, *Murraylink Valve Replacement, Project Options Assessment*, 17 June 2022,

### 3.4.2. Starting Spares and Minimum Threshold Spares

The starting stock of spares included in the model was 165. This is based on information provided by APA.

The minimum number of spare IGBTs that, once breached, results in a capex solution being built in the model, is 50. We have tested the sensitivity of changing this threshold, the results of which are contained as a sensitivity in section 4 of this report.

## 3.5. NPV Modelling

We have constructed an NPV model in Microsoft Excel. The key parameters of the model are:

- WACC = 6% real, pre tax
- Modelling timeframe = 20 years
- Spares Threshold = 50

The model works as follows:

- The model **randomly** combines a **failure curve** with a **CAPEX solution** to create a **"scenario"**. The model runs 40 scenarios at a time, however the model has been run multiple times to generate the results that are contained in section 4 of this report;
- For each of the 40 **scenarios** in the model, we have:
  - A starting stock of spares (which is the same across all scenarios at 165, see above)
  - A forecast stock of spares for each year of the model, which is driven by:
    - the starting stock of spares (above),
    - *less* the number of IGBT failures that are assumed to occur in that year (which depends on the randomly selected failure curve assigned to that scenario), and
    - *plus* the additional stock of spares that are assumed to be created in a year *if* a CAPEX solution is activated in the model under that scenario.
- CAPEX solutions are automatically activated in the model in the **year after** the stock of spares reduces below 50 (with sensitivity testing around this figure – see the results section).
- Different CAPEX solutions (which, as stated earlier, are randomly ascribed to a scenario):
  - Create different amounts of spares (see above for details):
  - Impose a different capital cost against that scenario (see above for details); and
  - Impose a different outage cost against that scenario, which results from the different outage durations applicable to different capex solutions as well as the year in which the outage occurs in the model.
- The base modelling results assume that outages are **planned with perfect foresight**, hence the impact of any outage on the market (which is what is included in the NPV analysis, based on the difference between the "with" and "without" Murraylink dispatch costs from the PLEXOS runs) is based on the minimum impact over 70 /150 consecutive days (depending on the CAPEX solution) in the year the CAPEX solution occurs in the model;

- If, after the initial capex solution occurs, the stock of spares breaches the 50 spare threshold again, then another CAPEX solution (of the same type) occurs. For the avoidance of doubt, it is noted that the **model caps the number of investments** that can occur, with this cap dependent on the CAPEX solution that has been adopted in that scenario (e.g., only 6 "GEN2 to GEN3 (per phase)" capex solutions can occur; the model will only ever replace 2 converter stations, being either two separate replacements of a single converter station or a single replacement of both converter stations).
- The marginal economic cost of **not undertaking any capex solution** is calculated for each scenario, based on the difference between the "with" and "without" Murraylink PLEXOS outcomes, for the **duration of its unavailability** (i.e., from the year of its **first failure until 2042** – which is the end of forecast time horizon in the NPV model).

In addition to the above analysis, we have also undertaken two additional PLEXOS model runs (one *with* and *without* Murraylink), with each assuming a full Heywood outage during an "at-risk period" between 10 June and 24 July (inclusive) every year.

The purpose of undertaking this analysis was to identify the materiality of any additional "insurance value" Murraylink might provide the market during what might otherwise be considered a low probability / high consequence event such as a Heywood outage. To convert the wholesale market outcomes into a probability weighted outcome for inclusion in the NPV model, we have:

- Simulated Heywood outages, by:
  - Ascribing a 1-in-100 year probability of occurrence, and
  - Only including that outage in modelled outcomes if the simulated year falls in a year (a) within the modelling horizon (20 years), and (b) when Murraylink is assumed to not be operational.
- Further discounted that value by the probability of that outage not occurring in the '*at risk period*', based on the proportion of days in that 'at risk' period (relative to the entire year).

Overall, for each of the scenarios modelled, the final NPV result reflects:

- The costs that must be incurred to maintain Murraylink in operation under that scenario, which includes:
  - The cost of the CAPEX solution that is required to maintain Murraylink under that scenario; *plus*
  - The cost of the planned outage(s) that is required to implement that CAPEX solution.
- The benefits resulting from maintaining Murraylink's operation under that scenario, which includes:
  - The cost to the market if Murraylink were not available (i.e., the difference between the "with" and "without" Murraylink wholesale dispatch costs), from the year Murraylink was first unavailable under that scenario through to 2042; and
  - The impact on overall dispatch costs if Murraylink was not available, and an outage on the Heywood interconnector occurred in the 'at risk' June / July period (when renewable droughts tend to occur).

# 4. Results of our analysis

The following sections summarise the key results of our analysis. It includes:

- 3 base model runs, each of which assumes 50 spares is the threshold, which, after being breached, a new capex solution is activated in the model (in the following year); and
- 4 sensitivity runs:
  - Sensitivity Run 1 – which assumes that the spare threshold is reduced to 10;
  - Sensitivity Run 2 – which assumes that (a) the spare threshold is reduced to 10, (b) that the “worst timing” (in terms of its impact on the market) occurs for that outage, and (c) that it takes longer to undertake a single-phase upgrade as compared to the base model runs (100 days, instead of 70 days);
  - Sensitivity Run 3 – which assumes a higher WACC (with all other parameters being the same as the base model runs); and
  - Sensitivity Run 4 – which assumes that the number of recoverable spares is lower than in the base model runs.

## 4.1. Base Model Run 1 – 50 threshold

The following figure summarises the results of base model run 1 (40 scenarios).

Figure 5: Raw Results for Model Run 1

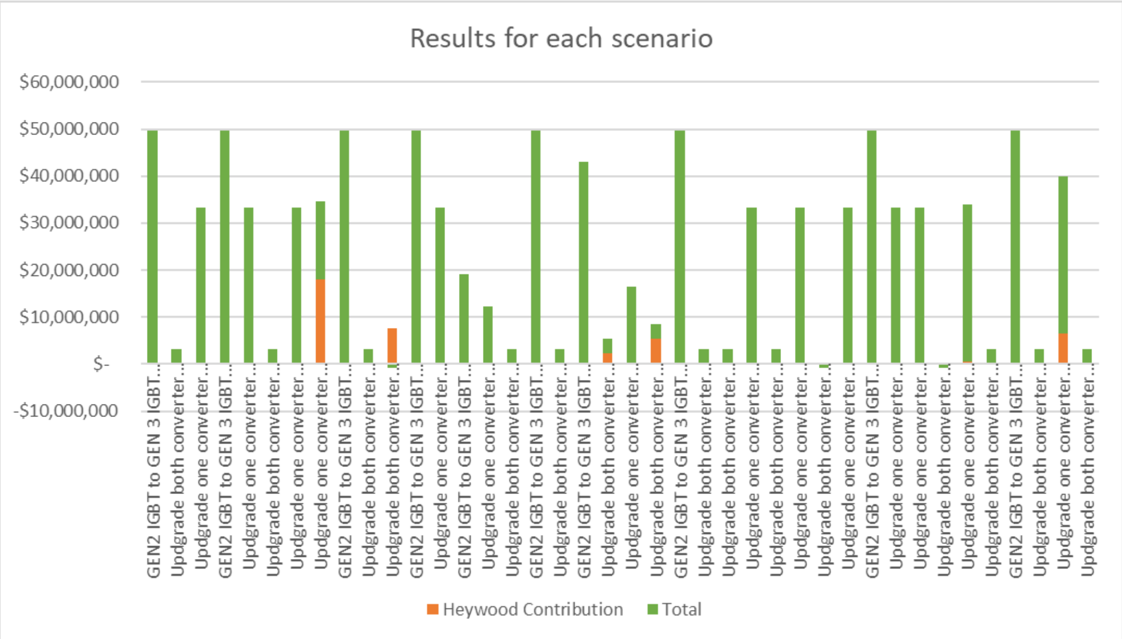


Figure 6: Ranked NPVs and Timing (Model Run 1)

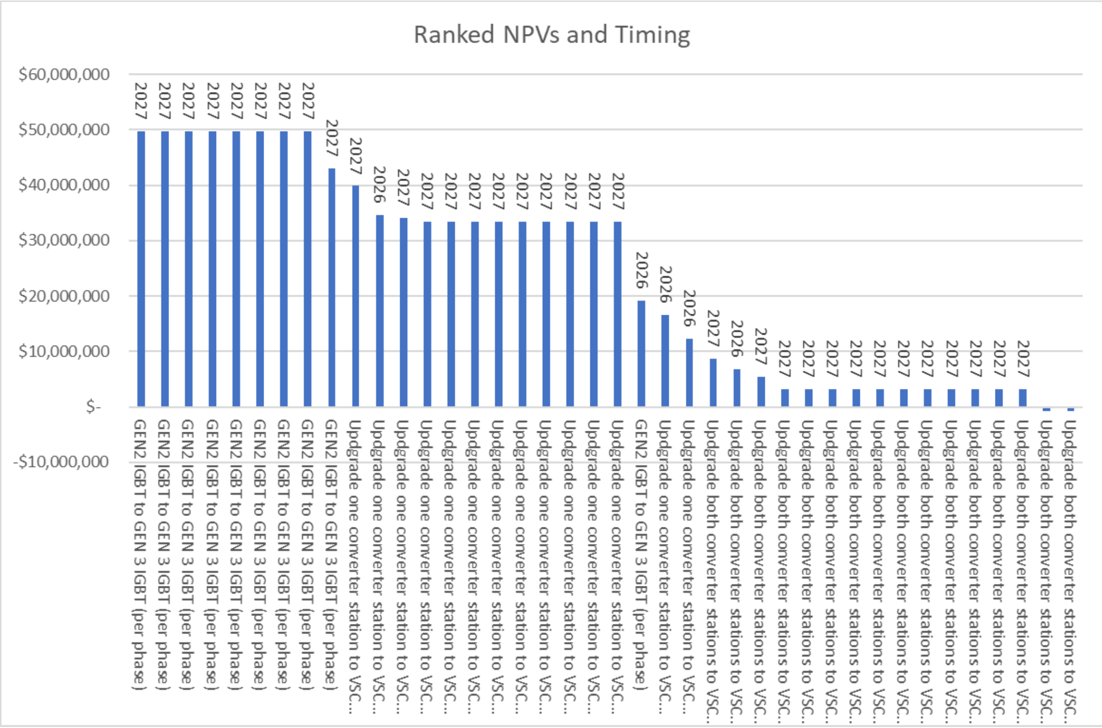



Figure 7: Total and Average NPVs across scenarios by CAPEX solution (Model Run 1)

| Technology | Total NPV across scenarios | Ave NPV across scenarios | Ave WTP (Upfront) |
|---|---|---|---|
| GEN2 IGBT to GEN 3 IGBT (per phase) | $ 459,260,288 | $ 45,926,029 | $ 23,811.59 |
| Updgrade one converter station to VSC MMC | $ 438,081,882 | $ 31,291,563 | $ 51,747.61 |
| Updgrade both converter stations to VSC MMC | $ 55,259,383 | $ 3,453,711 | $ 99,871.14 |

Notes: "Ave WTP (Upfront)" reflects the lessor of a scenario's gross NPV result and the cost incurred in achieving that result, divided by the total number of spares used under that scenario to achieve that result. This 'Ave WTP' figure therefore provides a guide as to how much Murraylink may be willing to pay Cross Sound for spare Gen 2 IGBTs, assuming those spares have similar failure rates to the failure rates included in our modelling.

The key conclusions are:

- Upgrading phase-by-phase is the best outcome under this model run.
- The timing of the first upgrade is 2027 under almost all our failure rate scenarios (with a small number at 2026).
- The worst outcome associated with undertaking a single-phase upgrade is $19m in NPV terms (Scenario 14). This scenario requires 5 single-phase upgrades to be made, with 4 of these upgrades being required in the last 7 years. This occurs because this scenario is randomly allocated a failure curve that sees a 20% per annum increase in failures.
- The benefits of mitigating the impact of a Heywood outage only affects a small number of scenarios, and it only materially contributes to one scenario's NPV.
- Upgrading both converter stations has lower a much lower NPV on average. To offset this lower NPV, APA would need to be able to sell spare IGBTs to Cross Sound at some combination of the following:
  - 6000 spares @ ~$7k per spare;
  - 3000 spares @ $14.1k per spare; or

- 1500 spares @ $28.3k per spare.

## 4.2. Base Model Run 2 - 50 threshold

The following figure summarises the results of base model run 2 (40 scenarios).

Figure 8: Raw Results for Model Run 2

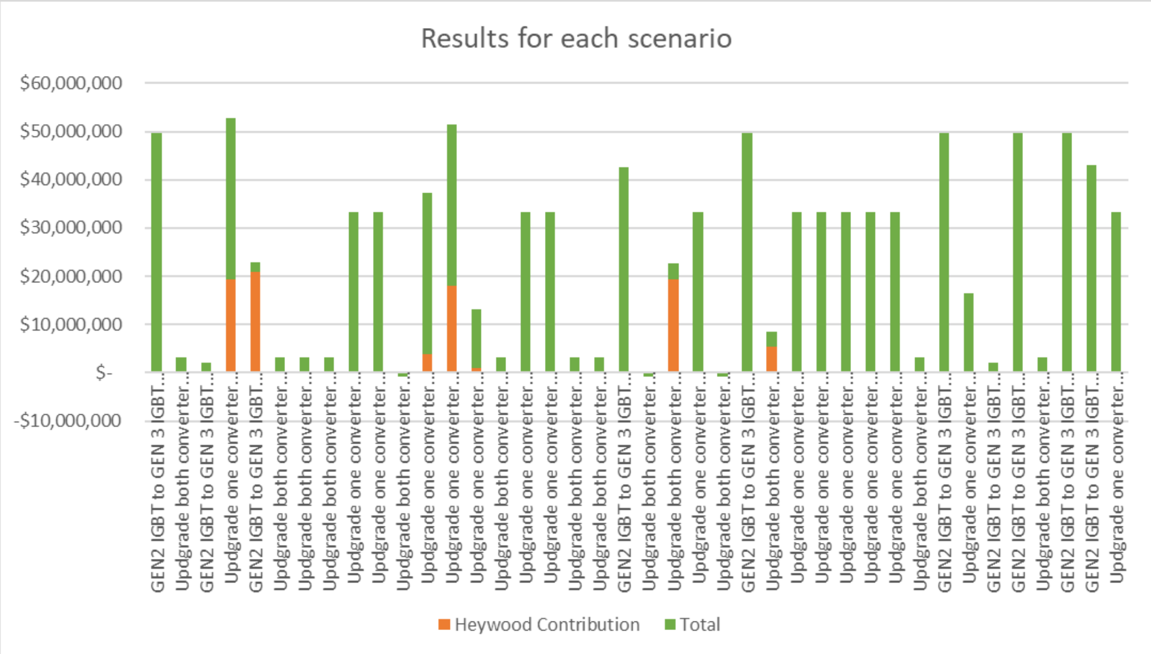



Figure 9: Ranked NPVs and Timing (Model Run 2)

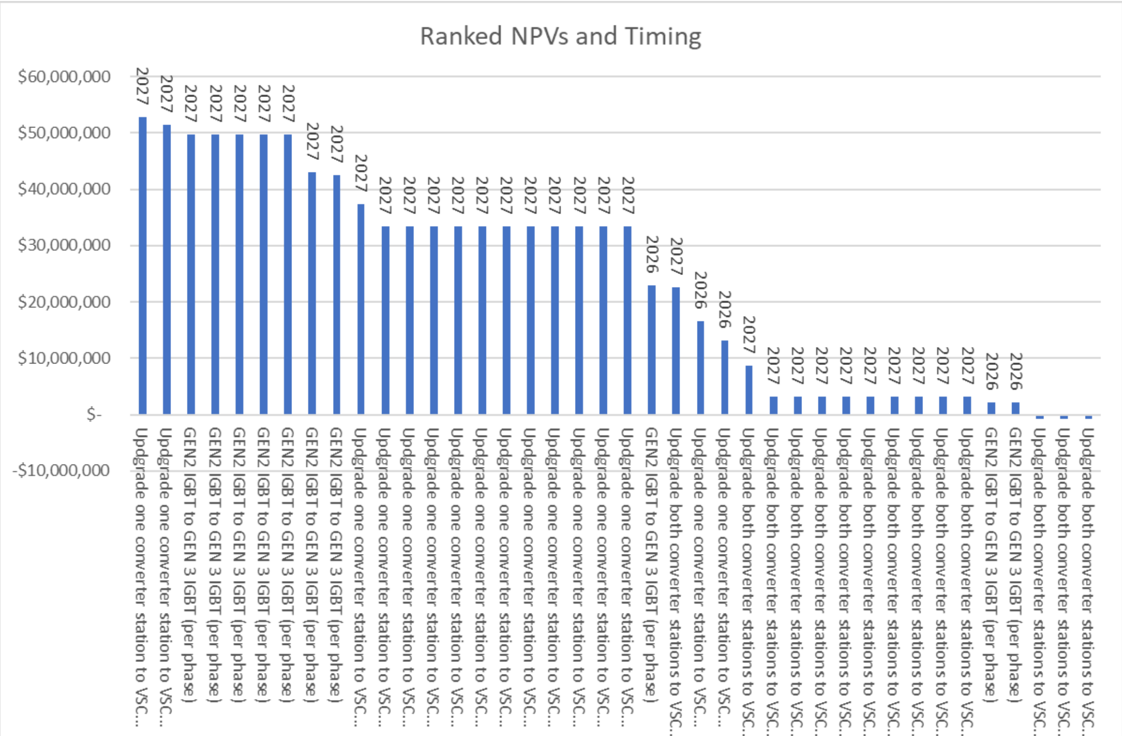


Figure 10: Total and Average NPVs across scenarios by CAPEX solution (Model Run 2)

| Technology | Total NPV across scenarios | Ave NPV across scenarios | Ave WTP (Upfront) |
|---|---|---|---|
| GEN2 IGBT to GEN 3 IGBT (per phase) | $ 361,212,557 | $ 36,121,256 | $ 26,026.38 |
| Updgrade one converter station to VSC MMC | $ 538,907,618 | $ 33,681,726 | $ 48,126.79 |
| Updgrade both converter stations to VSC MMC | $ 58,280,952 | $ 4,162,925 | $ 96,647.61 |

The key conclusions are:

- The option of upgrading one of the converter stations delivers the two best outcomes in NPV terms in this model run, however, Heywood outages contribute materially to both of those results.
- The next 7 best results are associated with a single-phase upgrade.
- The timing of the first upgrade is 2027 under almost all our failure rate scenarios.
- Upgrading both converter stations clearly delivers the worst outcome in NPV terms, although this excludes any benefit from being able to sell spares to Cross Sound. To offset this lower NPV, APA would need to be able to sell spare IGBTs to Cross Sound at some combination of the following:
  - 3000 spares at ~$10.6k per spare; or
  - 1500 spares at ~$21.3k per spare.

## 4.3. Base Model Run 3 - 50 threshold

The following figure summarises the results of base model run 3 (40 scenarios).

Figure 11: Raw Results for Model Run 3

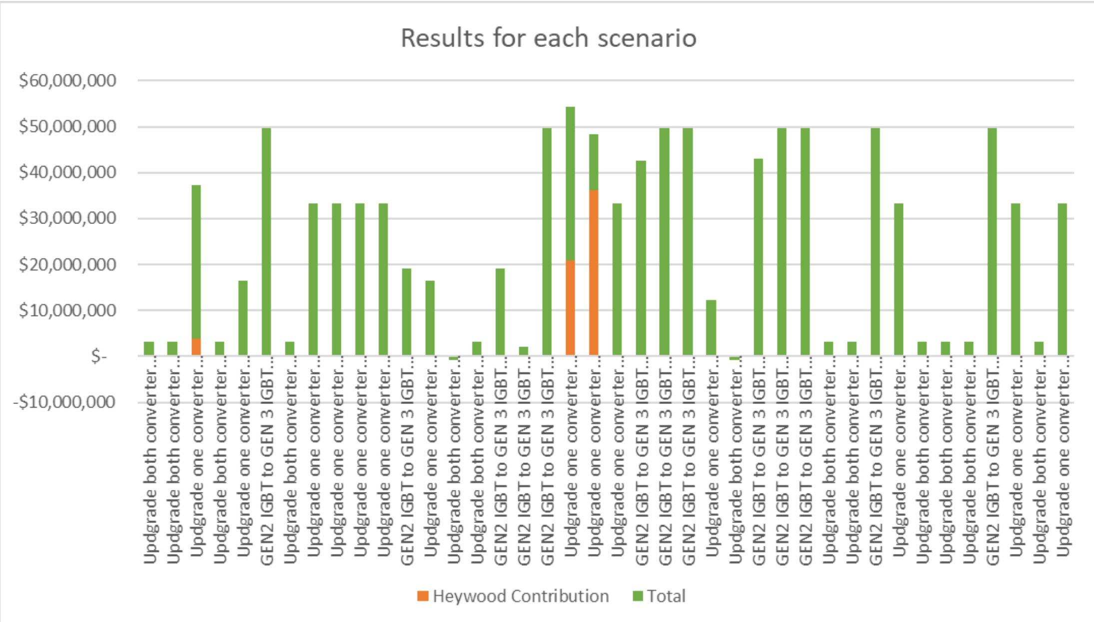


Figure 12: Ranked NPVs and Timing (Model Run 3)

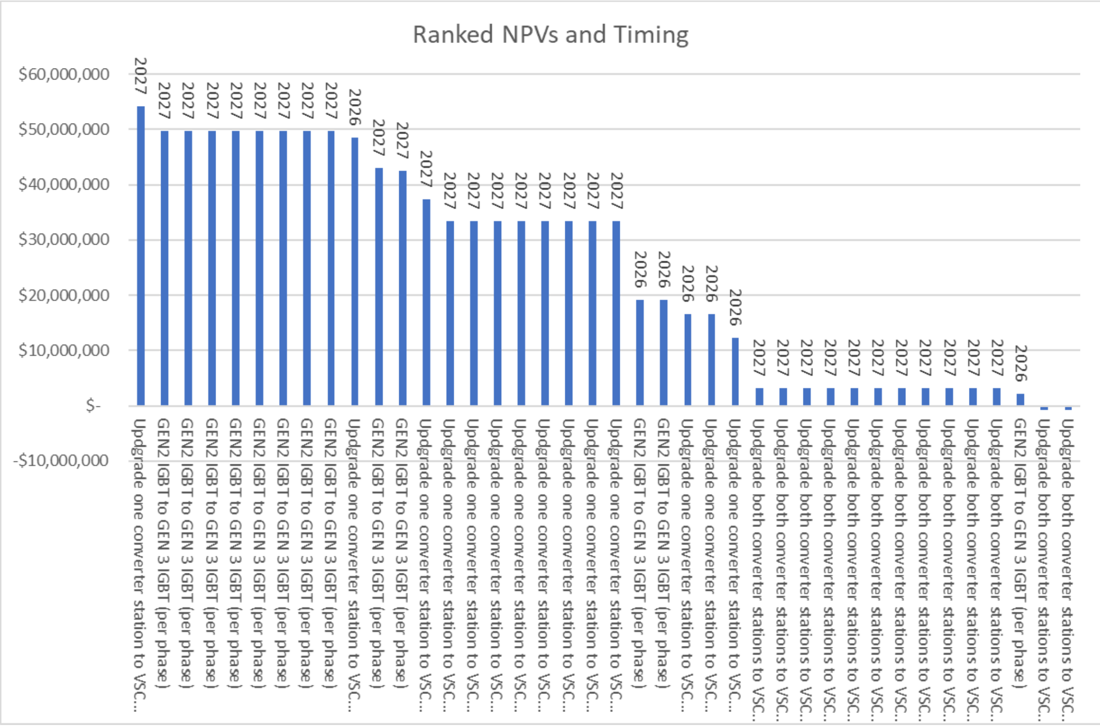



Figure 13: Total and Average NPVs across scenarios by CAPEX solution (Model Run 3)

| Technology | Total NPV across scenarios | Ave NPV across scenarios | Ave WTP (Upfront) |
|---|---|---|---|
| GEN2 IGBT to GEN 3 IGBT (per phase) | $ 523,143,711 | $ 40,241,824 | $ 23,548.31 |
| Updgrade one converter station to VSC MMC | $ 452,880,783 | $ 32,348,627 | $ 42,385.17 |
| Updgrade both converter stations to VSC MMC | $ 34,323,275 | $ 2,640,252 | $ 97,044.81 |

The key conclusions are:

- Upgrading one converter station has the best NPV, although this includes a material contribution from a Heywood outage.
- Otherwise, the single-phase upgrade solution provides the best outcomes in this model run.
- The timing of the first upgrade is 2027 under almost all our failure rate scenarios.
- The worst outcome associated with a single-phase upgrade is $2.2m in NPV terms (Scenario 17). This scenario was randomly allocated a failure curve that increased by 33% per annum, which drives the maximum 6 upgrades to be made in the model.
- Heywood materially contributes to the results of 2 scenarios.
- Again, the upgrading of both converter stations clearly delivers the worst outcome in NPV terms, although this excludes any benefit from being able to sell spares to Cross Sound. To offset this lower NPV, APA would need to be able to sell spare IGBTs to Cross Sound at some combination of the following:
  - 3000 spares at ~$12.8k per spare; or
  - 1500 spares at ~$25.6k per spare.

## 4.4. Sensitivity Run 1 - 10 threshold

The following figure summarises the results of sensitivity run 1 (40 scenarios).

Figure 14: Raw Results for Sensitivity Run 1 – 10 threshold

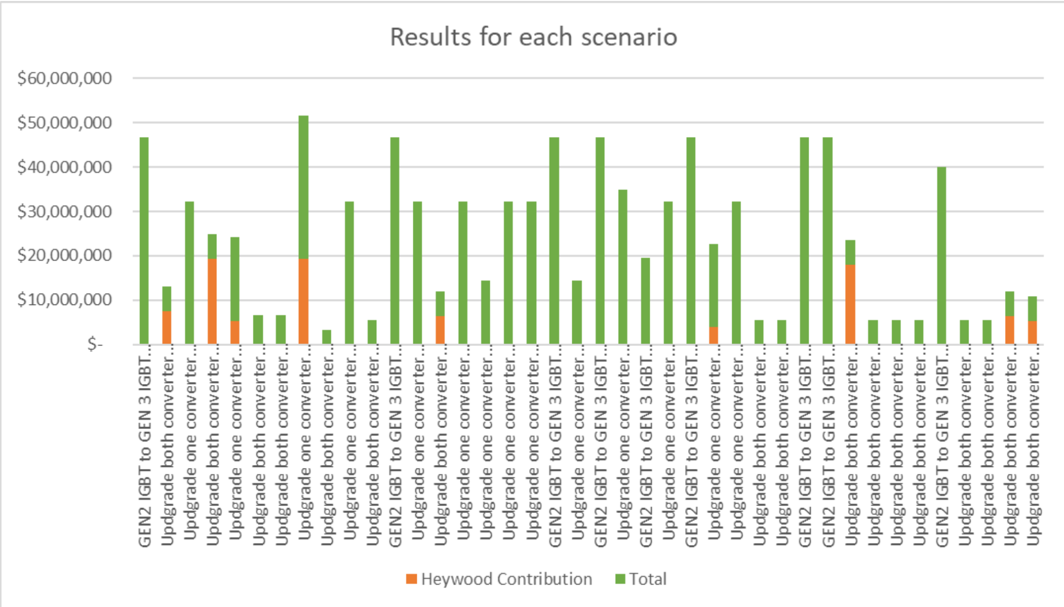



Figure 15: Ranked NPVs and Timing (Sensitivity Run 1 – 10 threshold)

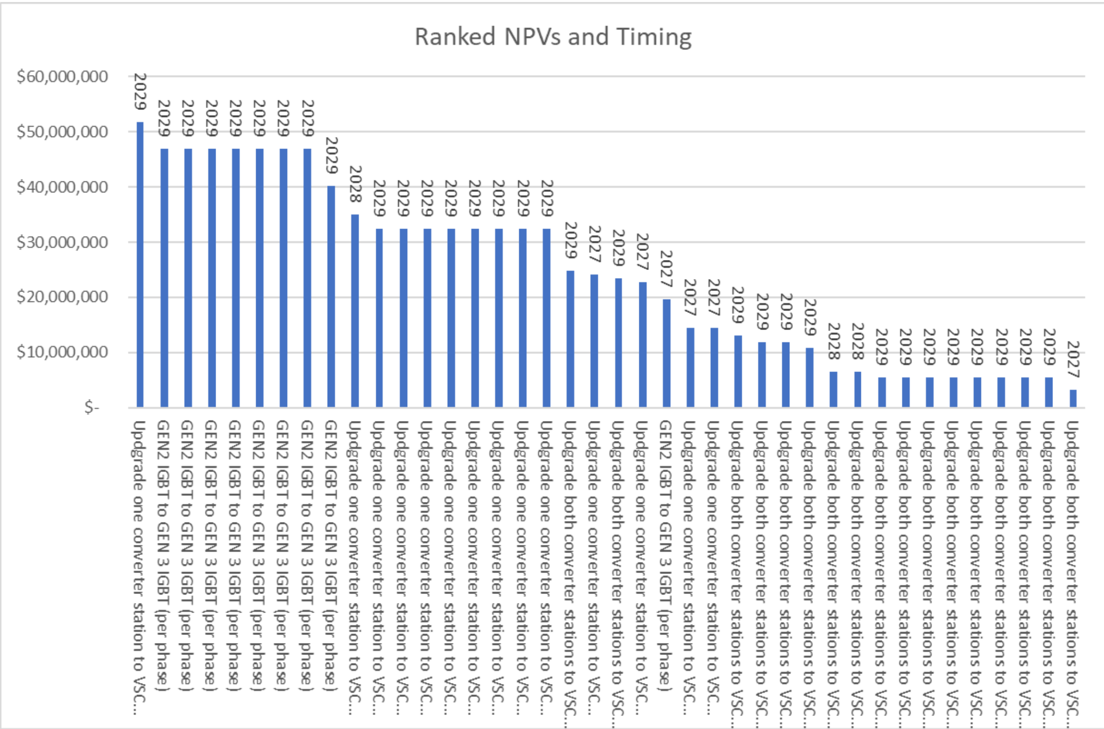



Figure 16: Total and Average NPVs across scenarios by CAPEX solution (Sensitivity Run 1 – 10 threshold)

| Technology | Total NPV across scenarios | Ave NPV across scenarios | Ave WTP (Upfront) |
|---|---|---|---|
| GEN2 IGBT to GEN 3 IGBT (per phase) | $ 387,526,967 | $ 43,058,552 | $ 29,229.53 |
| Updgrade one converter station to VSC MMC | $ 421,165,455 | $ 30,083,247 | $ 34,298.89 |
| Updgrade both converter stations to VSC MMC | $ 156,329,902 | $ 9,195,877 | $ 96,050.43 |

The key conclusions are:

- The timing of the first upgrade is 2029 under most failure rate curves. This is two years later than under our base model runs. This reflects our lower threshold (10, compared with 50) for when a capex solution is activated in the model.
- Similar to the base model runs, the single-phase upgrade is the best outcome in most cases.
- Upgrading both converter stations is the least economic solution in most cases, although this excludes any benefits from being able to sell spares to Cross Sound.

## 4.5. Sensitivity Run 2 - 10 threshold, worst timing and longer time to replace a single-phase

The following figure summarises the results of sensitivity run 2 (40 scenarios).

Figure 17: Raw Results for Sensitivity Run 2 – 10 threshold, worst timing and longer time to replace

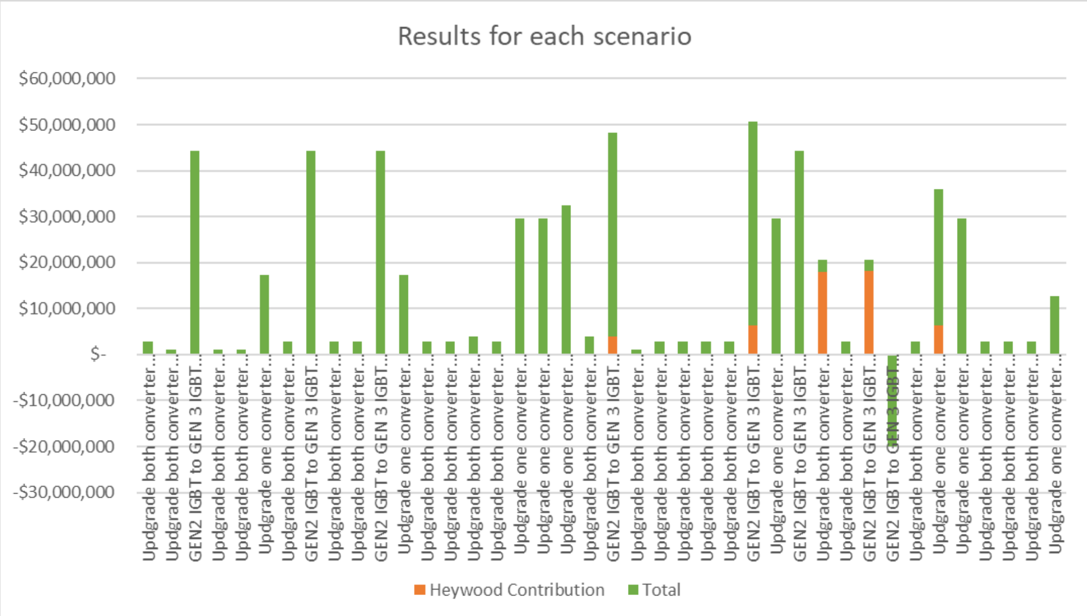


Figure 18: Ranked NPVs and Timing (Sensitivity Run 2 – 10 threshold, worst timing and longer time to replace)

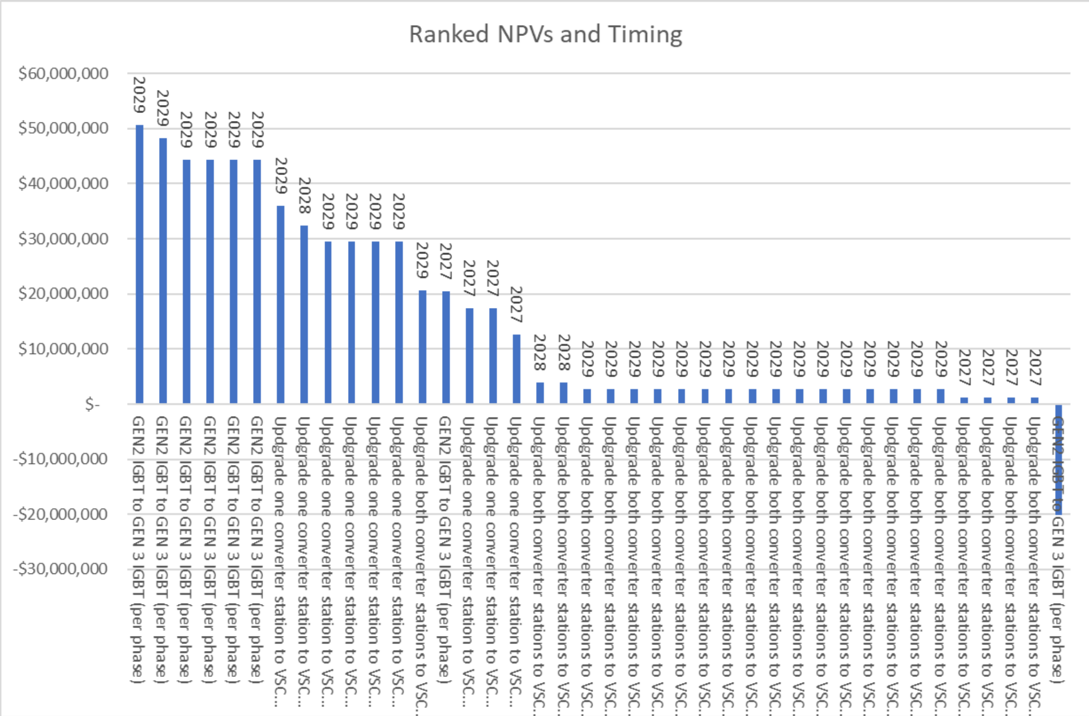



Figure 19: Total and Average NPVs across scenarios by CAPEX solution (Sensitivity Run 2 – 10 threshold, worst timing and longer time to replace)

| Technology | Total NPV across scenarios | Ave NPV across scenarios | Ave WTP (Upfront) |
|---|---|---|---|
| GEN2 IGBT to GEN 3 IGBT (per phase) | $ 276,574,956 | $ 34,571,869 | $ 28,119.67 |
| Updgrade one converter station to VSC MMC | $ 234,067,237 | $ 26,007,471 | $ 36,266.55 |
| Updgrade both converter stations to VSC MMC | $ 76,702,266 | $ 3,334,881 | $ 88,868.24 |

The key conclusions are:

- The timing of the first upgrade is 2029 under most failure rate scenarios.
- Similar to our base model runs, a single-phase upgrade is generally the best outcome, although it also has the worst result, at -$20.08m. This is because this scenario has been randomly allocated a failure curve that results in a 33% pa increase in failures, which necessitates 6 single-phase replacements occurring.
- Upgrading both converter stations is, generally, the worst solution in NPV terms, although this excludes any benefits from being able to sell spares to Cross Sound.
- Overall, the total NPV across the model runs is worse than in the base model runs.

## 4.6. Sensitivity Run 3 – Higher WACC

The following figure summarises the results of sensitivity run 3 (40 scenarios).

Figure 20: Raw Results for Sensitivity Run 3 - Higher WACC (8%)

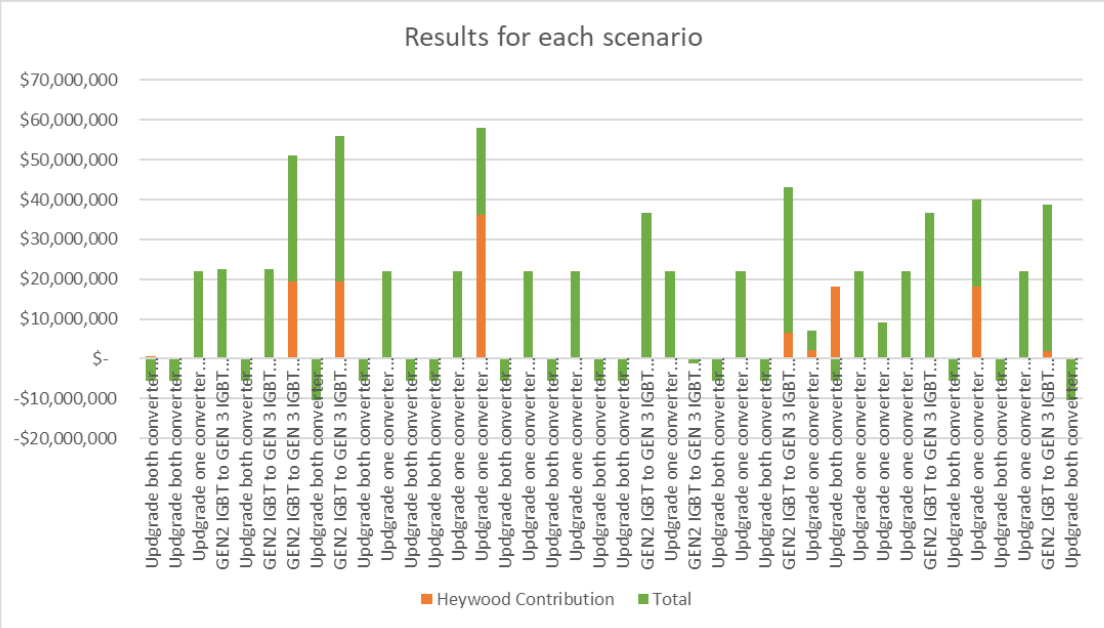



Figure 21: Ranked NPVs and Timing (Sensitivity Run 3 - Higher WACC (8%))

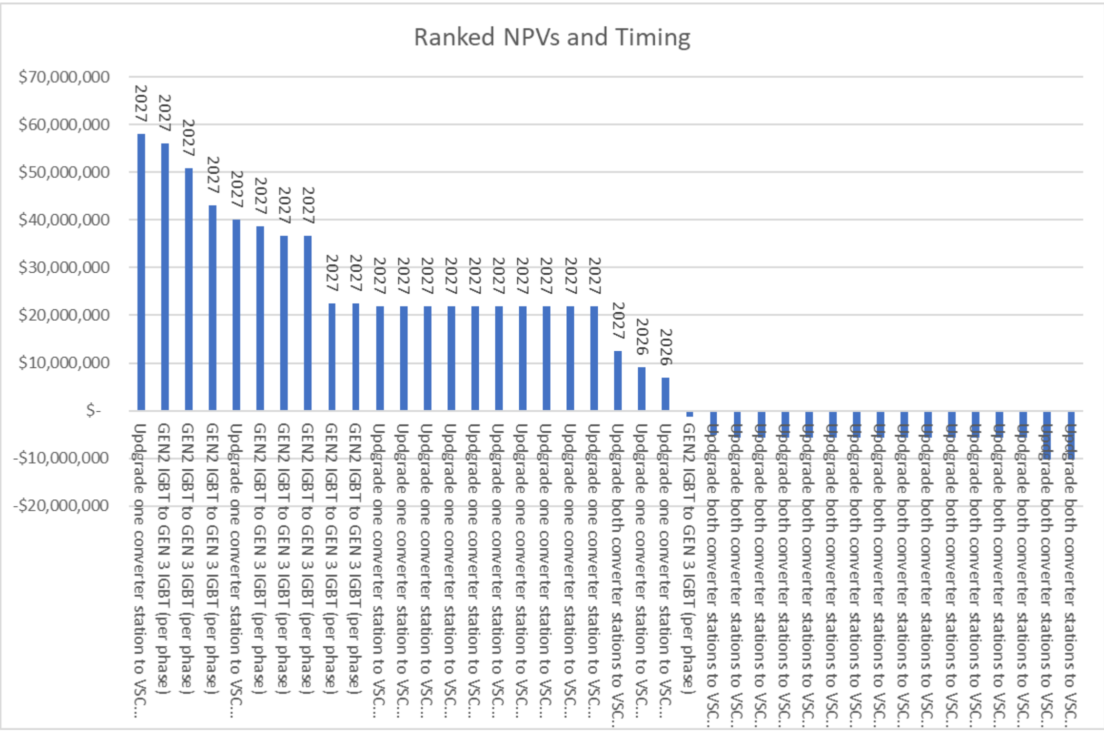



Figure 22: Total and Average NPVs across scenarios by CAPEX solution (Sensitivity Run 3 - Higher WACC (8%))

| Technology | Total NPV across scenarios | | Ave NPV across scenarios | | Ave WTP (Upfront) | |
|---|---|---|---|---|---|---|
| GEN2 IGBT to GEN 3 IGBT (per phase) | $ | 305,936,467 | $ | 33,992,941 | $ | 23,174.83 |
| Updgrade one converter station to VSC MMC | $ | 332,854,599 | $ | 23,775,328 | $ | 48,164.70 |
| Updgrade both converter stations to VSC MMC | -$ | 85,856,663 | -$ | 5,050,392 | $ | 84,373.08 |

The key conclusions are:

- Upgrading one converter station has the best NPV, however a Heywood outage materially contributes to this result.
- Similar to the base model runs, a single-phase upgrade is generally the best outcome.
- The timing of the first upgrade is 2027 under most of our failure rate scenarios.
- Upgrading both converter stations leads to negative economic benefits in NPV terms under almost all of the scenarios it is featured, although this excludes any benefits from being able to sell spares to Cross Sound.
- Not surprisingly, NPVs reduce across the board as the WACC increases, reflecting the fact that each option involves making an upfront capital investment to deliver a stream of ongoing economic benefits.

## 4.7. Sensitivity Run 4 – Fewer spares created

The following figure summarises the results of sensitivity run 4 (40 scenarios). Note for completeness that we tested 700 recoverable spares for the single-phase upgrade solution (instead of 900 under the base model runs), and 2600 recoverable spares for a single converter station upgrade solution (instead of 3000 under the base model runs).

Figure 23: Raw Results for Sensitivity Run 4 – Fewer Spares

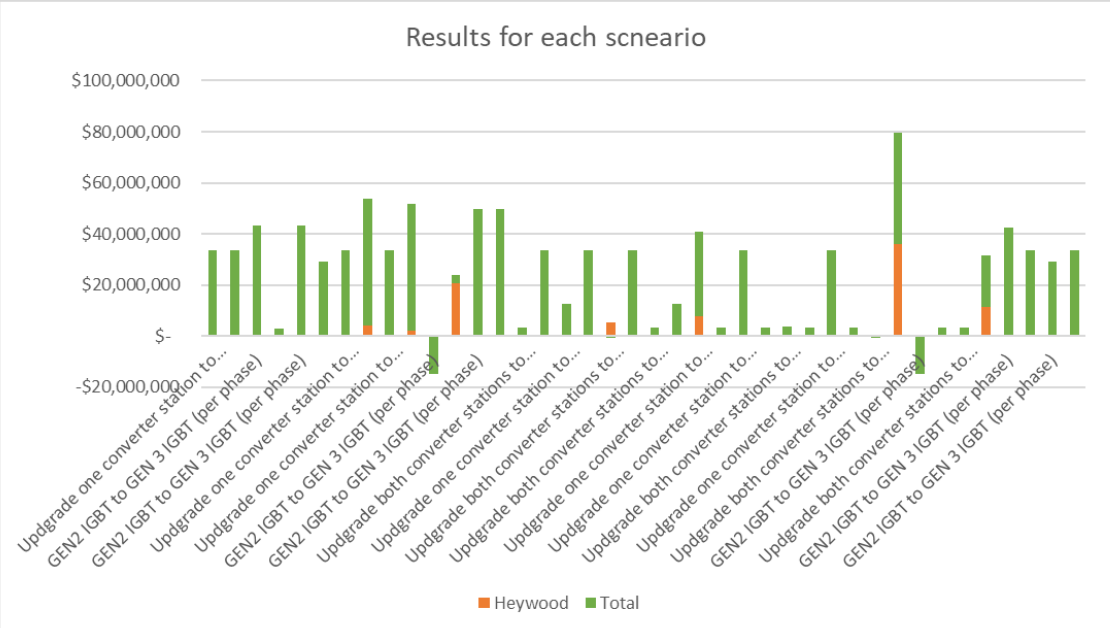


Figure 24: Ranked NPVs and Timing (Sensitivity Run 4 – Fewer Spares)

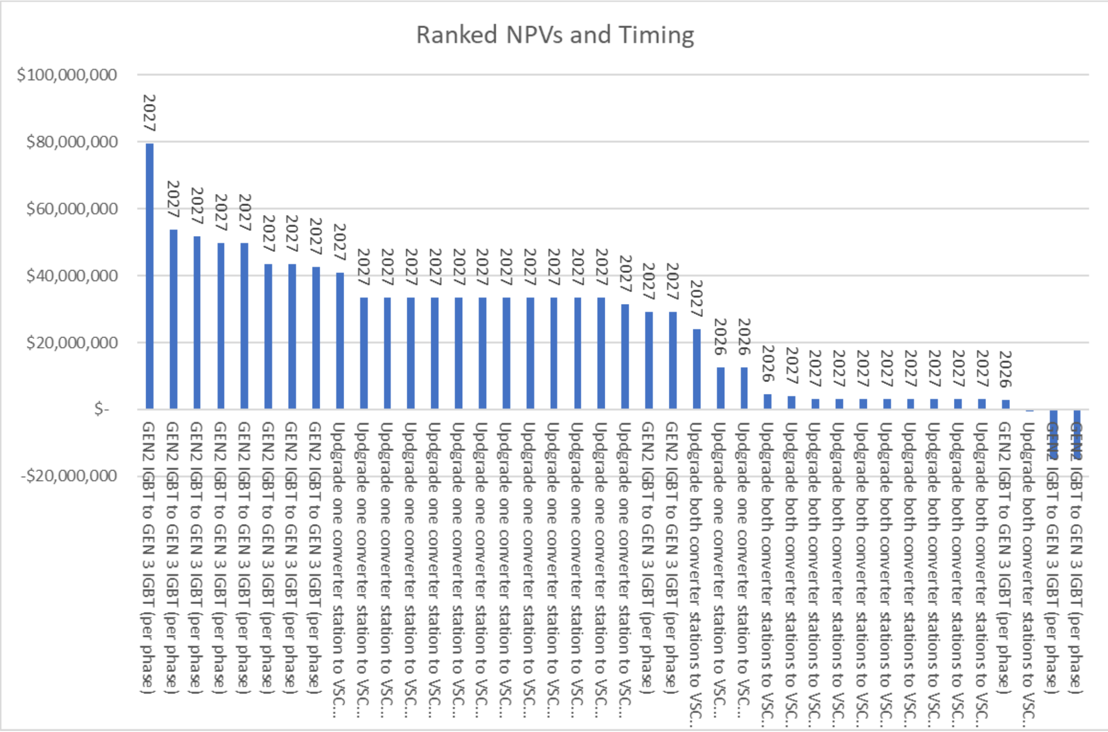



Figure 25: Total and Average NPVs across scenarios by CAPEX solution (Sensitivity Run 4 – Fewer Spares)

| Technology | Total NPV across scenarios | Ave NPV across scenarios | Ave WTP (Upfront) |
|---|---|---|---|
| GEN2 IGBT to GEN 3 IGBT (per phase) | $ 444,507,523 | $ 34,192,886 | $ 22,123.04 |
| Updgrade one converter station to VSC MMC | $ 465,095,149 | $ 31,006,343 | $ 48,752.67 |
| Updgrade both converter stations to VSC MMC | $ 57,861,044 | $ 4,821,754 | $ 86,169.24 |

The key conclusions are:

- Similar to the base model runs, a single-phase upgrade is generally the best outcome.
- The timing of the first upgrade is 2027 under most of our failure rate scenarios.
- A single-phase upgrade also has the worst two outcomes, both negative $14m, with both having been randomly assigned a failure curve that would result in 33% per annum increases.

# 5. Conclusions

Our conclusions are as follows:

- Upgrading phase-by-phase delivers a positive NPV and is likely to deliver the best results in NPV terms. This outcome is not materially influenced by either the WACC assumed, or the threshold number of spares that, once breached, activate a capital solution being adopted in the model;
- The NPV of this type of solution declines, the more failures there are and hence, the more single-phase upgrades that are required;
- Based on the different model runs contained in this report, to make upgrading a single converter station the preferred option would require[16]:
  - 5 single-phase upgrades (Run1)
  - 6 single-phase upgrades (Run 2)
  - 5 single-phase upgrades (Run 3)
- The failure rates associated with these are:
  - 20% per annum (Run 1)
  - 33% per annum (Run 2)
  - 20% and 33% per annum (Run 3)
- However, removing the randomness of the failure rates, and looking at the specific results of different scenarios with the same failure rates indicates that at a 20% per annum increase would require 5 single-phase upgrades and two single converter station upgrades, and:
  - Despite the raw CAPEX being lower for upgrading a single converter station twice, the NPV over 20 years is similar to undertaking the 5 single-phase upgrades; and
  - This occurs because an upgrade of a single-phase “buys” around 9 years between upgrades in the earlier part of the evaluation period (when failures are growing off a low existing base), with this timing an important influence on NPV outcomes.
- The timing of the initial capex solution is 2027 under most scenarios. However, applying a lower threshold (than the 50 spares that we have assumed in our base modelling) would:
  - Lead to replacement occurring later in the modelling horizon (~2029); however
  - Lead to there being a greater risk of having to adopt an unplanned (instead of planned) replacement.
- Future capex (beyond the first upgrade) is significantly impacted by what future failure rates are assumed, which, at this stage is inherently uncertain. In saying this:
  - Whilst the model can give an idea of the timing and number, as time goes by, better empirical information will become available upon which to base decisions; and

16 It is important to note that this doesn’t account for the different failure curves that may have been ascribed to different capex solutions in those runs

  - A possible approach to quantifying likely failure rates of the future spares is to undertake accelerated life testing under high temperature, voltage, and environmental conditions. This is commonly used for IGBTs that are used in Electric Vehicles and other power electronic components.
- Murraylink's willingness to pay for spares from Cross Sound is likely to be in the order of $20k to $25k per IGBT, however, based on feedback from APA, this solution is considered to have a very low probability of success; and
- Upgrading both converter stations is a poor solution when measured in pure NPV terms. To breakeven with the best option (single-phase upgrade), it would require APA to sell spare IGBTs to Cross Sound at around the following price and volume levels:
  - 6000 spares @ ~$7k per spare; 3000 spares @ $14.1k per spare; 1500 spares @ $28.3k per spare[17].
  - At this stage we have no insight as to Cross Sounds' potential WTP, or just as importantly, the number of spares it might be willing to purchase at any price point.

17 This reflects the outputs of one model run, however the results for the other model runs relatively similar.