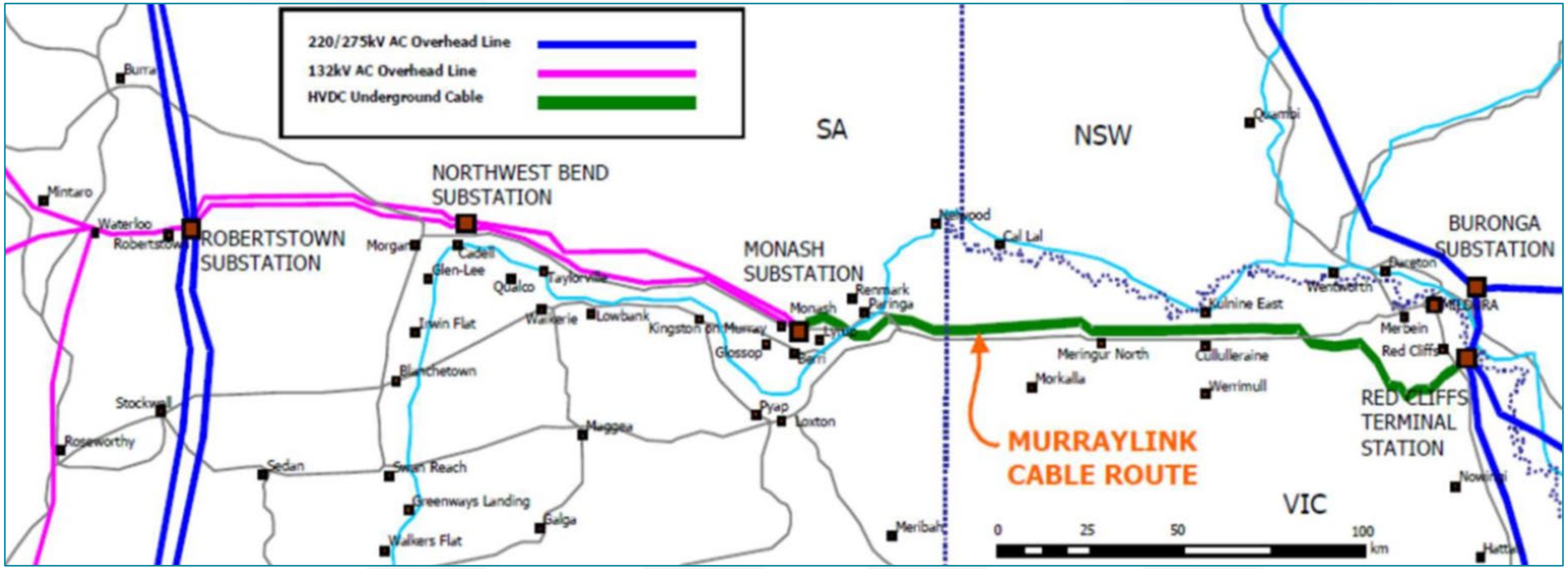
MURRAYLINK – IGBT ECONOMIC ANALYSIS

METHODOLOGY STAKEHOLDER FORUM



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Background

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Murraylink

Murraylink is a HVDC transmission line that connects the power transmission networks at Red Cliffs (in Victoria) and Berri (in South Australia) via HVDC cables and was constructed 20 years ago. The facility consists of the converter stations at Red Cliffs and Berri, the DC cables connecting the two converter stations and the AC cables connecting each converter station to the nearby AC substation (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.

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 the regulated Murraylink on behalf of Energy Infrastructure Investments (EII).

The key parameters of Murraylink:

- Bi-directional, with 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.

Overview of the Issue

Murraylink has an original design life of 40 years and become operational in 2002. Murraylink uses ABB's (now Hitachi) older Generation 2 Insulated Gate Bipolar Transistors (IGBTs)[1] 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 Generation 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 (115 in total).

The current failure rate is 24 per annum and the total available spares (Hitachi stock allocation + APA site stock) is estimated to support the current operation for another six years if failure rate remains constant.

Amplitude Consultants Pty Ltd (Amplitude) were engaged to undertake the necessary preliminary investigations into the 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 of upgrading to the newer modular multi-level converter (MMC) VSC technology.

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.

Modelling Options

VSC Technology (Existing)

BAU Option — Spare Gen 2 from Cross Sound

Key Threats:
- Unknown condition/likely failure rate from Cross Sound
- Likely to increased maintenance and downtime
- Will need existing cooling system upgrade to improve performance and improve IGBT life

Key Opportunities:
- No additional downtime for changeover
- Reuse existing control system
- Downtime for replacement moderate

Option 1 — One Phase Gen 3

Key Threats:
- Failure rate is unknown – model book ends
- Likely to increase maintenance and downtime
- Will need existing cooling system upgrade to improve performance and improve IGBT life

Key Opportunities:
- Generate spare Gen 2 IGBTs
- Reuse existing control system
- Downtime for replacement moderate

Option 2 — Two Phase Gen 3

Key Threats:
- Same as option 1

Key Opportunities:
- Generate additional spare Gen 2 IGBTs if failure rate high
- Differ capital expenditure
- Reuse existing control system
- Downtime for replacement moderate

MMC Technology (Current)

Option 3 — One Converter Station Upgraded

Key Threats:
- Requires major upgrade to infrastructure and control system at one converter station
- Long outage for upgrade
- Potentially the same impact on maintenance and downtime as option 1.

Key Opportunities:
- Generate significant additional spares
- Limit capital expenditure
- Marginal improvement in losses
- Existing cooling system adequate for MMC

Option 4 — Both Converter Stations

Key Threats:
- Long outage for upgrade.
- Largest capex option upfront
- Control and protection system will need upgrade.

Key Opportunities:
- Gen 2 spares could be sold
- Improvement in losses
- Existing cooling system adequate for MMC
- Reliability and future proofing improvement

Any other cases worth considering?

Options identified by Amplitude

	Existing Technology (VSC - PWM)		Current Technology (MMC)	
Option	Continuing using existing 2nd Gen IGBT	Replace with 3rd Gen IGBT	Replace one converter station with new tech MMC valves, generate spare 2nd Gen IGBTs for other converter station	Replace both converter stations with new tech MMC valves.
Infrastructure	Reuses most of the existing building infrastructure. Control system and protection system replaced in 2020	Reuses most of the existing building infrastructure. Control system and protection system replaced in 2020	Need to replace all phase, new clean room valve halls, possibly new control and protection systems with different suppliers for one converter station.	Need to replace all phase, new clean room valve halls, possibly new control and protection systems with different suppliers for both converter stations.
System losses	BAU (8.5% total)	BAU (8.5% total)	minor benefit of 1% improvement (7.5% total)	improvement of 2% (6.5% total)
Thermal Performance	BAU Derate at higher temps. Next RCP $3.21M to upgrade cooling systems (Currently rated @40 C, @45 C constrained to zero power flow)	BAU Derate at higher temps. Next RCP $3.21M to upgrade cooling systems (Currently rated @40 C, @45 C constrained to zero power flow)	MMC switching frequency less => exist cooling system more than adequate. Thermal performance limited by remaining converter station	Improved thermal performance due to lower switching frequency. Existing cooling system likely oversized. Potential for better performance at higher ambient temperature.
Service Life	Limited. Sustainable for 6-7 years. Will require one of the other options to be implemented. Possibility of purchasing spares from the Cross Sound DC link in the US to extend sustainable life. Operational life of IGBTs as spares unknown.	Replacement of one phase will free up sufficient IGBTs (900) to extend existing assets for 20 yrs (current failure rates optimistic outcome). Operational life of IGBTs as spares unknown and may need another phase conversion at a later date. Amplitude estimates are between 7 (2 years doubling) and 17 (10% per year) years.	Operational life of IGBTs as spares unknown, but does free up ~3000 spares sufficient to support the other converter station.	Operational life to at lease existing design life. Potential to extend further.
Suppliers	Single supplier	Single supplier	Multiple vendors available for MMC to provide competitive pressure. Potential interfacing issue with the different techs at each end.	Multiple vendors available for MMC to provide competitive pressure.
Complete Outage Requirements	BAU. Unscheduled outages are likely to occur more frequently. 7 hours mean time to repair.	10 weeks per phase	5 months (all phases) undertaken after 2025 when PEC commissioned.	5 months (all phases) undertaken after 2025 when PEC commissioned.
Capex (Concept level)	Sparing from Cross Sound unknown presently.	$17.8m per phase	$36.7m	$71.8m

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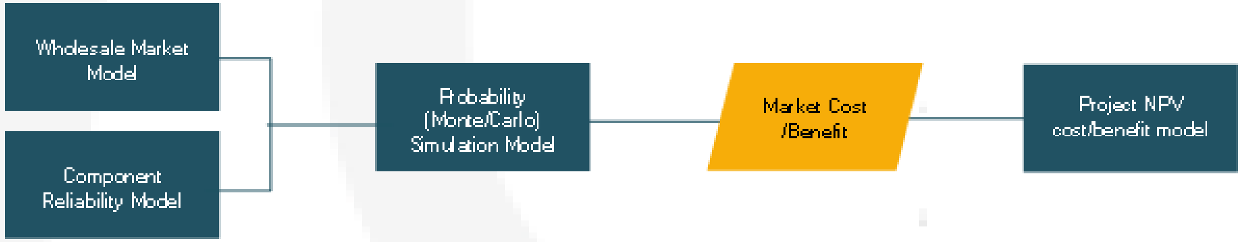
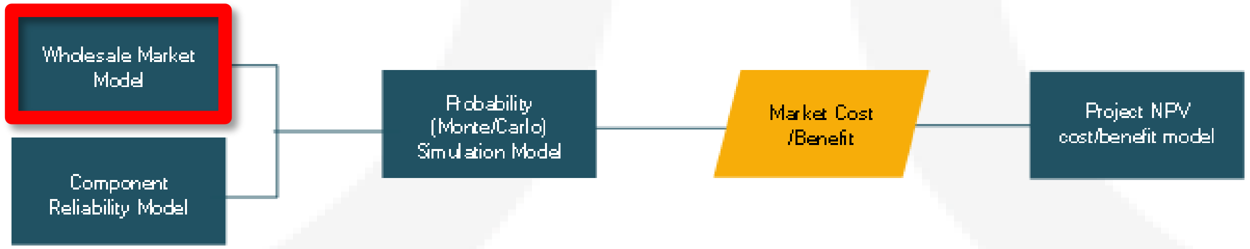
Proposed Methodology and Assumptions

Overview of the Methodology



- Plan to undertake a parallel modelling approach
- The wholesale market modelling will be used to develop “with” (reference case) or “without” (alternative) half hour NEM generation dispatch costs where the interval difference is the benefit or cost for that interval.
  - The advantage is the market modelling can be conducted independently of the timing of the outages or technology change overs.
- In parallel a System Reliability Model will be developed that include the potential reliability of the individual IGBTs (based on Amplitude’s report and public information) and how they are installed in the existing system.
  - This model will be used to determine the probability of unscheduled outages.
- The Reliability Simulation Model using Monte Carlo analysis the model will bring together the reliability and the market cost outcomes of scheduled and unscheduled outages using the older VSAC technologies over the modelling horizon.
- The final Project NPV cost/benefit model will take these results and identify the NPV of the different options consistent with RIT-T and other regulatory requirements.

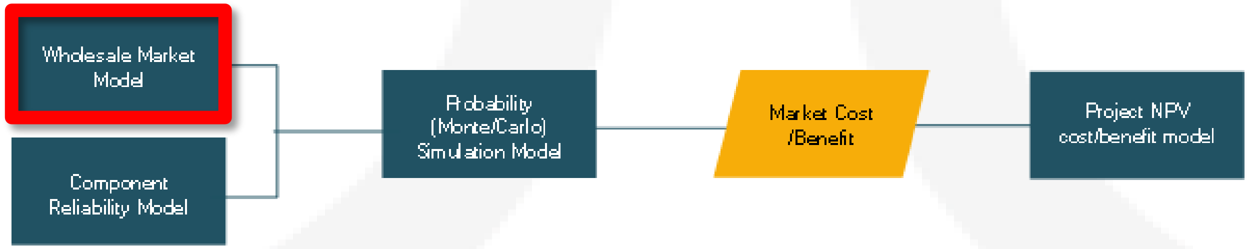
Overview of the Methodology - Wholesale Market Modelling



- Plan to undertake a parallel modelling approach
- Wholesale Market Model will be performed by using an existing calibrated PLEXOS model operated by EndGame.
  - The wholesale market modelling analysis will quantify the market benefit of different "Murraylink options" cases versus a reference case.
  - the exercise will focus on the dispatch cost-benefit of Murraylink options but use a fixed generation mix (for all Murraylink options and the counterfactual) based on draft 2022 ISPs new entrant and retirement forecast in the Step Change scenario.
    - New VRE driven by state schemes to 2030
    - Size of Murraylink (220MW) will have minimal impact on new entry schemes compared to state-based schemes
    - USE is likely to be minimal as any constraint will be for short periods.
  - Time horizon can run to 2042

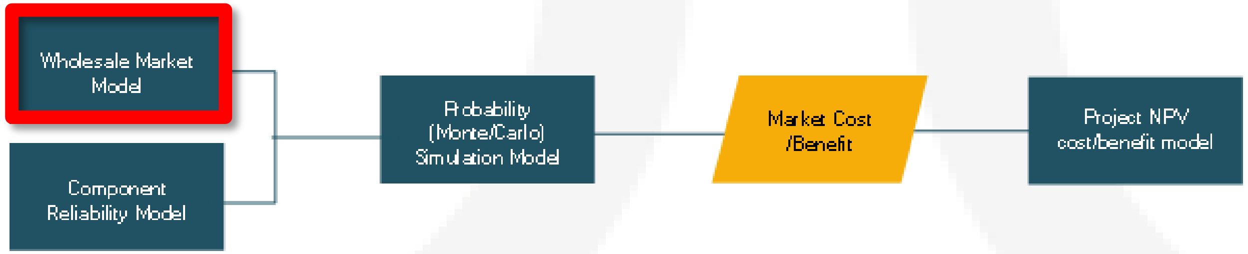
What is an acceptable time horizon for the wholesale market modelling?

Overview of the Methodology - Wholesale Market Modelling



- We are using only one scenario in the time and budget available for this assignment. The draft 2022 ISP Step Change Case has been selected based on stakeholder feedback suggesting the Step Change scenario is the most likely outcome.
- The following inputs from the selected ISP scenario will be 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.
- As we do not propose to model investment in the market modelling, the future generation and investment outlook will be based on the selected ISP scenario and used as exogenous inputs in the dispatch model. For generation this includes both the forecast entry and retirement.
- We will also incorporate future interconnector upgrades as per the draft 2022 ISP optimal development path DP2. Project EnergyConnect is operational in after 2025.

Overview of the Methodology – Wholesale Market Modelling

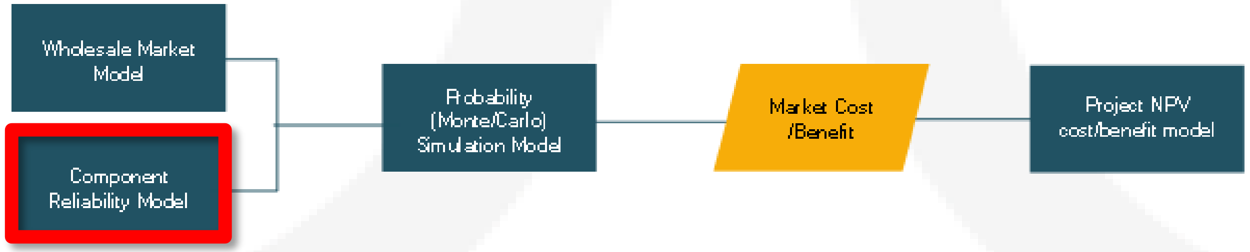


- The **reference case** for the wholesale modelling will be that the Murraylink ***is*** available as a business-as-usual case and based on AEMO's most recent draft 2022 ISP Step Change scenario.
- The **alternative case** for the wholesale modelling will be that the Murraylink ***is not*** available as a business-as-usual case and based on AEMO's most recent draft 2022 ISP Step Change scenario. 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.
- Each case will be modelled in PLEXOS to determine the total cost of generation dispatch cost (SRMC) for each half hour interval across the modelling timeframe.
- The differences between the reference case and the alternative case total dispatch cost for a half hour interval will identify the market cost for an outage during that half hour. The approach to estimating the probability of that outage occurring (and which alternative case it is aligned to) in each half hour is discussed in latter. The methodology will also apply for the scheduled outage.
- **Additional cases** will be run on the same basis and use the MMC technology efficiency benefits which present as lower losses in the Murraylink transmission.

The wholesale market modelling does not consider the market costs of not having Murraylink at all and only will be used to reference for small durations of outage for the purposes of assessing the impact of the different IGBT options.

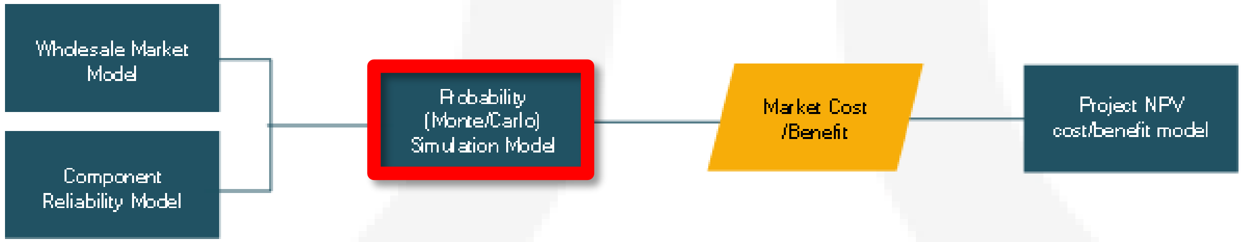
That is, it uses the ISP2022 draft step change scenario which includes Murraylink to determine the new build capacity which is fixed for this analysis.

Overview of the Methodology - System Reliability Model



- Reliability block diagram (RBD) will be developed to represent the physical configuration of the IGBTs, valves, and valve arms.
- This will allow the development of a reliability equation to be defined based on the potential IGBT failure rates. While these are somewhat unknown, Amplitude has identified some bookend for consideration as suitable assumptions.
  - Doubling of failures every 2 years
  - 10% increase per annum
- These options and others can be considered sensitivities on the Gen 3 option.

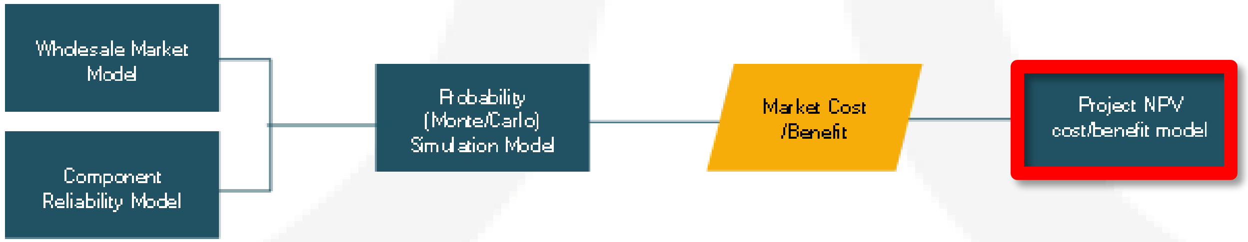
Overview of the Methodology – Probability Simulation Model



- The Probability Simulation Model will bring together the wholesale market model outputs (being the total dispatch costs under our ‘reference case’ and each of our ‘alternative cases’) and the reliability model outputs to generate the distribution of market costs that are attributable to unplanned outages and the possible reliability of extending service with the Gen 2 IGBTs.
- Across each simulated year, the model will randomly generate a failure of components based on the modelled reliabilities.
- Where a failure is being simulated for a particular time (e.g., a sequence of 1/2 hour intervals), the converter bay/s are assumed to be unavailable and are not returned to service based on the mean time to repair (MTTR).
- i.e if the MTTR = seven hours (AEMO assumption book)
  - then the cost for the outage is assumed to be the aggregate of the difference between each ½ hour interval total dispatch costs of the base case and the representative alternative case of Murraylink’s capacity being reduced due to the unscheduled maintenance.
- The monte carlo runs will run the process a significant number of times (e.g., 500) for each forecast year for the entirety of the evaluation period, to develop a distribution of costs that can be attributed to a P10,P50,P90 outcome. This will be done for the different probability of failure curves developed in the previous section (‘Component Reliability Model’).

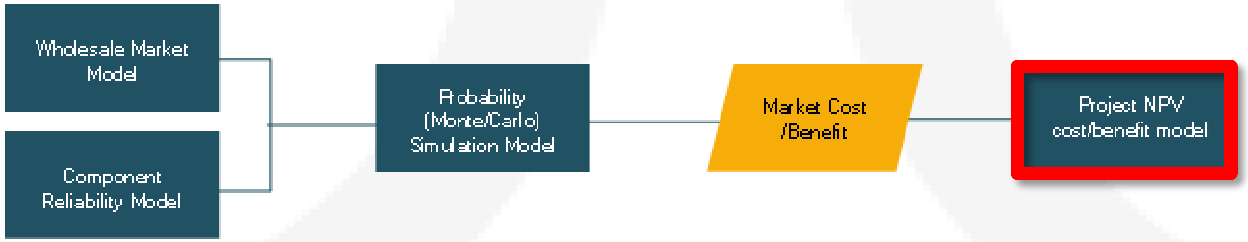
An opportunity exists to obtain spare Gen 2 IGBTs from Cross Sound DC link located in Connecticut and New York. Their condition is unknown. What might be the considerations and differences needed to covered if these were used for Murraylink?

Overview of the Methodology – Project NPV Cost/benefit Model



- The input of market costs/benefits will be incorporated into a sophisticated NPV model that will include annual economic costs and benefits, and an agreed WACC, to allow comparison of the options identified by Amplitude. We will ensure that the approach is consistent with the requirements of a RIT-T, and broader regulatory requirements.
- For options that increase the pool of spare GEN2s (i.e., single phase replacement with GEN3; purchasing from Cross Sound; single converter station replacement with MMC), we will include:
  - Capital costs of different options;
  - Cost to market caused by upfront downtime of Murraylink (70 days, 5 months depending on option)
    - NOTE: Due to planned nature of works, model selects timing to minimise market outcomes;
  - Benefit to market from efficiency improvements (only for single converter station replacement); and
  - Ongoing risk of GEN2 failures impacting Murraylink availability
    - Model will allow monte carlo simulation of different probability of failure curves (from 'Component Reliability Model') related to pool of GEN2 spares (which will differ in the model depending which option is being modelled), with this overlaid on Wholesale Market Modelling outcomes;

Overview of the Methodology – Project NPV Cost/benefit Model



- For options that <u>remove the GEN2 issue all together</u> (i.e., replacement of both converter stations with MMC technology)
  - Capital costs of different options;
  - Benefit generated from GEN2 spares created in next best use (e.g., sell to Cross Sound)
  - Cost to market caused by upfront downtime of Murraylink (5 months); and
  - Benefit to market of subsequent efficiency improvements in Murraylink.

Overview of the Methodology – Project NPV Cost/benefit Model

- Beyond the monte carlo simulation modelling, other sensitivities will include:
  - Changed capital costs of different options;
    - Ranges supported by conventional engineering ranges, given Amplitude's basis for original cost
      - AACE Class 4 or Class 5 estimates
    - Breakeven capital costs (i.e., what would costs need for NPV to just breakeven)
  - Changed upfront outage periods (e.g., sensitivity around the 70 days/5 month outage periods);
  - Changed WACC
  - Changed value of spares in next best use.

	Primary Characteristic	*Secondary Characteristic*			
ESTIMATE CLASS	**LEVEL OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]	**PREPARATION EFFORT** Typical degree of effort relative to least cost index of 1 [b]
Class 5	0% to 2%	Concept Screening	Capacity Factored, Parametric Models, Judgment, or Analogy	L: -20% to -50% H: +30% to +100%	1
Class 4	1% to 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to +50%	2 to 4
Class 3	10% to 40%	Budget, Authorization, or Control	Semi-Detailed Unit Costs with Assembly Level Line Items	L: -10% to -20% H: +10% to +30%	3 to 10
Class 2	30% to 70%	Control or Bid/ Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: -5% to -15% H: +5% to +20%	4 to 20
Class 1	50% to 100%	Check Estimate or Bid/Tender	Detailed Unit Cost with Detailed Take-Off	L: -3% to -10% H: +3% to +15%	5 to 100

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