Memorandum

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Subject	PM-SH Underground Cable Option	Project Name	North West Transmission Development
Document Number	IS370322-SO22-EE-MEM-0002		
Attention	Damian Vermey	Project No.	IS360322
From	Willem Visagie		
Date	8 October 2021		
Copies to	Sarel Marais		
Revision	0		

1. Background

As part of the North West Transmission Development in Tasmania to accommodate the connection of the 1.5GW Marinus Link interconnector, TasNetworks is looking to replace the existing PM-SH single circuit 220kV Transmission line with a new 220kV double circuit twin conductor (sulphur) transmission line. The construction of this line will require widening of the existing easement by at least 20m. The line runs through substantial areas of agricultural farmland and some stakeholders have queried the use of the traditional overhead transmission lines (OHL) as opposed to the possibility of Underground (UG) cable. TasNetworks has informed the relevant stakeholders that this could be between 6-10 times more expensive than traditional transmission line construction. The Tasmanian Minister of Energy has requested TasNetworks to develop an analysis that would substantiate this claim on a more empirical basis.

This memo includes concept level design and costing for the equivalent underground cable option in 220kV AC, for the 80km transmission line between Palmerston and Sheffield (PM-SH). The memo also includes an Appendix (H) which comments on the cost of and equivalent High Voltage Direct Current (HVDC) solution. The memorandum has not considered a hybrid overhead line and underground cable solution, but it is noted that such an arrangement would introduce increase in cost and high levels of technical complexity.

> *Disclaimer: The pricing in this memo and its supplementary files, was compiled for this comparison to illustrate primarily the quantum of the cost difference between the use of Overhead Line and Underground Cable in the high voltage power transmission context. As such it should not be used to inform any budget setting or commercial commitments related to the project. The concept level design was conducted specifically for the PM-SH link and no expansive system studies was conducted.*

2. Cable Sizing

For this circuit, the Tasmanian transmission system requirements specify a cable system capable of transmitting 900MVA at 220kV under N-1 conditions (single contingency outage of one circuit). This means, should one circuit trip the remaining circuits shall be adequately sized to carry the full 900MVA load. In the context of this memorandum, it results in the specification of a 3-circuit arrangement for the copper option and a 4-circuit arrangement for the aluminum option.

A preliminary XLPE land cable was selected from the ABB 'XLPE Land Cable Systems User's Guide' catalogue (Rev 5) with the following properties:

- Single Core
- Nominal Voltage: 220kV
- 185mm^2 screen
- Conductor Cross Section: 2000mm^2

Consideration was given to both Copper and Aluminium conductor cables, and both will be discussed below.

All circuits were assumed to be buried in Flat Formation and Cross-Bonded. The cables were analysed at a 90^{o}C maximum temperature rating.

2.1 Cable Model

A cable model was generated in CYMCAP 7.3 Rev 1 analysis software, based on the information found in Table 28 of the ABB Catalogue – reproduced as Figure 1 below.

The same model was used for both the Aluminium and Copper cables with the only variance being the conductor material.

TECHNICAL DATA FOR XLPE LAND CABLE SYSTEMS

Table 28

Cross-section of conductor	Diameter of conductor	Insulation thickness	Diameter over insulation	Cross-section of screen	Outer diameter of cable	Cable weight (Al-conductor)	Cable weight (Cu-conductor)	Capacitance	Charging current per phase at 50 Hz	Inductance ∴	Inductance •••	Surge impedance
mm²	mm	mm	mm	mm²	mm	kg/m	kg/m	μF/km	A/km	mH/km	mH/km	Ω
Single-core cables, nominal voltage 220 kV (U_m = 245 kV)												
500	26.2	24.0	77.6	185	94.0	8.3	11.4	0.14	5.8	0.44	0.60	40.2
630	29.8	23.0	79.2	185	95.8	8.8	12.7	0.16	6.4	0.42	0.58	36.4
800	33.7	23.0	83.1	185	100.3	9.7	14.7	0.17	6.9	0.41	0.56	33.8
1000	37.9	23.0	87.3	185	104.9	10.7	16.9	0.19	7.4	0.39	0.54	31.3
1200	42.8	23.0	93.8	185	111.8	12.0	19.4	0.21	8.2	0.38	0.52	28.8
1400	46.4	23.0	97.4	185	115.6	12.9	21.6	0.22	8.7	0.37	0.51	27.3
1600	49.8	23.0	100.8	185	119.2	13.8	23.7	0.23	9.1	0.36	0.50	26.0
2000	54.4	23.0	105.4	185	124.2	15.4	27.8	0.24	9.7	0.35	0.49	24.5
2500	62.0	23.0	113.0	185	132.4	17.6	33.1	0.27	10.6	0.34	0.47	22.3

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Figure 1: ABB Catalogue Table 28 Excerpt

The following, Figure 2 shows the construction of the proposed cable.

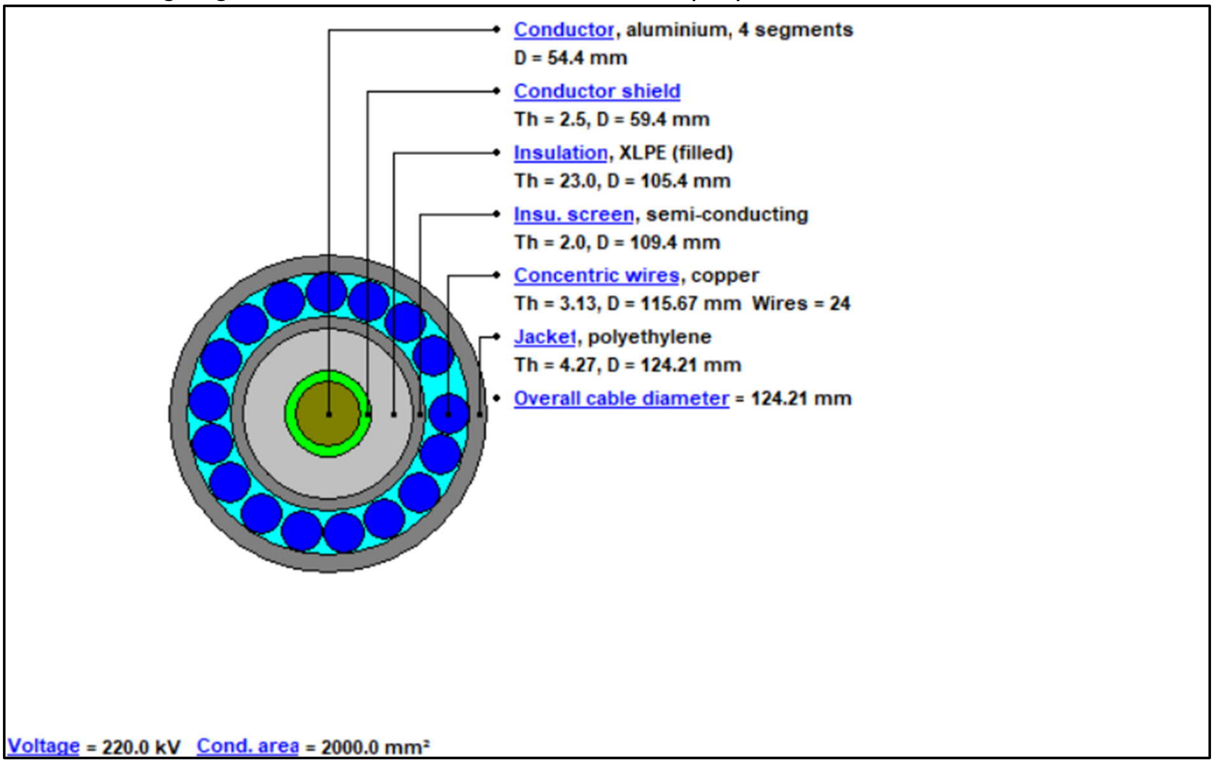


Figure 2: CYMCAP Aluminium cable model.

2.2 Cable Model Calibration

The cable models were calibrated against the ratings and parameters provided in the ABB catalogue (See Appendix A and B). Results within a 5% margin of error were considered viable. This is summarised in Table 2-1

Table 2-1: CYMCAP Model ABB Cable Calibration Results

Cable Selected	ABB Catalogue Current Rating	CYMCAP Model Current Rating	Margin of Error (%)	Margin of Error within 5%?
ALUMINIUM 2000mm^2, 110-500kV Rated Voltage, Cross-bonded, 90°C Temp Rating, Flat Formation	1275	1326	4	Yes
COPPER 2000mm^2, 110-500kV Rated Voltage, Cross-bonded, 90°C Temp Rating, Flat Formation	1705	1710	0.3	Yes

Both cable models were considered viable.

See Appendix C for CYMCAP model parameter and output screenshots.

2.3 Cable Rating

CYMCAP was used to model the chosen Aluminium and Copper conductors in typical trench/corridor configurations to generate their expected installed ratings, in both normal operation and N-1 conditions. Results were compared against the desired 900MVA output.

The following assumptions were used for each test:

- Cables are buried in ducts. Modelled from Vinidex Catalogue - Electrical and Comms Brochure "Heavy Duty Electrical Orange" PVC conduit. 200mm ID, 225.6mm Mean OD. 6m lengths.[1]
- 39% conduit fill factor
- 150mm spacing between conduits.
- Native Soil Thermal Resistivity = 2.0 ^{o}C.m/W
- Backfill Thermal Resistivity = 1.0 ^{o}C.m/W

A typical trench cross-section design was used for both conductors, as is shown in Appendix D and E.

However, the number of circuits and the configuration of the trenches within the overall working-corridor differs for each conductor type, and are discussed below:

2.3.1 Aluminium

To achieve the required connection rating, four circuits are required across four trenches arranged as per Typical Cross Section layout in Appendix D.

2.3.2 Copper

To achieve the required connection rating three circuits are required across three trenches equally spaced with 2000mm between them (4900mm between centres) per Typical Cross Section layout in Appendix E. The resultant connection rating calculations are shown in Table 2-2

Table 2-2: CYMCAP cable rating results

Test Condition	Voltage [kV]	Power transfer [MVA] (N)_Rating	Power transfer [MVA] (N- 1)_Rating	>900MVA?
4 x 2000mm^2 ALUMINIUM Circuits buried and arranged as per Typical Cross Section Working Corridor as per IS360300_VIC_HVDC_COST_INFO_003.	220	1449.14	1097.43	Yes
3 x 220kV 2000mm^2 COPPER Circuits buried and arranged as per IS360300 Typical Trench Construction _VIC_HVDC_COST_INFO_003, each trench equally spaced with a 2000mm gap in-between.	220	1384.36	932.43	Yes

See Appendix F for Aluminium conductor CYMCAP model parameters and results.

See Appendix G for Copper CYMCAP model parameters and results.

[1] It is assumed that Horizontal Directional Drilling (HDD) would be required along the route to cross key existing assets. As the cables will be installed in ducts through these bores, it represents the worst case thermally for the cable, hence the modelling as a ducted system. It is important to note that the capital estimate is based on a direct buried solution with an allowance for 55 HDD locations.

2.4 Cable Capacitance and Reactive Power Compensation

The capacitance of large high voltage cables is high in comparison to equivalent capacity overhead lines, and the underground cable circuits may need to be afforded with reactive compensation in the form of shunt reactors. The following Table outlines the total capacitance associated with the three circuit (Copper) 220kV underground cable link, which indicates that each cable circuit would supply approximately 400MVar of reactive power onto the transmission system.

Whilst reactive power can be useful in the context of operating a transmission system, this level of reactive power is expected to require compensation at each end of the cable circuits and/or along the length of the 220kV cable link. The exact quantum and ultimate arrangement require a comprehensive set of studies to be undertaken, but a conservative estimate of the compensation requirements is considered to involve the installation of 200MVAr shunt reactors at each end of each cable circuit (i.e. 6 x 200MVAr shunt reactors). Table 2-3 below shows the calculation of the capacitive contribution by the cable circuits and conversely the amount of reactive compensation required for a net zero effect for this link. It is important to note that the introduction of these shunt reactors will greatly increase the substation footprints on either end, it will also introduce significant audible noise at the substations.

Table 2-3: Cable installation capacitive contribution: 3 x 220kV, 2000mm^2 Cable Circuits

Item	Value	Units
Capacitance/m	0.34	micro-farads/m
Total length	80	km
Cable capacitance	27.2	micro-farads/m
Reactance	117	Ohms
Line Voltage	220	kV
Phase Voltage	127	kV
Amps	1085	Amps
Reactive power/cable	138	MVAr
Reactive power/circuit	414	MVAr
Number of circuits	3	
Total reactive power	1241	MVAr

2.5 Discussion

The models for each conductor configuration meet the 900MVA requirement in N-1 conditions - the Aluminium by 21.94% and the Copper by 3.60%.[2]

Copper cable is more expensive per unit length, but the Copper option requires one less circuit than the equivalent Aluminium arrangement, reducing the length of cable, the amount of trenching and brings a reduction in substation complexity. Most notably the Copper option has ≈240 less cable joints at a total of approximately 720 as supposed to a total of 960 (aluminium), therefore as the jointing activity will drive project critical path using Aluminum will increase the total construction time significantly.

[2] The use of larger conductors was also investigated, it has been confirmed that the use of 3000mm^2 copper cables will not produce a design where only two circuits (single circuit under N-1) is viable. See Appendix I

Optimisation of the Aluminium cable option could lead to the use of a smaller conductor which, due to longer drum lengths, could lead to a slight reduction in the number of additional joints, but this constraint remains material in the comparison.

3. Basis of Pricing

3.1 Summary of Order of Magnitude Pricing

The following table indicates the summary of the order of magnitude pricing for the works as described in this report. A breakdown of the basis for these numbers follows in this section.

Table 3-1 Summary of Order of Magnitude Pricing (excluding client costs)

Description	Unit	Quantity	Rate ($)	Total ($) **
Direct Costs (A)	Kilometre	78.8	$10,970,000	$ 863,727,716
Indirect Costs (B)	Kilometre	78.8	$ 2,550,000	$ 200,815,682
Total Buy Costs (C) = (A) + (B)	Kilometre	78.8	$13,510,000	$1,064,543,398

*Client costs are not included in Table 3-1, they are however indicated in the detailed pricing sheet and should be confirmed by TasNetworks. No allowance has been made for any client detailed electrical design, land acquisitions, easements, or other compensation for landowners or revegetation of land included. It being understood these D&A costs would be considered outside the above costs but likely would be similar for Overhead Line vs Underground Cabling but would need to be investigated further.

** Figures indicated are rounded

3.2 Jacobs Benchmarking Database

The cost estimate for the capital component of the works was determined through the utilisation of the Jacobs Benchmark Estimating Database (“Jacobs Benchmark Database”).

The Jacobs Benchmark Database utilised for this assessment was calibrated using characteristic site and characteristic project specific information (people/ plant/ equipment / materials / and work-methods) to ensure a reasonable and characteristic site-specific outcome for this estimate

The Jacobs Benchmark Database includes:

- Commercial-in-Confidence people /plant/ equipment / material rates (directly from plant-hire companies, and indirectly from Tier 1/ Tier 2 contractor pricing on other current projects and material suppliers);
- Commercial-in-Confidence materials rates (directly from suppliers and indirectly from Tier 1/ Tier 2 contractor pricing on other current projects);
- Commercial-in-Confidence sub-contractor rates (directly from subcontractors and indirectly from Tier 1/ Tier 2 contractor pricing on other current projects); and
- Jacobs benchmarking rates (Jacobs benchmarking rates being a Commercial-in-Confidence amalgamation of: first principles estimating for owners/ clients to determine capital and

operational costs; first principles estimating for tendering purposes for contractors; market quotes from multiple contractors' programs of works; actual costs and productivities (contractor / subcontractor); actual costs and productivities (client / owner side); and actual costs and productivities (suppliers / contractors / others).

- Pertinent projects include: power lines through mountainous regions in NSW, VIC, and similar in TAS.

3.3 Methodology

In order to determine the capital cost estimate an approach involving the following the key activities was undertaken:

- Top-down cost estimate – based on previous similar works delivered by other authorities.
- Characteristic first principles estimate based on the people, plant, equipment, subcontractors and materials for delivery of the project in this characteristic segment for the 80km line between Palmerston and Sheffield (PM-SH); and
- Characteristic allowances based on benchmarking for client costs, design costs, contingency allowance and escalation forecasts and other indirect and client cost allowances noted within the estimate.

3.4 Accuracy of the Cost Estimate

Jacobs's assessment of the accuracy of costing as per AACE Cost Estimate Classification System is that it should be considered as Class 5 for the works, as described in Table3-2, it being understood that there are elements of:

- Strategic design; and
- Jacobs Benchmarking database costing;
- Known market conditions for similar.

There are also multiple elements which are subject to further investigations.

Table 3-2: Accuracy of Estimate per Class

Estimate class	Estimate Name	Purpose	Project definition level	Estimate Methodology	EXPECTED ACCURACY RANGE
			Level of Engineering Design	Typical estimating method	Typical variation in low and high ranges at a 90% confidence interval
Class 5	Screening / Order of magnitude	Screening or feasibility	0% to 2%	Capacity orientated, judgement, guide all in costs from recent projects, and basic quantities	Low: -20% to -50% High: -30% to +100%
Class 4	Concept Design	Concept study or feasibility	1% to 15%	Basic quantities, recent rates, factored equipment costs, semi-detailed	-40% to +75%
Class 3	Functional Design Budget Estimate / Preliminary	Budget, authorization, or control	10% to 40%	Semi-detailed take-off with semi-detailed unit costs	-20% to +40%
Class 2	Detailed Design		30% to 70%		-10% to +20%

Estimate class	Estimate Name	Purpose	Project definition level Level of Engineering Design	Estimate Methodology Typical estimating method	EXPECTED ACCURACY RANGE Typical variation in low and high ranges at a 90% confidence interval
	Control Estimate / Pre-Tender / Substantive	Control or bid/tender		Detailed take-off with detailed unit costs	
Class 1	Tender Evaluation Definitive / Check Estimate / Bid / Tender	Check estimate or bid/tender	50% to 100%	Detailed take-off with detailed unit costs	Low: -3% to -10% High: +3% to +15%

3.5 Functional Make-Up of the Estimate

The development of the estimate has been based on: direct and indirect costs with consideration of inherent, contingent, and escalation factors. This is indicated diagrammatically in Figure 3 Make-up of the Estimate

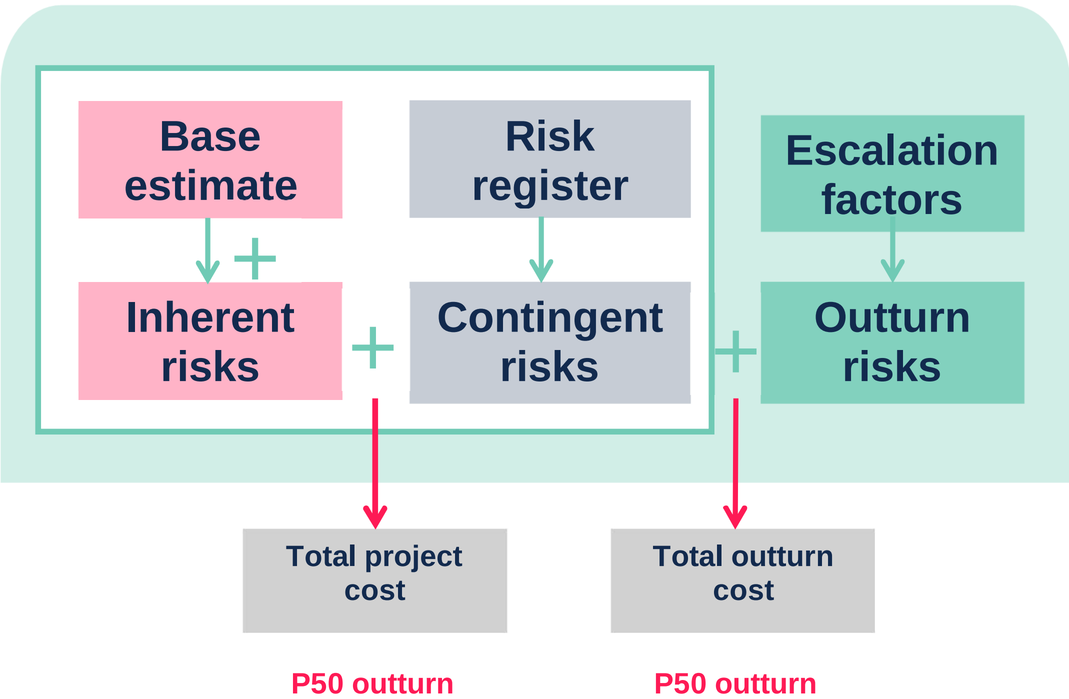


Figure 3 Make-up of the Estimate

3.6 Risk Ranging

Risk ranging for a project at this stage of development based on Best Practicing Estimating would be commensurate to a strategic estimate until further design and investigation works are undertaken.

Table 3-3 Indicative Risk-ranging

PHASE	P50 Risk equivalent

Strategic estimate	10% to 30%
Concept estimate	5% to 20%
Detailed estimate	3% to 10%
Tender estimate	2% to 5%

3.7 Quantification

Quantification of the works has been based on a combination of characteristic designs and relevant aerial imagery. There is inherent quantification variance due to the uncertainty of the quantification at the current stage of the estimate.

3.8 Schedule

The works delivery schedule has been estimated on the basis of an approximate sixty (60) month duration on-site (excluding design, procurement, and lead-in activities) – the key drivers for this duration are:

- Limitations in the number of skilled cable jointing crews; and
- Limitations in the number of directional drilling crews, subject to the construction methods adopted in the design.

The cable jointing limitations result in slowing down the overall production of other crews with a start-stop delivery and extended overall project duration.

3.9 Direct Costs ("Direct Costs")

The Direct Costs were determined based on the following key principles:

- Site establishment: including the following areas:
    - Site survey and investigation for delivery contractor developed design;
    - Establishment of site sheds and maintenance thereof for the contractors delivery of the works;
    - Establishment of the contractors' key resources for the site works.

These site establishment costs have been based on the works being delivered as an overall programme of works by a single Contractor for the complete portion between Palmerston and Sheffield (PM-SH).

- Site establishment / management costs: based on one (1) x primary site office including:
    - Site investigations and survey;
    - Design finalization and shop drawings;
    - Pre-mobilization and training
    - Mobilization of the site sheds, personnel, and other equipment to perform the works;
    - Site management team; and
    - Site running costs.
- Clearing / grubbing works: establishment of erosion and sediment controls, including:
    - Sediment fences;

  - Enviro or shaker grids at one (1) per Kilometre;
  - Civil works crew: dozer, graders, trucks hauling offsite and dust suppression;
  - Vegetation / mulching crew: allowance to mulch and cart offsite.

- Roadworks: allowance for the following:
  - Clearing / grubbing;
  - Minor creek / valley crossings at one (1) per Kilometre;
  - Enviro or shaker grids at one (1) per Kilometre;
  - Imported materials, placement and compaction including testing and allowance for extra materials with inherent double-handling of the works to remove and/or top-up subject to the requirements for the roadway; and
  - Directional drilling under road/rail/other impediments.

  Maintenance and removal of the works within the establishment allowances is included as indirect costs.

- Trenching & backfilling works, for the primary trenches and cable joint bays: allowance for the following:
  - Trenching crew performing excavation, side cast , and stockpile control activities;
  - Specialist backfill crew performing backfilling operations with suitable imported materials;
  - Backfill from side-cast crew utilising site-won materials; and
  - Seeding/make good crew performing final finishing works.

- Cable installation works: allowance for the following:
  - Ferrying, laying the cable in a direct-bury manner in open trenches and in ducts for all horizontally drilled sections;
  - Jointing crew following up;
  - Termination crew following up.

- Materials supply works: allowance for the following:
  - Supply from overseas for the primary and secondary materials
  - Supply for the capital new builds;
  - Haulage and ferrying to the site.

- Bonding and earthing requirements: these have been based on Jacobs Benchmarking Database costs for similar installations based on people/plant/equipment/productions achieved in-field;

- Switching stations including the reactive compensation stations envisaged: these have been based on Jacobs Benchmarking Database for similar.

- Testing / Commissioning:
  - These have been based on the contractor performing their own site acceptance testing utilizing a third-party inspector with percentage allowances based on Jacobs Benchmarking Database for similar

  - Handover and defects period, maintenance: these have been based on percentage allowances based on Jacobs Benchmarking Database for similar

  Interfaces at substations and client acceptance testing have been allowed for within client costs.

3.10 Indirect Costs ("Indirect Costs")

The following allowances have been made for the delivery Contractors' Indirect Costs within estimate:

- Design: no allowance other than that included in site establishment, viz: finalization of survey and investigation activities. It being understood the preliminary design is considered undertaken by the client prior to the delivery Contractor taking over the works.

- Preliminaries: these have been allowed at 2.5% at present and included to cover areas such as the delivery Contractors' allowances not directly covered elsewhere within the pricing, including: insurances, fly-in/fly-out, demobilization and maintenance of the overall site;

- Project Management: these have been determined to be 2% and are based on an approximate sixty (60) month delivery timeframe at present and included to cover the project management team who are not necessarily the site delivery team (included in the direct costs), including: offsite management team, scheduling team, and other support functions involved in the project but not necessarily on the site. These corporate allowances are similar to current Tier 1 and Tier 2 delivery contractors which vary between 2-5%.

- Contractor's Risk: these have been allowed at 10% at present to cover any risks apportioned to the Contractor side which they have not made within their direct costs;

- Contractor's Overhead and Profit: these have been allowed at 8% at present assuming a typical delivery Contractor overhead and profit for these types of works. These usually vary between 8% and 15% depending on the current market conditions and the size of the Contract works package.

3.11 Risk Assessment

A risk assessment needs to be discussed and developed with the project team. It is expected to be between 10-30% for a project at this level of development at P50 level or equivalent.

3.12 Escalation

Escalation needs to be discussed and developed with the project team. It is expected to be 4% per annum for a project of this nature at this point in time with the highest risk on labour and imported material components due to shortages in supply chains and labour. The project estimate makes no allowance for escalation in the Direct Costs save for the cable which has an inherent escalation of 7.5% added to the base price as advised by the supplier based on current market fluctuations.

3.13 Client Costs ("TasNetworks")

The following are recommended to be included (but does not feature in the cost comparison) as a percentage of the subtotal of direct and indirect contractor's cost to cover TasNetworks' costs based on similar projects delivered by utility asset owners / operators.

- Client Costs: 8%
- Client Overhead: 5%
- Client Contingency: 30% at this point in the project delivery cycle given the uncertainty in the project development
- Escalation: 4% based on the current market expectations.

3.14 Specific Exclusions

The following are specific exclusions within the estimate:

- No allowance is included in the estimate for GST.

- Pandemic or Covid 19 related costs
- No allowance for soft/sandy soils, trench shoring (collapse prevention) or dewatering

3.15 Specific Assumptions and Risks

The following are specific assumptions within the estimate:

- Allowance for clearing limited to eucalypt forest or similar
- Assumed that trenches will be dug with collected spoil to one side of trench
- No allowance for any clients detailed electrical design, land acquisitions, easements, or other compensation for landowners or revegetation of land included. It being understood these D&A costs would be considered outside these and likely would be similar for Overhead Line (OHL) vs Underground Cabling but would need to be investigated further.
- Rates as of September 2021. No allowance made for escalation beyond this point within the Direct Costs except for the allowance related to the cable cost.
- Total cable corridor length 78.8km based on similar routing to the OHL alternative.
- Nominal rock allowances as per Basis of Pricing
- Unfettered access permitted

The following are specific risks likely to impact the estimate:

- Undesirable outcomes from geotechnical conditions identified by contractor other than above noted.
- Risk of excessive disposal costs, we have assumed a low volumes of contamination disposal (not entire volume)
- Sizable commercial claims from Contractor, variation claims, or other items which have not been factored in specifically, but which need to be considered in the detailed contingent risk assessment. Trenched projects bring greater uncertainty than Overhead Line projects.
- Latent Conditions uncovered during excavations - rock / contamination or heritage.

4. Summary

A wide range of cable options and sizes (2000mm^2 – 3000mm^2) have been considered to ensure that, at concept level, the approach is logically coherent and the costing relevant, please see section 2 and Appendix I of this document. The focus of the under-ground vs overhead line transmission comparison was to provide a cost-based order of magnitude comparison.

Table 4.1 shows the HVAC Cable option to be more than seven (7) times more expensive than the overhead transmission line option. Though not a focus of this memo, it is important to note that due to the labor-intensive nature of HV cable jointing it is estimated that the HVAC cable option could take between 2.5 to 3 times longer to construct compared to the baseline (OHL) option. This option also poses a much greater risk of schedule blowout due to its greater reliance on favorable weather and favorable geotechnical conditions to achieve expected production rates.

The HVDC Cable option is almost ten (10) times more expensive than the baseline option, this is mainly due to the requirement of costly converter stations on either end of the connection to integrate with the AC distribution system.

Table 4.1: Option price comparison.

Palmerston to Sheffield transmission options cost comparison summary			
Option	Notes	Total Cost $'M	Factor of Baseline
Overhead Line Cost (Baseline)	220kV Double Circuit, twin conductor. Including contractor direct and indirect costs. Excluding cost for removal of existing 220kV single circuit line.	$ 144.5	1.0
HVAC Buried Cable Option	Based on 3 circuit (copper) 220kV design. Including reactive compensation.	$ 1,064.5	7.37
HVDC Cable Option	Based on 2 circuits # 320kV with a single pair of converter stations. Prices factored to suit 900MVA continuous operation.	$ 1,411.0	9.77

All pricing excludes client cost

APPENDIX A

ABB Catalogue 'XLPE Land Cable Systems' excerpt – pg. 10 Table 3 & 4

CURRENT RATING FOR XLPE LAND CABLE SYSTEMS

Table 3

Rated voltage 110-500 kV, aluminium conductor – 95 mm² screen																
Cross section con-ductor	Cables in Ground								Cables in Air							
	Flat formation ●●●				Trefoil formation				Flat formation ●●●				Trefoil formation			
	Cross bonded		Both ends		Cross bonded		Both ends		Cross bonded		Both ends		Cross bonded		Both ends	
mm²	65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C
300	415	495	365	445	395	475	385	460	465	625	415	565	410	550	400	540
400	470	565	410	500	450	540	435	525	535	715	470	640	475	640	460	625
500	540	645	455	555	515	620	490	595	620	835	530	725	550	745	530	720
630	620	740	500	610	590	710	550	670	730	975	595	820	640	865	605	830
800	700	845	540	665	670	805	610	745	840	1130	660	910	735	995	685	940
1000	785	950	585	720	745	900	670	820	960	1295	720	1005	830	1135	765	1055
1200	850	1025	610	755	805	970	710	870	1055	1420	765	1070	905	1235	825	1140
1400	910	1100	635	785	855	1040	745	915	1140	1545	805	1125	975	1335	880	1220
1600	960	1165	655	815	900	1095	775	955	1220	1650	835	1170	1035	1420	925	1285
2000	1050	1275	685	855	975	1190	820	1015	1355	1840	885	1250	1140	1570	1000	1395

Table 4

Rated voltage 110-500 kV, copper conductor – 95 mm² screen									Segmental conductor for 1200 mm² or higher							
Cross section con-ductor	Cables in Ground								Cables in Air							
	Flat formation ●●●				Trefoil formation				Flat formation ●●●				Trefoil formation			
	Cross bonded		Both ends		Cross bonded		Both ends		Cross bonded		Both ends		Cross bonded		Both ends	
mm²	65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C
300	530	640	440	535	505	610	480	580	600	805	500	685	525	710	500	685
400	600	720	485	595	575	690	540	650	680	915	565	775	605	820	575	785
500	685	825	530	650	655	785	600	730	790	1060	625	860	695	945	650	895
630	780	940	570	705	740	890	660	810	915	1235	685	950	800	1085	735	1010
800	870	1055	610	755	825	995	720	885	1045	1415	745	1040	905	1235	815	1130
1000	960	1165	645	800	900	1095	770	950	1175	1590	800	1125	1005	1380	895	1245
1200	1115	1345	690	860	1060	1280	855	1055	1395	1880	880	1240	1210	1650	1025	1425
1400	1205	1455	715	890	1145	1385	895	1110	1530	2065	920	1300	1320	1800	1090	1525
1600	1280	1550	735	920	1215	1470	930	1155	1665	2235	980	1355	1420	1940	1150	1615
2000	1410	1705	765	955	1320	1605	980	1220	1845	2500	1000	1425	1565	2145	1230	1740
2500	1540	1875	795	1000	1445	1755	1025	1285	2095	2845	1065	1515	1750	2410	1330	1890

10 XLPE Land Cable Systems | ABB

APPENDIX B

ABB Catalogue Current Rating Calibration Conditions

Continuous current ratings for single-core cables are given in tables 1-4. The continuous current ratings are calculated according to IEC 60287 series of standards and with the following conditions:

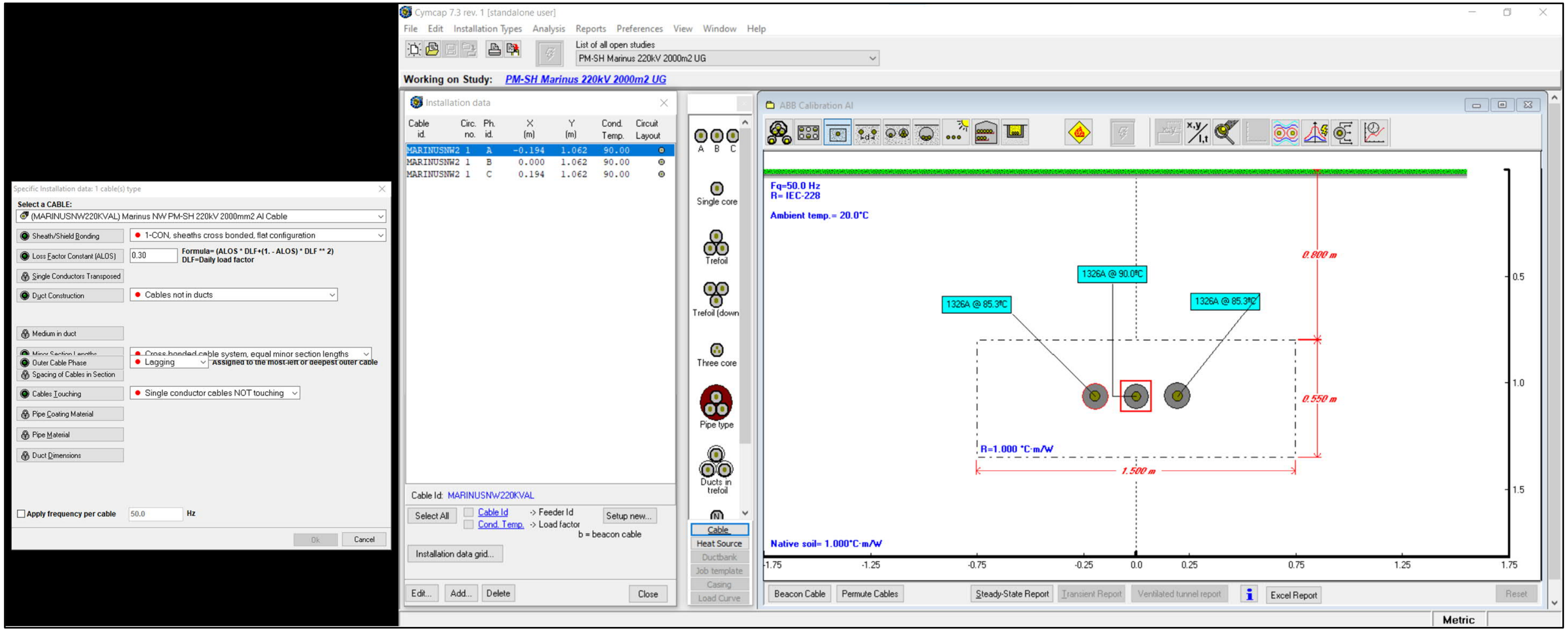
– One three-phase group of single-core cables	
– Ground temperature	20°C
– Ambient air temperature	35°C
– Laying depth L	1.0 m
– Distance “s” between cable axes laid in flat formation	70 mm + D_e
– Ground thermal resistivity	1.0 Km/W

Rating factors for single-core cables are given in Tables 5-13.

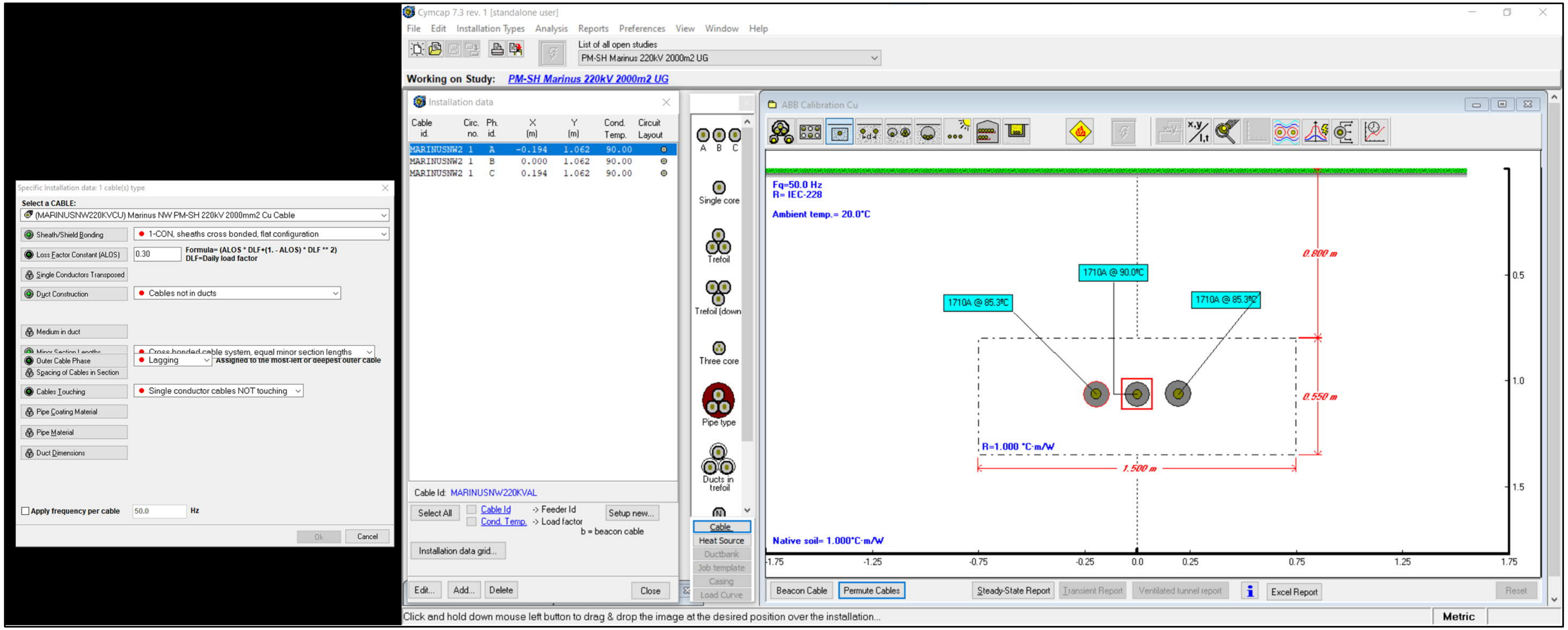
Note: The 1m depth was used to calibrate the cable models generated in CYMCAP to confirm accuracy of said models to the tech sheets provided. The actual system modelling was done at a laying depth of 1.35m (surface to center of cable) as per the cross-section geometry provided in Appendix D.

APPENDIX C

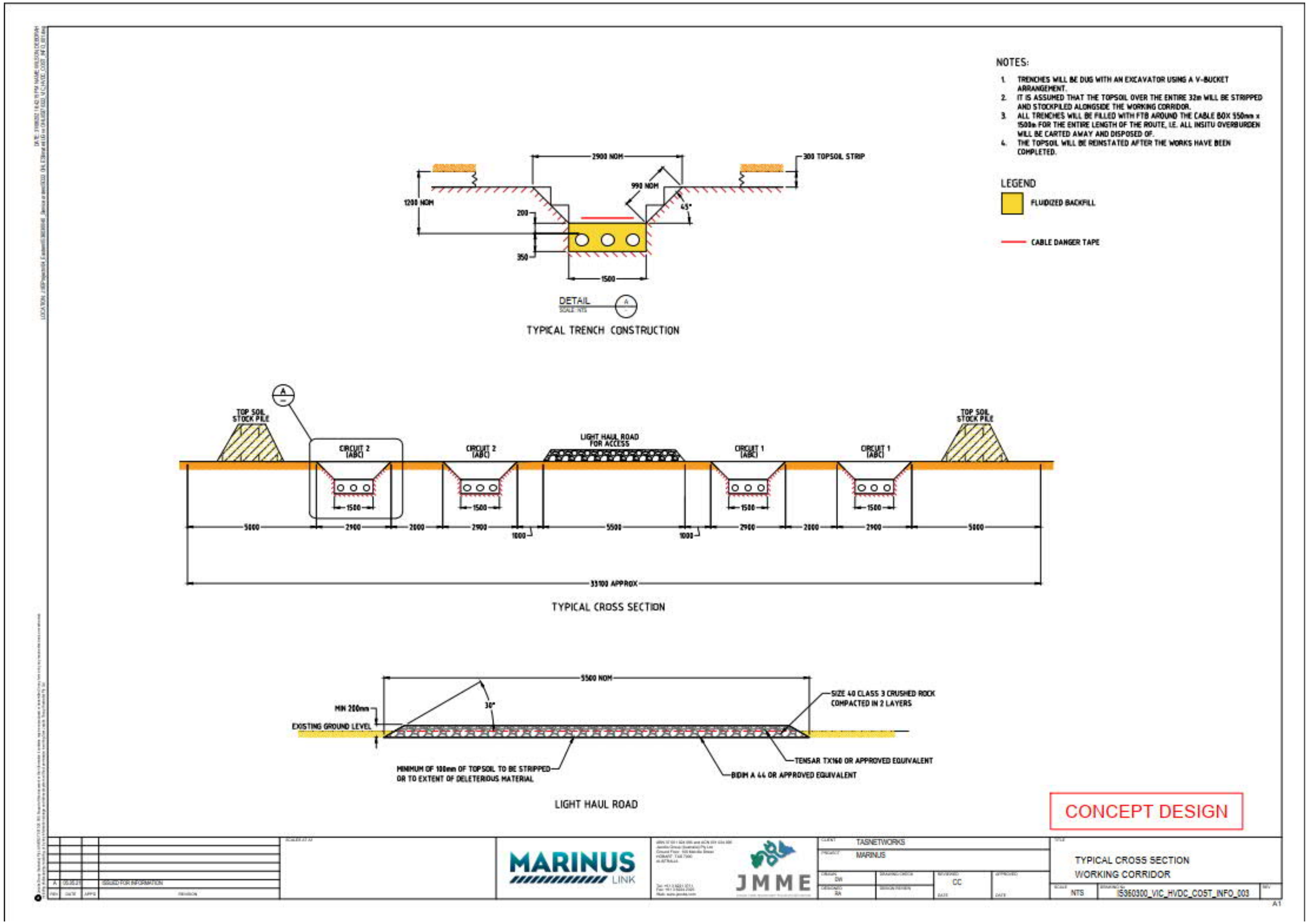
CYMCAP Model Settings and Results – ABB Aluminium 220kV, 2000mm^2 Cable Calibration model



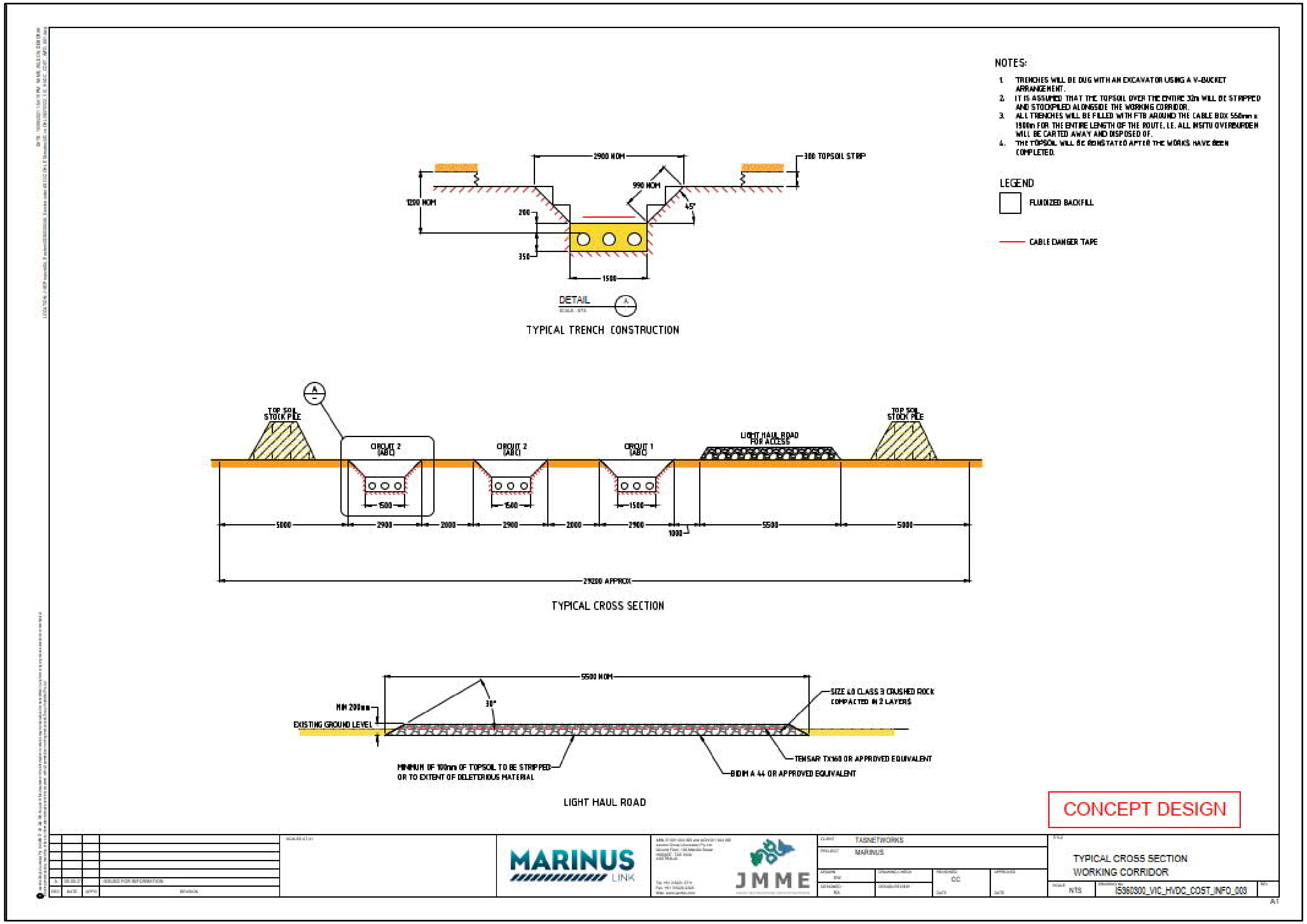
CYMCAP Model Settings and Results – ABB Copper 220kV, 2000mm^2 Cable Calibration model



APPENDIX D: TYPICAL CROSS SECTION WORKING CORRIDOR (Aluminium)



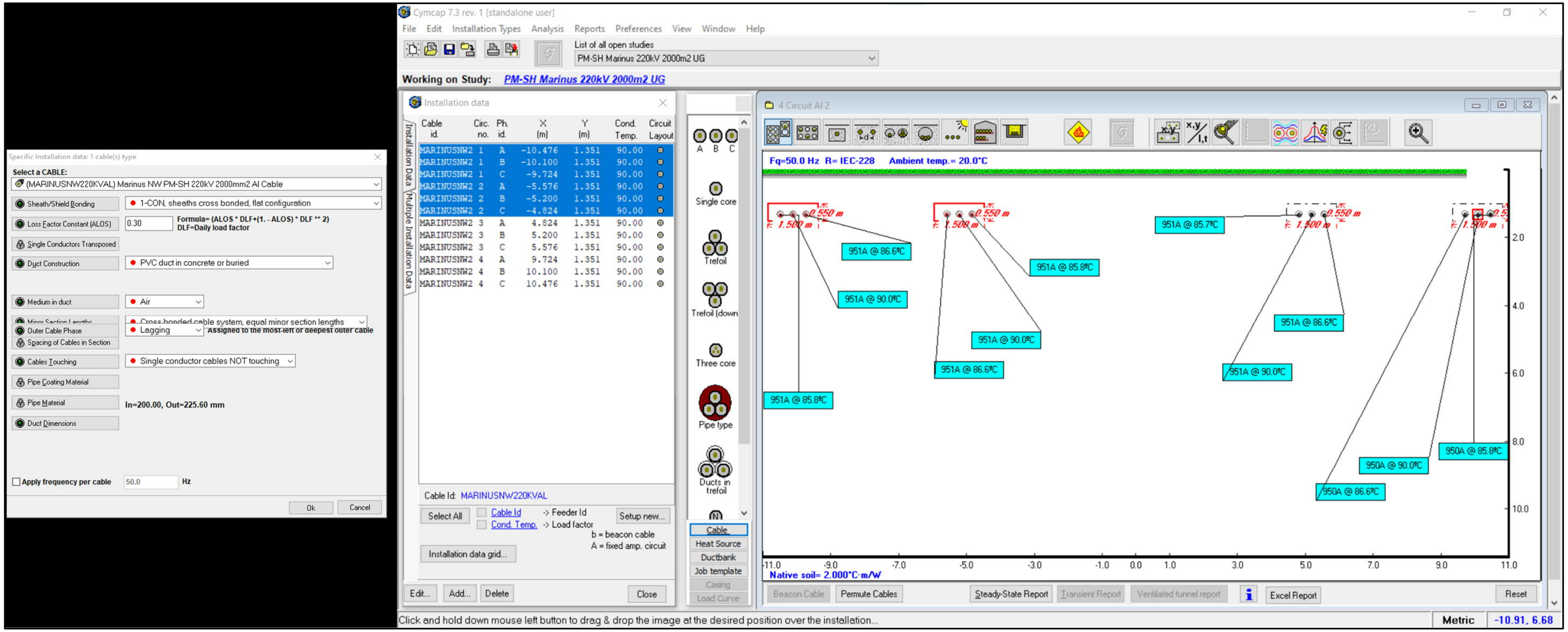
APPENDIX E: TYPICAL CROSS SECTION WORKING CORRIDOR (Copper)



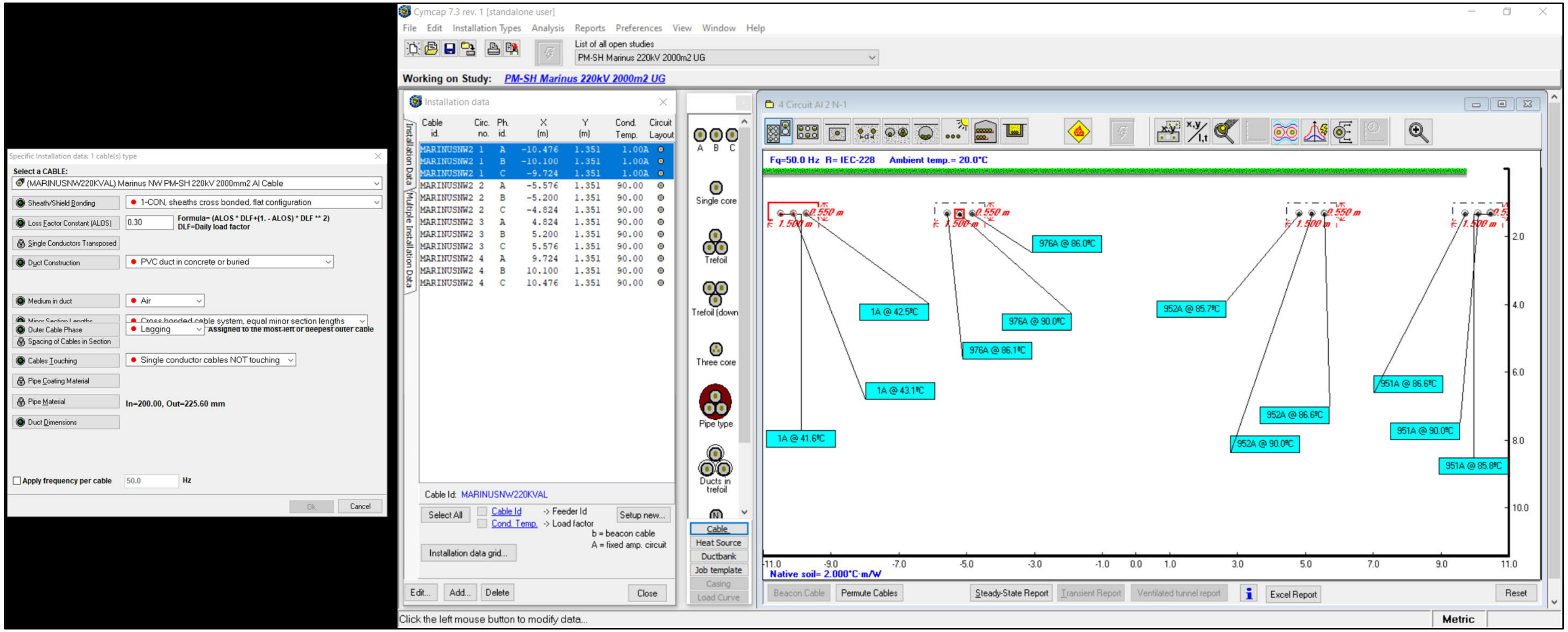
APPENDIX F

4 Circuit, Aluminium 220kV, 2000mm^2 Cable CYMCAP model settings and outputs

Arranged as per TYPICAL CROSS SECTION WORKING CORRIDOR: IS360300_VIC_HVDC_COST_INFO_003 (Aluminium)



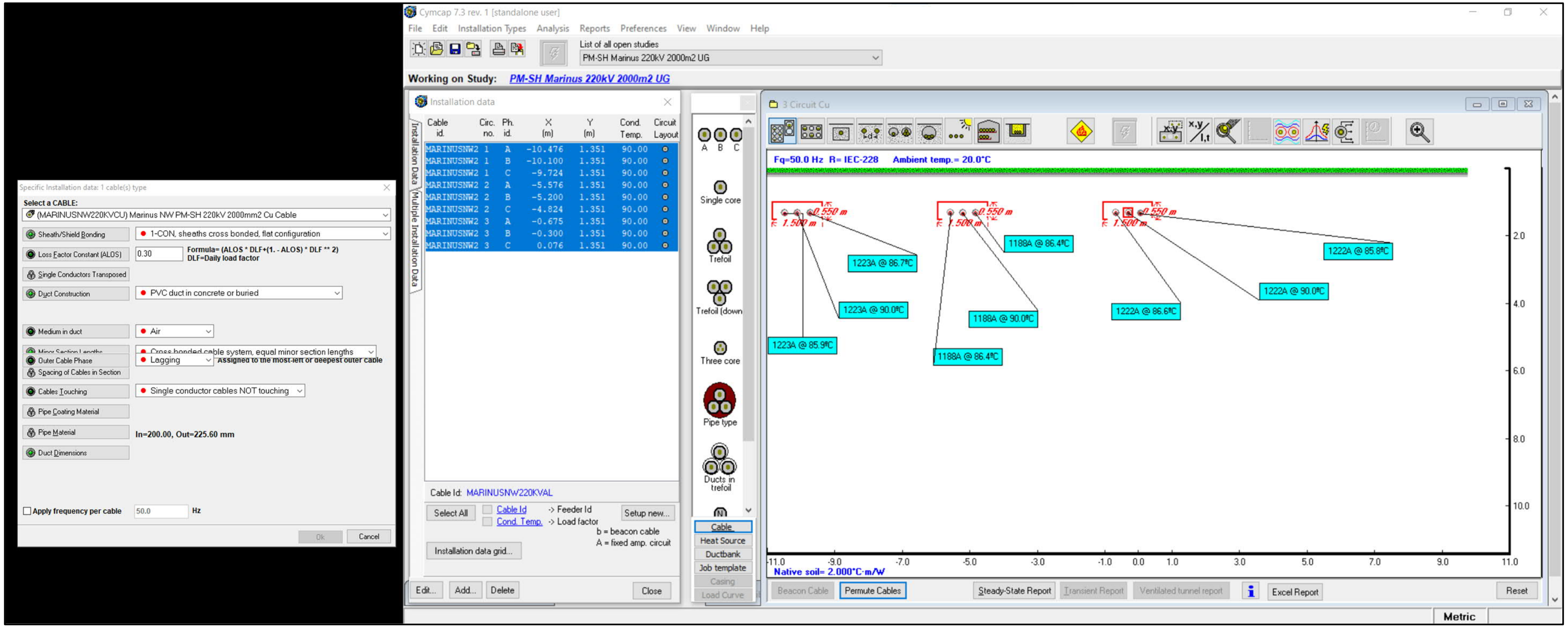
N-1 Condition: 4 Circuit, Aluminium 220kV, 2000mm^2 Cable CYMCAP model settings and outputs



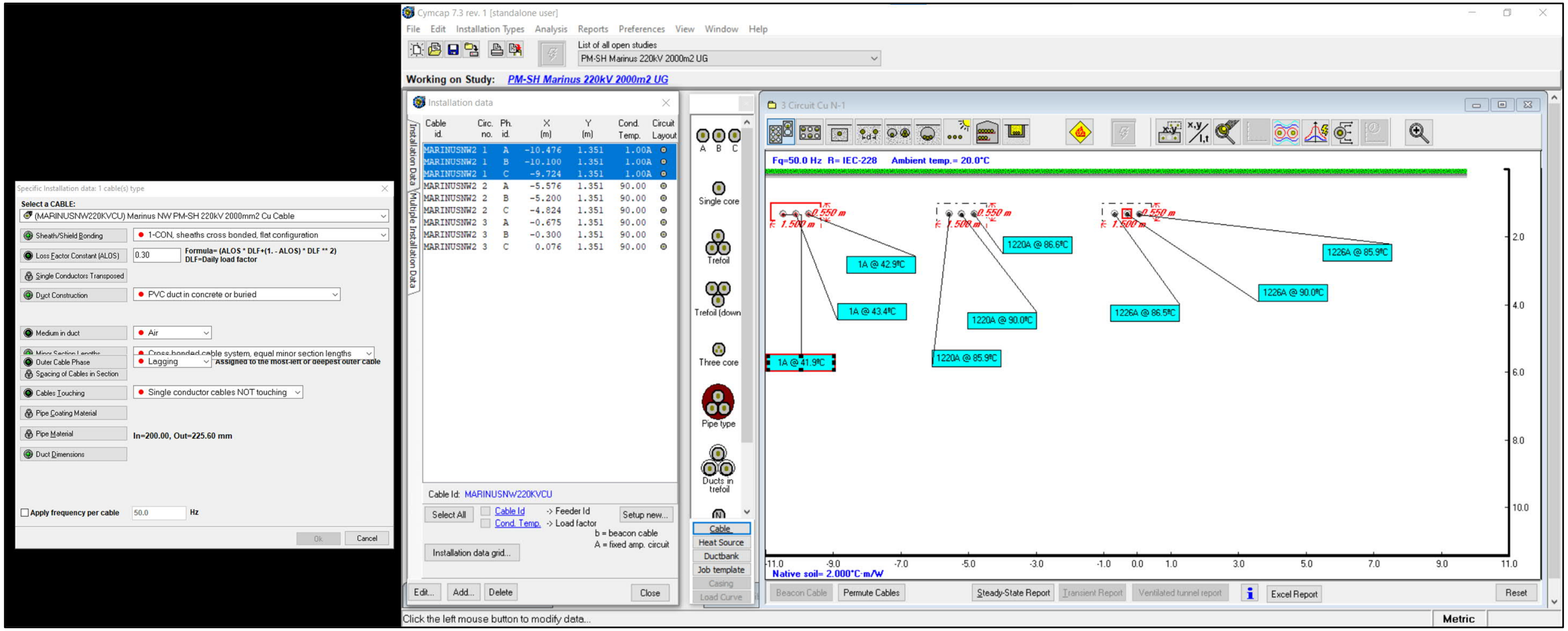
APPENDIX G

3 Circuit, Copper 220kV, 2000mm^2 Cable CYMCAP model settings and outputs

Trench/backfill dimensions as per Typical Trench Construction shown in: IS360300_VIC_HVDC_COST_INFO_003, but corridor consists of the 3 trenches equally spaced with a 2000mm gap between them.



N-1 Condition: 3 Circuit, Copper 220kV, 2000mm^2 Cable CYMCAP model settings and outputs



APPENDIX H: HVDC Option

Marinus Link will be utilizing HVDC technology to connect Tasmania with mainland Australia. HVDC technology is advantageous when transmitting large amounts of power using cables over long distances due to low transmission losses and the absence of the reactive issues usually introduced with AC cable systems. The downside of and HVDC system is that fact that it cannot be readily integrated into a meshed AC network and require HVDC converter stations on either end to accomplish this. The JMME team was asked to estimate the cost of an HVDC system between Palmerston and Sheffield in lieu of a traditional HVAC overhead transmission system.

The team utilised factored cost information compiled for works on Service Order #04 (Marinus Link Capital Cost Estimate) to represent a single pair of 900MVA (continuous operation) converter stations and two circuits (N-1) of 1600mm^2 cable (320kVdc) installed in a symmetrical monopole configuration. The Pricing summary is illustrated in the table below.

Excluding owners' costs and including contractor's direct and indirect costs this option is 9.7 times ($1.4bn vs $144m) more expensive than the traditional 220kV double circuit, twin conductor overhead line option.

PA-SH 320kV HVDC Option

Ref	Element / Package	Method	Reference	Qty	UoM	Rate	Contingency / Factor	Line Ext
1.01	D&A Costs	Excluded	N/A	1	Exc			
1.02	Land & Legal Costs	Excluded	N/A	1	Exc			
1.03	Easement / Land Agent	Excluded	N/A	1	Exc			
1.04	Convertor Stations	Escalated Historic ML Data	ABB Quote + TX	1	Pairs	$ 647,464,352	1.093	$ 707,678,537
1.05	Land Cable Cost	Historic ML Data	NKT Quote (Basis 4 X 90km)	160	km	$ 1,359,666	1.093	$ 237,778,468
1.06	Civils - Including Trenching, Minor HDDs Cable Pulling, Access Tracks	KM / SO4 Estimate	34 Mtr Easment - 2 Circuits(N-1) (900MVA)	80	km	$ 3,327,548	1.093	$ 290,960,762
1.07	Commissioning Costs	Allowance			Item			$ 5,000,000
1.08	Protection Upgrade							
	Sub-Total							$ 1,241,417,767
	Indirects							
2.01	Design	% of Total Cost		0	%	$ 1,241,417,767	1.093	$ -
2.02	Preliminaries	% of Total Cost		2.5	%	$ 1,241,417,767	1.093	$ 33,921,740
2.03	Project Management	% of Total Cost	Lump Sum		LS	$ 13,994,651	1.093	$ -
2.04	Contractors Risk	% of Total Cost		10	%	$ 1,241,417,767	1.093	$ 135,686,962
Total								$ 1,411,026,470

Estimate Notes;

Prepared for High level Cost planning reflecting Class 5 Accuracy (AAECi)

1.01 Not Considered
1.02 Not Considered
1.03 Not Considered
1.04 Convertor station based on Adjusted ABB quote 2019
1.05 Cable quote based on adjusted NKT quote 2019
1.06 Civils allowance based on S04 88KM Rev G Route. No Geo Info for routing considered
1.07 Whole System Commissioning Costs LS Allowance
2.01 Not Considered
2.02 P&G @ 2.5%
2.03 PM Costs as a lump sum
2.04 Contractors Risk Allowance

Appendix I

Cable upper limit size sensitivity check:
This check is to verify if the 900MVA rating be achieved by 2 circuits (N-1) of Copper conductors, rather than 3 using larger cables sizes.

The viability of a two-circuit system is dependent on the worst-case N-1 contingency scenario, where only one circuit is in operation. Previous results suggest that a 2000mm^2 cable is likely unsuitable to achieve such a rating, and so larger conductors must be explored.
3000mm^2 Copper Conductors represent a practical upper limit to the size of potential conductors. Many manufacturers only specify cables up to 2500mm^2 in their catalogues, however, some do advertise conductors this large, and others may be able to facilitate such orders upon request. Conductors at those sizes can become difficult and costly to install and joint.

As such, the viability of a two-circuit solution was explored using a 3000mm^2 copper conductor. Should this arrangement not produce the desired 900MVA rating as a single circuit, N-1 condition, the use of larger conductors to reduce the number of circuits would likely not be a feasible option.

Curve Fitting from ABB Catalogue Data

The previous 2000m^2 Copper conductor had been specified from the ABB 'XLPE Land Cable Systems' catalogue, which only specifies cables up to 2500mm^2. The expected rating of a similarly designed 3000mm^2 conductor was extrapolated from graphing the rating data of all other cables in the series (see Appendix A - Table 4 - Column 3 for the ABB rating data table. See Figure 1 for graph). A 3rd order polynomial curve was fit to the data. While 4th and 5th polynomial solutions had minutely higher R^2 values, the cubic's behaviour appeared more reasonable over the expected extrapolation range – out to 3500mm^2 in this case.

In order to facilitate 900MVA at 220kV, the conductor would have to be rated to a current of nominally 2362 A. From the graph in Figure 1, a 3000mm^2 conductor may only be rated to 1993 A.

This corresponds to a power rating of 759.4 MVA, over 100 MVA below the desired 900 MVA.

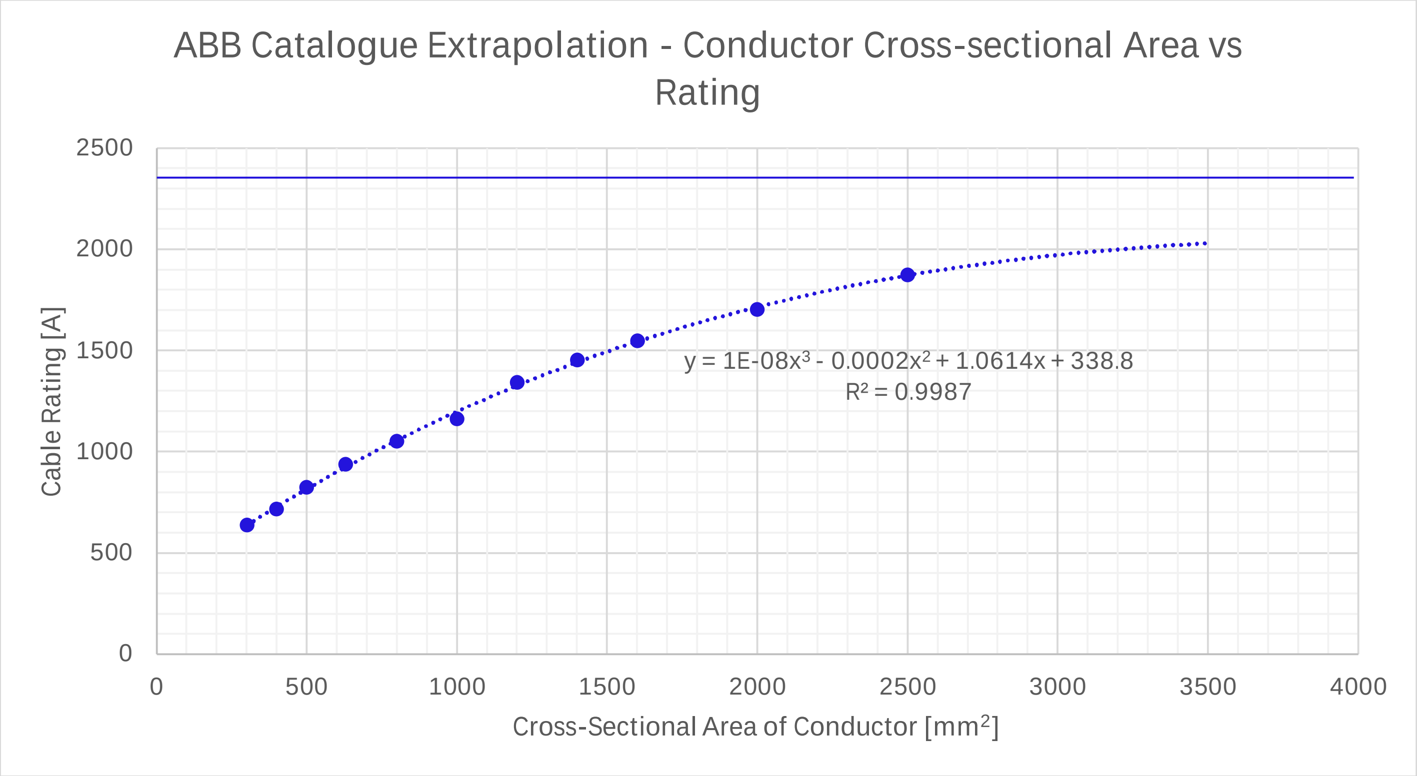


Figure 1: ABB catalogue cable rating data vs cross-sectional conductor area, extrapolated out to 3500mm^2.

CYMCAP Modelling 3000mm^2 Conductor

To further verify the viability of a two circuit, *3000mm*^{2} conductor system, a model was constructed in CYMCAP.

Cable Model

Due to ABB not specifying a *3000mm*^{2} conductor in their catalogue, the previous *2000mm*^{2} model was altered by scaling the cable's conductor accordingly.

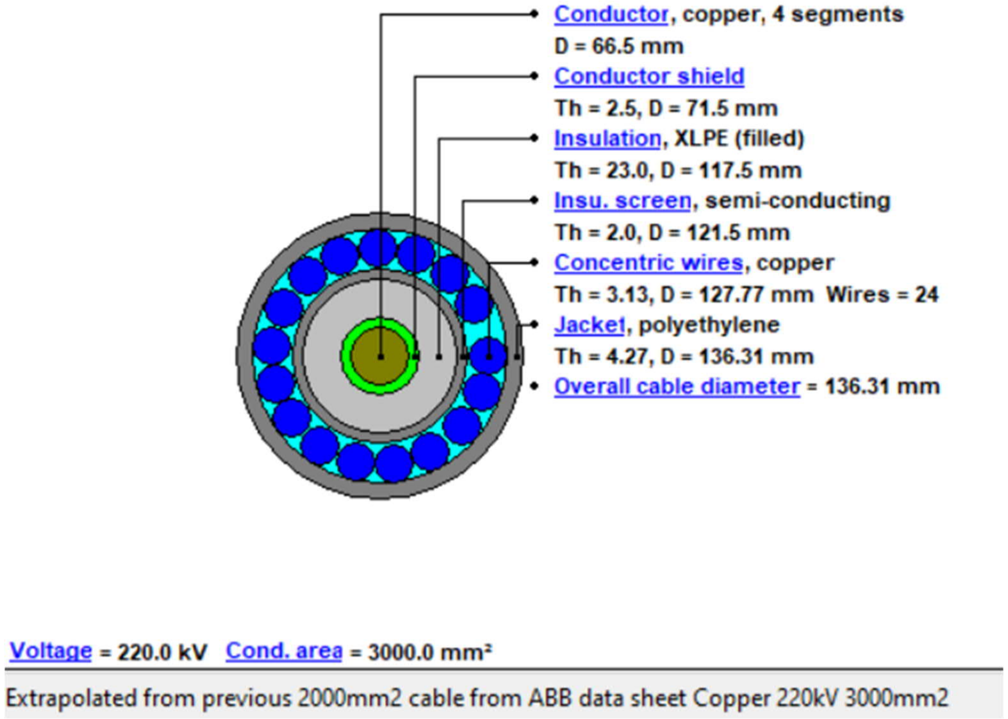


Figure 2: *3000mm*^{2} 220kV Copper conductor CYMCAP model

A calibration model was constructed as per the ABB catalogue conditions in Appendix B, and the resulting rated current was within 7.5% of the estimated rating from the previous curve fitting extrapolation - 2152 A compared to 1993 A, respectively (See Figure 3). Due to the uncertainties associated with the previous rating extrapolation values, a 7.5% margin of error was considered acceptable for the purposes of thie sensitivity check. (5% previously used).

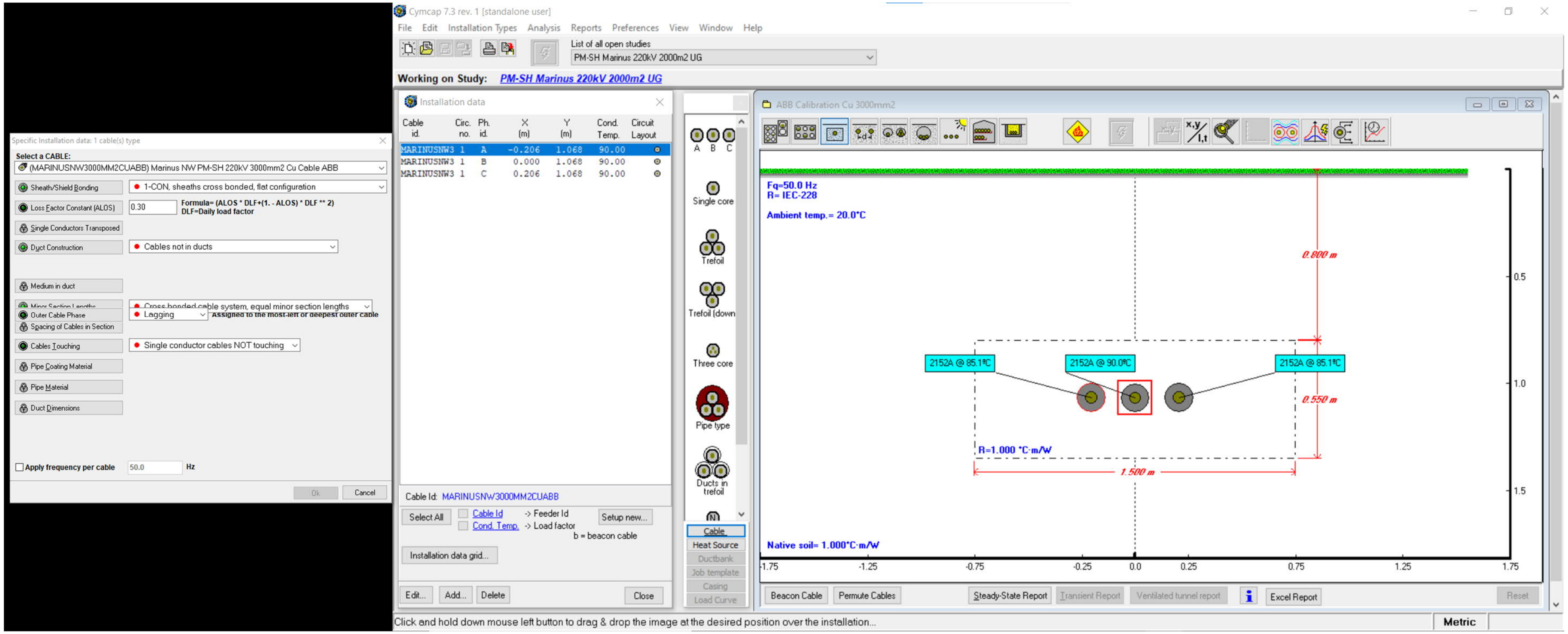


Figure 3: 3000mm2 Copper Conductor calibration model, as per ABB catalogue conditions.

Cable Rating

The *3000mm*^{2} cable was modelled in a two (2) circuit configuration, with depths and trench geometry similar to the three (3) circuit Copper configuration shown in Appendix F – two trenches spaced 2000mm apart (4900mm between centrelines). However, in this case, the cables were modelled as direct buried. It is assumed that the direct burial will result in the highest current rating, representing the best-case conditions to achieve the desired output. If the 900MVA requirement is not met under N-1, single circuit conditions when direct buried, modelling the cables in conduit would also be considered unviable.

Under N-1, single circuit, worst-case conditions, a rating of 1694 A is achieved (see Figure 4), corresponding to 645.5 MVA at 220kV. This result is well below the desired 900 MVA value, suggesting that a two (2) circuit solution is not made viable by specifying larger cables. The 2000mm^2 copper 3 circuit arrangement achieved the 900MVA requirement with only 3.6% spare capacity under N-1 conditions which indicates that size selection is optimum in the context of this memorandum where the aim is to illustrate the difference in order of magnitudes between an underground cable option and an overhead line option.

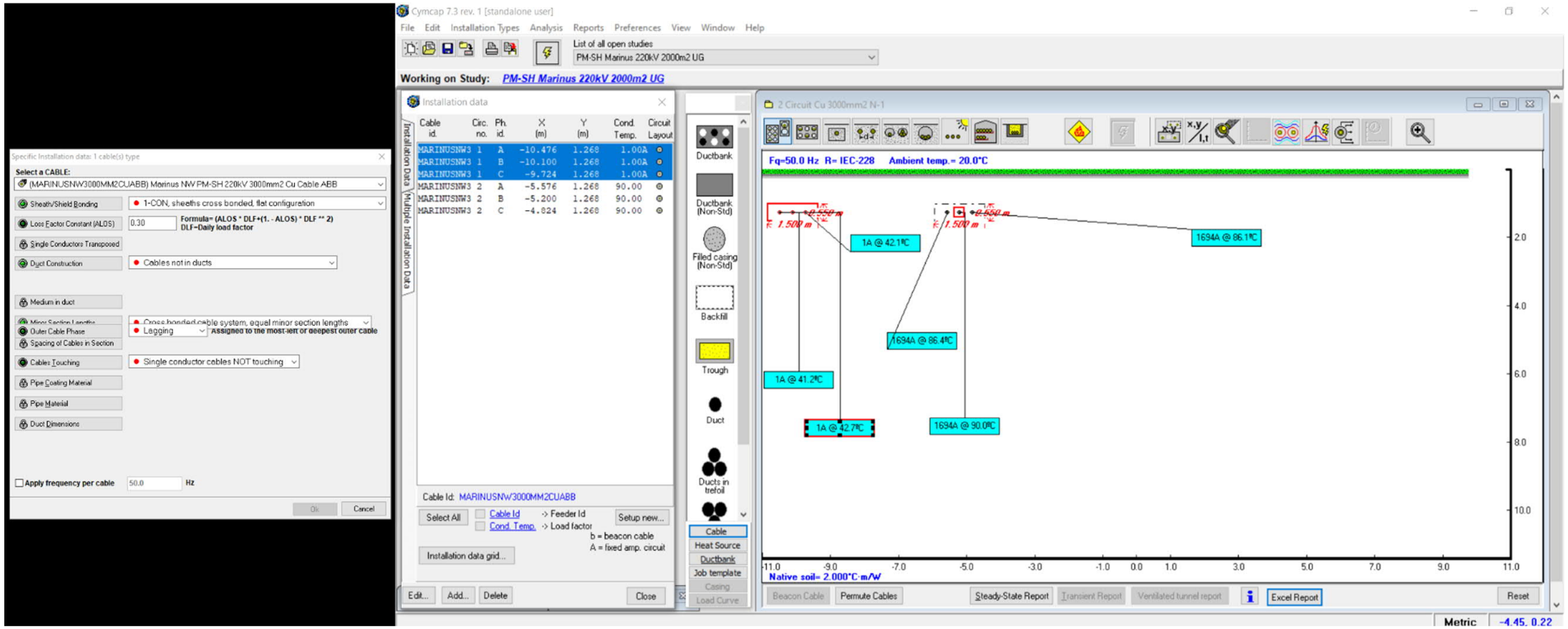


Figure 4: N-1 Condition: 2 Circuit, Copper 220kV, 3000mm^2 Cable CYMCAP model settings and outputs