HumeLink Undergrounding

Review of Transgrid Report and Costing of HVDC Alternatives

Amplitude Document Number:

PAU0351-REPT-001

Date of Issue:

03 October 2023

Revision:

Rev 3



Revision History

Revision	Prepared By	Reviewed By	Approved By	Date
1	A. Kayrin, L. Brand	T. Govender	L. Brand	28/08/2023
2	A. Kayrin, L. Brand	T. Govender	L. Brand	03/10/2023
3	A. Kayrin, L. Brand	T. Govender	L. Brand	03/10/2023

Address: Amplitude Consultants PTY LTD
Level 2, 15 Astor Terrace
Spring Hill QLD 4000
Australia

E-mail: info@amplitudepower.com

Phone: (07) 3905 9030

Website: https://amplitudepower.com/

Table of Contents

List of Figures

List of Tables

Executive Summary

Amplitude Consultants Pty Ltd (Amplitude) was engaged to undertake a critical review of the GHD Report commissioned by Transgrid and to provide high-level cost estimates for selected HVDC underground options presented in the GHD Report.

The outcomes of the detailed review are summarised in this report. We have presented a number of concerns regarding the costing (both capex and opex) of the AC and HVDC undergrounding options, the schedule of these projects and the general unbalanced way in which the undergrounding options are compared qualitatively to the AC overhead option.

Amplitude was also requested to develop a high-level technical solution and cost estimate for the GHD's option 2A-1, the all underground HVDC option, with an allowable loss of 700 MW in the event of a credible contingency (modified option 2A-1). The technical solution was based on the selection of HVDC technology, topology, configuration, and the DC voltage which was determined from Amplitude's recent experience with similar activities. Amplitude has also presented a cost for a direct point to point HVDC connection (the same rating as HumeLink) between Maragle and Bannaby using HVDC underground cables, also with an allowable loss of 700 MW in the event of a credible contingency (Maragle to Bannaby direct connection – Option 1C-new).

Amplitude presents in this report a high-level cost estimate for the modified option 2A-1 of circa $7.3 billion. A summary of the cost estimate is shown in the table below.

Project Variant	GHD 2A-1 Cost Estimate	Amplitude Modified 2A-1 Cost Estimate	Difference ($AUD)	Difference (%)
Capex Total	$11,490,000,000	$7,319,242,000	$4,170,758,000	36.3%
Transmission Line Capex	$7,717,000,000	$4,242,535,000	$3,474,465,000	45.0%
Transmission Line Capex /km	$11,349,000	$6,239,000	$5,110,000	45.0%

Amplitude also presents in this report a high-level cost estimate for the 1C-new HVDC Option Maragle to Bannaby direct connection of circa $5.46 billion.

Based on the Transmission Expansion Options Report, August 2023 [1] the cost for the AC overhead HumeLink option of $4.89 billion, the "multiple" for the modified option 2A-1 is 1.5 times the cost of the AC overhead line option. Amplitude estimates are considered as Class 5 for converters and Class 4 for the transmission line.

The 2020/21 costs presented by TransGrid for the option 1C-new in their Addendum Report [2] is $2.695 billion. This cost when elevated to the present day value based on the escalation that was noted for Option 3C in [1], makes the cost of this option $3.99 billion. The option 1C-new HVDC alternative is 1.37 times the cost of the AC overhead line project.

Amplitude have calculated losses for the two HVDC systems discussed above and have compared them to the equivalent AC system losses. These are presented in the table below. The HVDC losses include both the transmission line and converter losses.

Option	Connection Points	Combined System Losses (%) at Max. Power	
		HVDC System Losses	AC System Losses
Modified Option 2A-1	Bannaby, Maragle, Gugaa	2.20%	2.55%
Option 1C-new HVDC Alternative	Bannaby, Maragle only	2.29%	2.91%

Overall, the electrical losses of the HVDC underground option is approximately 13.5% lower than the equivalent AC overhead option at maximum power for the 2A-1 Option.

For the Option 1C-new HVDC Alternative (Maragle to Bannaby direct connection) the losses are expected to be approximately 21.3% lower than the equivalent AC overhead option at maximum power for the complete HVDC link including the converter stations. The HVDC losses can be further optimised by selecting larger cable conductors, but at a higher capital cost to the project. The optimal solution can be determined by a techno-economical assessment in the detailed design phase of the project.

1 Introduction

1.1 Background

HumeLink is a proposed transmission network augmentation project that connects Snowy 2.0 and reinforces the New South Wales southern shared network, which includes new transmission lines that span a distance of approximately 360 km. Transgrid undertook a RIT-T to identify the preferred option to augment this corridor. The Transgrid Project Assessment Conclusions Report (PACR), the third report of the RIT-T published in July 2021, identifies Option 3C as the preferred option which involves the linking of Maragle, Wagga Wagga and Bannaby at a voltage level of 500 kV double circuit.

Communities along the study corridor have raised serious concerns about the social, economic and environmental costs of a 500 kV double circuit AC overhead transmission line impacting their regions.

During 2022, Transgrid engaged a consultant (GHD) to develop underground options for HumeLink and provide a report that presents these options, compares the relative pros and cons and provides cost estimates. The report "Concept Design and Cost Estimate, HumeLink Project – Underground" was prepared by GHD to present the outcomes of this work ("GHD Report"). The latest revision (Rev 3) is dated 22 August 2022 and was issued in the public domain by Transgrid[1].

The HumeLink Undergrounding Study Steering Committee was formed in late 2021 to oversee this process. The membership of this steering committee included an independent chair, Transgrid, community/landowner community consultative group representatives (CCGSCs), Amplitude Consultants (also representing the CCGSCs) and other independent parties. A response from the CCGSCs on the outcomes of the undergrounding study and the content of the GHD Report was submitted to Transgrid in August 2022.

The GHD Report included cost estimates for a number of AC and HVDC undergrounding options. The CCGSCs have raised concerns about these cost estimates, in particular the costing for the HVDC undergrounding options. It was considered that the costs per kilometre applied in the GHD Report were significantly higher than they should be, even in light of recent cost increases in both cable supply and installation.

In addition, during the performance of the work, GHD advised that they received advice that a loss of 700 MW was allowable in the event of a credible contingency outage (instead on N-1). The GHD Report includes consideration of this (a new sub-option "C") for some of the scenarios, but not for a 100% underground HVDC option (GHD's option 2A-1).

The GHD Report had shown estimates for the cost of electrical losses for the AC and HVDC underground options to be very close, almost the same. This is despite the overall expectation that long distance HVDC underground cable projects are typically expected to have lower overall electrical losses than the AC equivalents. The GHD Report did not provide the results of their loss calculations (in MW or MWh) so it makes it hard to establish if/how this outcome could be justified.

[1] https://www.transgrid.com.au/projects-innovation/humelink#Resources

Amplitude was engaged to undertake a technical review of the GHD Report, and a part of that review required Amplitude to develop a high-level cost estimate and an estimate of the electrical losses for two technical options selected by the client, namely:

1. Option 2A-1 in the GHD Report with 2,570 MW maximum transfer capacity, but with an allowance of loss of 700 MW in the event of a single contingency (“modified option 2A-1”); and
2. A direct Maragle to Bannaby connection option with 2,510 MW maximum transfer capacity, but with an allowance of loss of 700 MW in the event of a single contingency (“option 1C-new HVDC alternative”).

The option 1C is defined as a credible option for the Humelink project and was the subject of the Addendum to HumeLink PACR, December 2021 [3].

2 Authors

The primary Amplitude team members that took part in performing this high-level study and authors of this report are Les Brand, Ken Barber and Alexander Kayrin. A summary of their credentials and industry experience is presented below.

2.1 Les Brand – Managing Director

Les Brand (FIEAust, CPEng, RPEQ) is an experienced electrical engineer with over 30 years of experience in the transmission and distribution industry in Australia, Asia and the USA. He has held senior and executive roles within the power transmission and distribution sectors, including utilities, consultancies and private companies.

Les has held senior technical roles for a number of HVDC interconnection projects including Directlink (Australia), Murraylink (Australia), Basslink (Australia) and Trans Bay Cable (California, USA). Until late 2019, Les was the convenor of the CIGRE Australian Panel for HVDC and Power Electronics (B4) and was also convenor of the international working group B4.63 “Commissioning of VSC HVDC Systems” which published a technical brochure that is now the standard for commissioning VSC HVDC converter stations. Les is also the convenor of Joint Maintenance Team 7 (JMT 7) of IEC Technical Committee 99 responsible for the revision of IEC TS 61936-2 “Power installations exceeding 1kV AC and 1.5kV DC – Part 2: DC” which defines the safety, maintenance and general installation requirements for HVDC facilities. Les is currently the convenor of the working group B4.90 “Operation and Maintenance of HVDC and FACTS Facilities”. Les is also the lead author of Section 7 “Implementation of HVDC schemes” for the CIGRE Green Book on HVDC which is under development and due for release in 2023. Since Amplitude’s inception, Les has led the HVDC elements of key projects, including a number of HVDC projects under development in Australia, support on a HVDC project in Canada and upgrades on Directlink and Murraylink (Australia) as well as various AC vs HVDC and HVDC framing/scoping studies for proposed projects in Australia and the UK.

Les set up the initial operations and maintenance structure and procedures for both Directlink and Murraylink and was directly responsible for the operation and maintenance of these, Australia’s longest underground HVDC cable projects, while in his tenure as Operations and Maintenance Manager.

Les is a joint recipient of the 2020 National Professional Electrical Engineer of the Year award from Engineers Australia.

2.2 Ken Barber – Underground Cable Specialist

Ken Barber has been employed in the Electric Cable industry since 1961. He has worked for Cable plants in UK, India, Malaysia, and Australia, and for 34 years commencing in 1976 was responsible for Olex Australia's R&D and HV cable systems. He was the Chairman of the Australia Standards committee for Insulated cables for more than 20 years and on standards committees for overhead line conductors and the Australian wiring rules.

In 1979, with technology from Sweden, Ken was responsible for the introduction of Aluminium Alloy 1120 for transmission line conductors in Australia. He has been involved in supply and installation of 2,000 km of HV and EHV cable for more than two hundred projects in the Asia Pacific region. As an example, in 1990 Ken was responsible for OLEX winning the 9 km, 220 kV cable link in Melbourne and in 2010 the 88 km, 220 kV cable link to the Victorian Desalination plant.

After the acquisition of Olex by Nexans in 2006, Ken became part of the Nexans Technical and HV team based in Asia Pacific with the position of Sales Director for HV cables - Asia Pacific region. He retired from Nexans in June 2012.

Ken is a Life Member of IEEE (SMIEEE) and was the Convener of the CIGRE Asia-Oceania Regional Council (AORC) B1 panel from its formation 2003 until 2016. In 2013, Ken took on the role of Convenor of a CIGRE B1 Working Group WG B1.47 which developed the Technical Brochure TB 680 "Implementation Issues relative to Long Length AC cable systems" published in 2017. Ken is an individual member of AESIEAP, is on the Technical Committee of JICABLE, is a member of the SC B1 Strategic Advisory Group and has authored a large number of technical papers.

Ken has his own consultancy company "Istana Park Pty Ltd," registered in Australia for more than 20 years and through this company he works for organisations on a direct consultancy basis. He has had contracts with Hydro Tasmania and TasNetworks on HVDC submarine and land cable projects. He currently working for Marinus Link Pty. Ltd. on the proposed 1,500 MW DC 350 km link from Tasmania to Victoria.

Ken has assisted Preformed Line Products (PLP) Australia on the design of cables and suitability of fittings for partially insulated aerial cable systems in the Asia Pacific region and is currently assisting a Malaysian company on the manufacture of cable for rural electrification. He also assisted Swedish Neutral in the introduction of their REFCL system for Bush Fire protection in Victoria and has worked for Ausnet Services on cable and conductor design issues.

2.3 Alexander Kayrin – Senior Consultant

Alexander Kayrin is an electrical engineer with over ten years of experience in utility distribution networks, industrial high voltage systems, renewable energy projects and HVDC projects. He specialises in HVDC transition systems, AC and HVDC cable system design and cost estimation, application of lightning protection, earthing, power, lighting and high voltage equipment for high voltage substations in Australia.

Alexander also has experience in the design documentation, specifications and calculations for industrial electrical and control systems and in undertaking technical investigations, feasibility studies and network risk assessments. Since joining Amplitude, Alexander has performed as the owner's engineer for the Directlink and Murraylink HVDC control and protection system replacement, including site supervision during installation and commissioning, and participated in the development of the technical specifications for the proposed 600 MW Ceres HVDC project which included 16 km of HVDC underground cable in South Australia, along with over 60 km of subsea cable. Alex led HVDC cable failure investigations and is responsible for pre-FEED activities for a long distance AC submarine cable off the Western Australian coast. Alexander was a key member in the performance of the AC vs HVDC assessment for large scale solar in Victoria and in the development of Basis for Transmission and Scoping studies for the Australia – Asia Power Link and other proposed HVDC projects in Australia and overseas.

3 Review of GHD Report

Amplitude reviewed the version of the GHD Report available on Transgrid's website, dated August 2022.

During the review, Amplitude identified a number of concerns regarding the costing (both capex and opex) of the AC and HVDC undergrounding options, the schedule of these projects and the general unbalanced way in which the undergrounding options are compared qualitatively to the AC overhead option.

This report does not present all of the concerns raised, however three of the bigger items are in relation to the cost per kilometre of the HVDC underground cable sections, operating costs and the schedule as explained in the following sections.

3.1 Capital Cost of HVDC Underground Cable

- "*The estimates are based on reference to recent bids received by Stantec for EuroAsia and Harmony link HVDC projects as well as information received from equipment suppliers.*"

  We are of the view that these projects are inappropriate to base a long distance underground cable project on, because:

  - EuroAsia – this is a predominantly subsea cable project, with only 23 km of the 1,208 km cable route using underground cables. The impact on cost of supply and installation is significant for shorter lengths, resulting in very high costs per kilometre.
  - Harmony link – similarly, this is also predominately subsea cable, with only 40 km of the overall 330 km long cable route being underground cable.

  For the above reasons, it is expected that using these two projects as a cost reference would necessarily result in a much higher cost per kilometre for land cables than would be expected for circa 680 km of underground land cable.

- "*The Final estimate breakdown for all options 2-4 are based on the middle range numbers.*"
  - This statement does not appear to be correct.

  - The middle range number stated for Option 2A-1 on the same page, is an $8.3 million AUD per km rate. However, the installed rate per kilometre for Option 2A-1 (Table 4.11) quotes $11.35 million AUD per km.

- It is disappointing that the 2A-1 option was not considered, i.e., a fully underground HVDC option which allows for a loss of 700 MW (as apparently advised by AEMO to Transgrid/GHD as being acceptable during the study). Given how close in cost 2A-1 is to 4C-2, we are confident that the 2A-1 option would have been competitive and 100% underground.

- The cost per km for the 1,713 MW HVDC bipole with metallic return is shown as $11.35 million per kilometre, excluding indirect costs (engineering, project management, pre-construction, distributions and allowances), biodiversity and land offset costs.

  - Based on a number of recent costing exercises for underground HVDC cables in Australia and various benchmarking of global projects, this is significantly more than should be expected. Our high-level estimate in 2023 for the same scope as 2A-1 is circa $7.8 million per kilometre (69%) of their 2022 cost/km.

  - AEMO's Transmission Cost Database (TCD) (last updated March 2023) – which is used to compare AC and HVDC options during the PADR and PACR processes in the NEM, but without risk factors applied, show a cost circa $5.5 million per kilometre.

  - From the above, and even within the range of accuracy and considering current market cost pressures, it is clear that the cost per kilometre used by GHD is excessive.

- The costs do not appear to have been built up, but appear to have been developed using a "top down" approach. It is not clear how then the values from the European cable project examples were then applied to account for Australian conditions.

- Generally, we are satisfied with the estimated cost for the converter stations, which are within the range of accuracy of these estimates, and sit within the range of Amplitude's estimates for VSC HVDC converter stations.

3.2 Operating Costs

There are also some concerns regarding the losses and operating cost assumptions in the GHD Report, these concerns are as follows:

- Loss assumptions – annual costs of losses are presented in Appendix F of the GHD Report and indicate that the cost of losses for the HVDC options are similar or close to that of the AC options. This is not typically what is expected. No results of loss estimates which these cost estimates were based on are provided in the report. Therefore, there is no way to understand how GHD have reached this conclusion. Amplitude's own loss estimates of HVDC vs. AC options show the HVDC losses to always be lower, and in some cases up to 24% lower than the AC options.

- The operating cost estimate values for the HVDC options are significantly beyond what is currently reported for operating standalone HVDC systems in Australia. This table is reporting annual operating costs for the HVDC options between circa $80 million and $110 million per year. From Appendix F, it can be seen that around 45-55% of these costs are losses, and circa

$36 million to $60 million per annum for O&M costs. The forecast operating expenditure for Murraylink (180 km) is circa $5 million per year which includes the O&M of both converters and the underground cables in between. Directlink (56 km) is reporting at circa $4.7 million per year for the same.

- From our experience in setting up O&M budgets and in the O&M manager role for HVDC projects with long distance cables in Australia, opex for underground cables is not significantly tied to route length. Additional cable length may add a few hours or a few days to the monthly route inspection, but much of the other opex expenditure (such as preparation for cable repairs etc) would not be dependent on the route length.
- The opex cost for HVDC converter however does depend on the number of HVDC converters being maintained. Given Murraylink has two converters, compared to six for the Option 2A-1 options, then multiplying by three gets circa $15 million – multiples less than the numbers presented by GHD.

3.3 Schedule

- It should be noted that the procurement strategy chosen will seriously impact the schedule. The GHD Report has assumed a "traditional" procurement process (1.5 years) for a HVDC system of going to market. This is where a fair amount of engineering is required up front and then HVDC vendors typically request 6 months+ to respond to tenders. There are however other procurement strategies that can compress these durations, to less than 12 months, including early contractor engagement models where the studies/engineering is done in parallel with the selected vendor and no need for the 6-month bidding period.
- "*Direct burial rate of 1.5 circuit km / month / installation crew*" - This is a slow rate and likely more in line with construction of underground cables in heavily populated areas. Careful planning and the exploration of innovative cable installation techniques can be justified for these large, long distance underground cable projects. Murraylink is an excellent example where methods of simultaneously burial and install were applied, similar to the installation of underground gas pipelines. This project installed 180 km in a 4 m construction corridor, including placement of spoil. An HVDC underground option for HumeLink will likely have this type of planning and innovation applied and therefore it is expected that the cable install rate will be significantly quicker.
- "*Land joint assembly of approximately 1 week to install joints per location (including set up and take down)*" – For long distance cable projects, innovative means to quickly set up and remove cable jointing huts will be applied, as was done on Murraylink. One week is too long. We estimate no more than three days per joint location, on average across the project.
- "*Transportation of DC cable to site: Duration depends on the cable factory location*" - This statement is not very helpful under an "assumptions" heading. Surely GHD had assumed something, which should be stated here.
- "*Commissioning times have been allowed to accommodate the complexity of the systems*" - We note that a commissioning duration of 8 months+ has been assumed. This is significantly too long – Murraylink was commissioned in one month, back when there was little experience with the technology. These durations are more in line with HVDC for offshore wind farms

where time is needed for the wind turbines to be commissioned. We suggest no more than three months and even that is being conservative.

- Schedule for Option 2A-1 – Based on our comments above, with the right procurement strategy and a more reasonable commissioning duration, the period should be reduced to five to six years. The schedule of the overhead option was four to five years in the GHD Report. Based on a decision now, this would mean completion by August 2029.
- Note also that this project could be staged, where one bipole (1,285 MW) can be expeditated over the other bipole. For example, Maragle to Bannaby. In our view this could bring first power transmission (up to 1,285 MW) within 5 years, or late 2028 if able to commence the project today.

4 HVDC System General Information for Costing Inputs

4.1 Converter Station Technology

For HVDC transmission, the two major technology options currently available in the market are line commutated converters (LCC) and voltage source converters (VSC).

LCC converters have been in operation since the mid-1950s and are often referred to as “conventional” or “classic” HVDC. In the early years, mercury arc valves were used to perform the commutation. Since 1972, LCC systems exclusively use thyristor valves to commutate the current to create a DC current at the rectifier (sending end) and an AC current at the inverter (receiving end).

VSC technology has been developed more recently than LCC systems, with the first commercial systems commissioned in the late 1990s. VSC technology uses the switching of insulated gate bipolar transistors (IGBTs) to create an AC voltage waveform of sufficient amplitude and phase angle difference to cause both active power and reactive power to flow in either direction. The same IGBTs are used to create a DC voltage to allow active power to flow to or from the other converter. Consequently, VSC systems are capable of bi-directional, four-quadrant power transmission.

VSC technology can be configured either as a two-level or three-level converter or as a modular multi-level converter (MMC).

A two-level or three-level converter uses pulse width modulation (PWM) to derive the required DC and AC waveforms, employing series connected insulated gate bi-polar transistors (IGBT) modules to switch between the positive and negative DC voltages. The very high switching frequency results in significant switching losses, and filters are required on the network side to limit harmonic distortion.

An MMC converter is comprised of a number of submodules, each consisting of a number of IGBTs and an energy storage capacitor. Each submodule is independently switched to build the required DC and AC waveform. As the switching frequency is much lower than a two-level or three-level converter, switching losses are much lower. The construction of the AC waveform using capacitor charging and discharging also minimises harmonic distortion for the MMC, and minimal (if any) filters on the AC network side are required.

A comparison of the considerations for selection of the appropriate technology and topology for the HumeLink project is shown in Table 1.

Table 1 – Considerations for Converter Selection

Parameter	LCC	MMC VSC	Two-Level or Three-Level VSC
AC Network Strength Requirements	High	Low - High	Low
Power Transfer Levels	High - Very High	Medium - High	Low - Medium
Use with Overhead Lines	Yes	Yes (Full Bridge only)	No
Converter Losses	Low	Low - Medium	Medium - High
Harmonic Filtering	High	Minimal or Zero	Medium
Voltage Control	Limited	Yes	Yes
Construction Footprint	Large	Smallest	Small
Overload Capacity	Yes	Limited headroom	Limited headroom

In summary, Amplitude consider MMC VSC technology as the most appropriate for this application. This is due to the required power transfer level, relatively lower losses and some considerations that are given to the connecting AC system strength that may be expected to be lowering due to increasing renewable generation penetration.

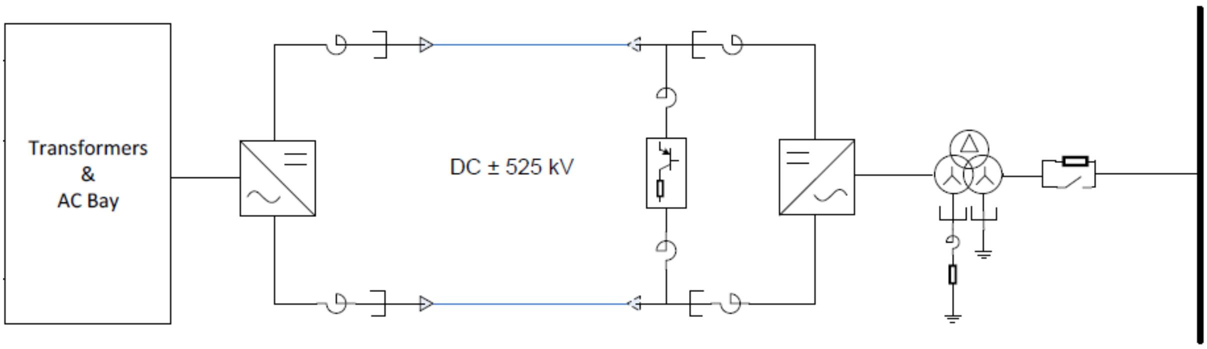
4.2 HVDC System Configurations

HVDC systems can be installed in various configurations each providing different capabilities, levels of redundancy and availability under outage conditions. The two most common HVDC system configurations for this application are the bipole with metallic return (MR) and symmetric monopole options.

4.2.1 Symmetric Monopole

A symmetric monopole is comprised of a single converter at each end (referred more broadly as a "station") with fixed HVDC "poles" at positive and negative on the DC side. A concept symmetric monopole system is shown in Figure 1.

Figure 1 – Concept Symmetric Monopole HVDC Connection [4]



While capable of providing high power transfer there is no redundancy in this configuration, meaning a fault on one transmission line or converter will cause both converters and the DC lines to trip. Any outage in the VSC converters or on either HVDC cable will result in the complete loss of the HVDC transmission system. Events that cause these outages include:

1. Pole outage due to converter failure (forced outage).
2. Pole outage due to HVDC cable failure (forced outage).
3. Pole outage due to scheduled maintenance (planned outage).

In the case of a DC pole to ground fault, very high over voltages can occur in the healthy pole and will have challenges with insulation coordination and on the HVDC cable design.

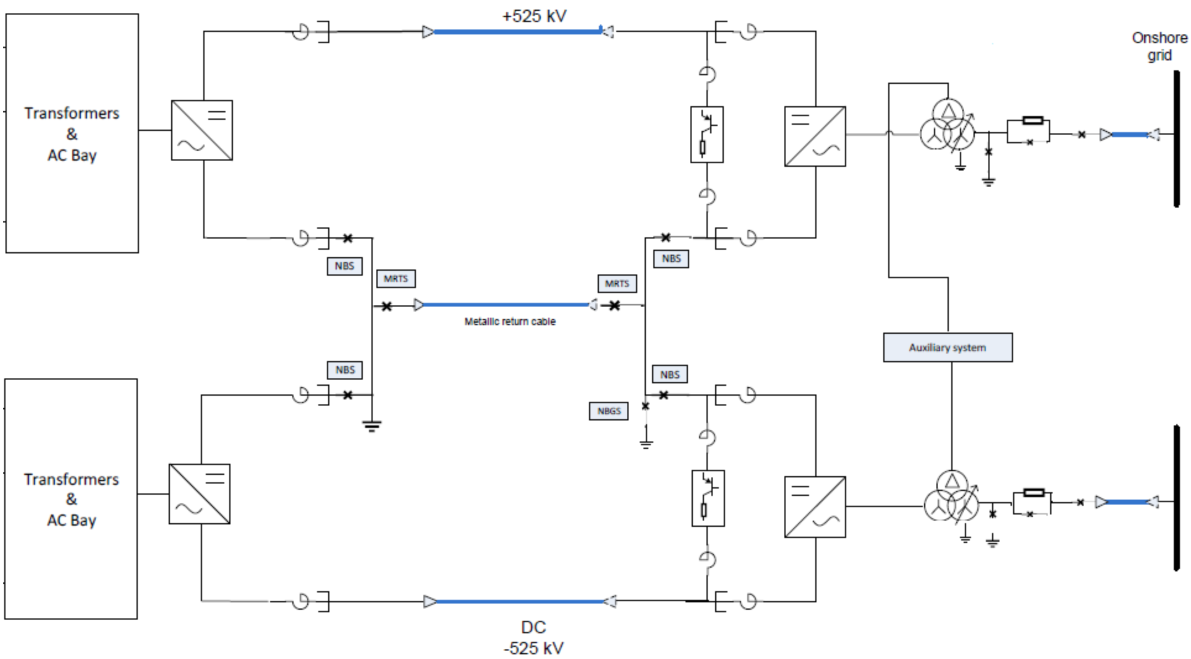
Some key benefits of the symmetric monopole configuration include relatively lower currents on the DC side (compared to asymmetric monopole configurations) resulting in smaller cables or conductors on the DC side and the potential to use "standard" two or three winding transformers instead of more complex HVDC transformers.

4.2.2 Bipole with MR Configuration

A bipole configuration is comprised of two HVDC converters per station, two HVDC cables plus a means to return any unbalance current (or full current while operating in monopole mode) – which can be either through the mass of earth via electrodes or via a third cable, referred to as a metallic return (MR) cable. Earth return systems are not popular for offshore or onshore systems due to the complexities involved with earth electrodes and environmental consenting challenges with jurisdictional authorities. Overcoming such complexities and difficulties can be worthwhile for very long distance HVDC systems due to the substantial cost savings from avoiding a dedicated return conductor, at the relatively lower cost of the electrodes at each end. However, given the relatively short length of DC transmission for this project, Amplitude has assumed every bipole in this assessment will have a MR.

For the bipole with MR configuration, the two HVDC pole cables operate like those in the symmetric monopole configuration, rated for full power and high voltage. The MR cable is also typically rated for the continuous operation at the full DC current. However, it does not have a voltage impressed on it and will have a lower voltage rating (to account for voltage rise due to the current flowing through the cable resistance). A concept bipole with MR system is shown in Figure 2.

Figure 2 – Concept Bipole with MR HVDC Connection [4]



The requirement for two separate converters per converter station and the addition of the MR cable means that this configuration tends to have a higher HVDC converter capital cost than the symmetric monopole configuration. This configuration does however provide considerable operational advantages having the higher level of redundancy and availability. The presence of the MR cable enables an instantaneous transition from bipole to monopole operation in the case of DC pole outages (planned or unplanned), retaining at least 50% of the transmission capacity, even during HVDC cable failures.

4.2.3 Comparison of HVDC Configurations

A comparison of key aspects of the two HVDC configurations considered in this chapter is shown in Table 2.

Table 2 – Converter Configuration Evaluation

Configuration	Advantages	Disadvantages
Symmetric Monopole	• No ground current. • Smaller cables/conductors (compared to asymmetric monopole configurations). • Use of “standard” AC transformers.	• No redundancy – loss of a pole means 100% outage. • Higher losses than ground return monopole or bipole options.
Bipole with MR	• Virtually no return/ground current (during normal balanced operation). • Inherent redundancy of 50% or higher if overload capability is specified.	• Higher Cost. • Requires three cables.

While both configurations come with advantages and disadvantages, a bipole with a metallic return cable is used in this application to match the system configuration selection in the GHD Report. Their configuration selection was reviewed and considered appropriate for this application as it has a reduced quantity of cables for the long transmission route lengths while being able to accommodate a loss of 700 MW limit due to availability of redundancy with one system. This in turn is expected to reduce the capital cost of the overall HVDC system.

4.3 HVDC System Ratings and Loss of Infeed Considerations

The bipole with MR shares the load across two separate poles, with a total of two poles as the name suggests. A bipole allows for smaller or more manageable equipment ratings per pole, however there will need to be more or less two of everything (control and protection systems, cooling systems, sets of transformers, buildings etc.) compared to other available HVDC system configurations such as symmetric monopoles. This increases the converter station footprint size, making it larger than the equivalent symmetric monopole option.

A bipole system requires two HVDC cables and one MR cable, which is at a lower voltage. The MR cable will need to be sized to carry the same amount of current as the HVDC power cables, and therefore will not be significantly smaller than the HVDC power cables.

The system is rated and designed to be able to handle the loss of no more than 700 MW which can be achieved considering the two parallel bipoles rated at 1,285 MW per bipole (i.e. 642.5 MW per pole). In this case, the loss of any single pole (converter or cable) will result in a loss of 642.5 MW, meeting the loss of infeed requirement without any need for overloading.

4.4 HVDC Cable Technology

4.4.1 HVDC Cable Types

For HVDC systems, the two main types of cable used on the DC side are mass impregnated (MI) and polymeric cables. The key difference between these is the insulating medium, with MI cables using insulation made of layers of paper impregnated with high viscosity fluid while polymeric cables use extruded polymer-based insulation material.

The selection of cables is dependent on a number of factors, where the first, and often the deciding consideration, is typically the HVDC technology of the converter stations. Polymeric cables cannot withstand the regular polarity reversals which are required in LCC systems to change the direction of active power flow. Therefore, MI cables must be used for LCC HVDC systems. VSC systems do not require this polarity reversal and therefore, MI or polymeric cables can be used. Unless there is a specific requirement for MI cables (such as requiring a voltage level not already type tested), polymeric cables are typically used for VSC systems as they are lighter and easier to transport and install.

Polymeric cables use triple extruded polyethylene as the main insulation system, which to date has typically been crosslinked polyethylene (XLPE). New innovations have introduced high performance thermoplastic elastomer (HPTE) to achieve higher operational temperature capability than MI cable, 70 – 90°C [5] [6] for polymeric cables compared to 55°C for the MI cables [7]. This means that more power could be transmitted through polymer insulated cables of the same sized conductor than for MI cables. The actual values depend largely on the cable supplier and the temperature characteristics of their insulation technology. This means that smaller polymeric cables can be used for the same power transfer. Polymeric cables also present a lower environmental risk than MI cables.

Amplitude considers, given that the converter station is to use MMC VSC technology, and there is no specific requirement to use MI cables, that it is appropriate to select polymeric cables. The added benefit of polymer cables is that they will be lighter and easier to install, which will play a considerable factor in the installation portion of the project given the long length of transmission route.

4.4.2 HVDC Cable Construction

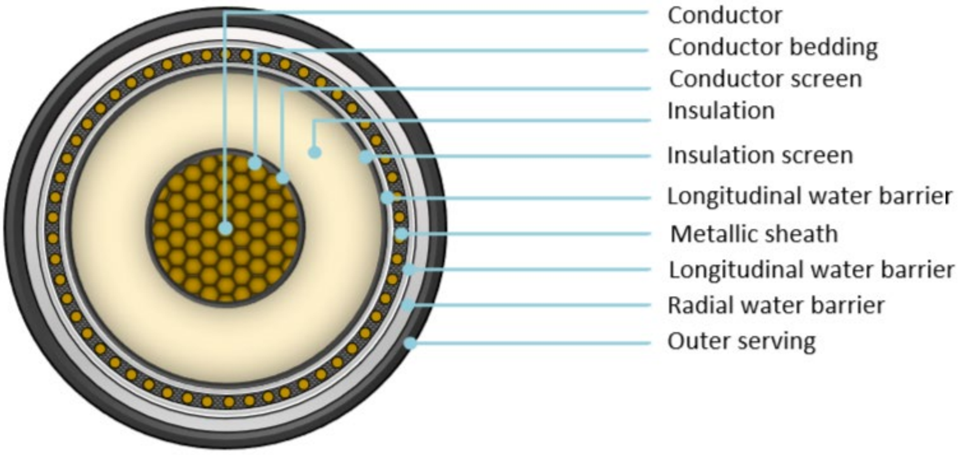
A HVDC cable consists of a conductor with the appropriate layers of insulation, water blocking and protection layers to allow the cable to be buried underground. These various layers are arranged concentrically.

A typical HVDC land cable would comprise the following key components and layers:

- Cable core – a metallic conductor and polyethylene (PE) layers (insulation and semi-conductor screens) which insulate the HV conductor from the outer mechanical protection layers and manage the electrical stresses surrounding the conductor.
- Mechanical protection layers – these layers provide the necessary mechanical protection to the cable core and protect it from water ingress where required.

A cross-section of the typical HVDC land cable construction is shown in Figure 3.

Figure 3 – Typical Land HVDC Cable Construction



The selection of the HVDC system configuration will directly influence the sizing and number of cables required.

4.4.3 Fibre Optic Cable System

With the installation of power cable infrastructure, consideration may also be given to the installation of direct fibre optic communication links along with the HVDC cables. Fibre optic cables (FOC) can provide a number of benefits when installed with a HVDC system, including improved coordination and control of the HVDC control systems, underground cable condition monitoring fault identification and improved voice and visual communication between the converter station sites.

The FOC can either be installed as a separate cable to the HVDC cables or it can be integrated into the overall construction of the HVDC cables, as is now being done for modern HVDC long distance transmission projects such as SuedLink [8] and SuedOstLink [9]. For the purpose of this assessment, Amplitude have assumed that the FOC cable will be integrated into the overall construction of the main HVDC power cables and that a separate FOC cable is not required.

4.4.4 HVDC Cable Ratings and Capabilities

The electrical characteristics of the HVDC cables and accessories are designed to meet the required DC current levels, the switching impulse withstand levels, lightning impulse withstand levels and short circuit levels determined during the technical studies performed for the project. The design of the HVDC cables should also take into account the maximum allowable losses determined during the optimisation of the transmission system.

The key factors that impact the design of the HVDC cables include:

- The required current carrying capacity, which is driven by:
  - the continuous active power transfer capability of the HVDC scheme.
  - the rated DC voltage.
  - any required additional short-time ratings and the frequency and duration of the additional loading cycles.
  - the number of HVDC cables required by the selected HVDC configuration.
- The thermal resistivity (TR) of the surrounding medium (soil types) along the cable route.
- The expected ambient temperature of the soil.
- The maximum conductor temperature allowed by the insulation.
  - typical maximum conductor temperature of up to 70°C, but higher temperatures can be considered (for example 90°C) subject to cable type testing, prequalification testing and contract experience.
  - for this assessment, a temperature of up to 70°C for the HVDC cables is assumed.
- Layers for water blocking and mechanical protection.

4.5 Summary HVDC System

A summary of the key parameters selected for the HumeLink HVDC options is shown in Table 3.

Table 3 – HumeLink HVDC System Key Parameters

Parameter	Value	Reasoning and Discussion
Converter Technology	VSC	Voltage source converter (VSC) technology is more suitable for the power transfer capacity and consideration of other factors such as the current and declining system strength of the AC networks in the region.
Converter Topology	MMC	Multi-level modular converter (MMC) topology has been selected for the project as it is anticipated to produce a lower level of harmonic emissions, therefore requiring less filtering equipment, less land area, and lower capital cost. MMC topology also results in lower converter losses, closer to those expected from LCC converters, than other VSC topologies.
Configuration	Bipole with MR	This configuration provides a degree of redundancy required to be able to handle the loss of one system element (credible contingency) while not losing more than the allowable limit for largest loss of infeed of 700 MW. This is also able to be achieved with one HVDC system with lower rated converters and less cables in total when compared to a monopole configurations.
Voltage Level	±525 kV	For the required power transfer capacity, this DC voltage represents a reasonable balance between keeping the current at a level to allow for reasonable cable sizing and the cost of the converter stations.
HVDC Cable Technology	Polymeric	This is becoming the more common cable technology used on VSC HVDC systems and provides ease of installation benefits over MI cables as well as other benefits such as lower weight and reduced environmental risks.

These inputs are used to further develop the HVDC system in terms of sizing, ratings and cost estimation for the converters and cables.

5 High-Level Capital Cost Estimates

Amplitude's scope included development of a high-level EPC (engineer, procure and construct) capital cost estimate for two HVDC solutions based on HVDC converter unit and cable rates derived from publicly available information.

These high-level capital costs have been developed for the purpose of comparing HVDC and AC options and selecting a preferred transmission method only.

The HVDC converter and HVDC cable supply costing used for this assessment is based on "per/MW" and "per/km" rates derived from selected publicly available cost sources. These estimates are suited for the comparison of projects and are to be considered to be careful but high-level estimates.

The next phase after this high-level assessment should include additional engineering and the engagement of manufacturers and suppliers to determine a more accurate cost estimate for the HVDC system transmission solution.

5.1 Costing Assumptions

The following cost estimate assumptions were applied:

1. This high-level estimate (AUD, July 2023) has been developed for the purpose of presenting a cost for the selected HVDC solutions as discussed in this report.
2. The capital cost estimates are limited to the costs directly related to the engineering, procurement, manufacture, construction, installation, testing and commissioning of the selected HVDC solutions.
3. For the "non-EPC" items, such as biodiversity offset costs and land cost, Amplitude used the same percentage assumptions as applied by GHD in the GHD Report (and presumably accepted by Transgrid), as shown in Table 4. Please refer to the GHD Report for a description of these items.

   Table 4 – Non-EPC Cost Assumptions and Allowances

Item	Assumed Percentage of EPC Cost
Engineering & PM	8%
Pre-Construction	7%
Distributions	5%
Allowances	3%
Biodiversity Offset Cost	6%
Land Offset Costs	1%

4. Other assumptions, exclusions, and details of the level of accuracy of the cost estimates are as described in this report.

The cost estimates for this high-level assessment have been based on high level unit rates for the converters (per MW) and for underground cable on a per kilometre basis, which have been derived from costing information from publicly available sources, which may include:

1. Published feasibility and technology reports.
2. Announcements and press releases from HVDC converter and HVDC cable suppliers.
3. CIGRE technical brochures and papers.
4. Rawlinson's 2023 Construction Guide.

5.2 HVDC Converter Station Costs

There is a high degree of secrecy in relation to the costing of VSC HVDC converter stations from known suppliers, and this is even more so for the costing of individual components making it not possible to develop bottom-up cost estimates of any reasonable level of accuracy. Further, HVDC converter costs can vary from year to year and are greatly dependent on the level of global demand for HVDC projects. At present, there is significant global demand for HVDC projects, and it is known that HVDC vendors are carefully selecting which projects they wish to bid for.

In Amplitude's experience, initial costing assessments for early feasibility or AC vs HVDC assessments can be done using publicly available sources if these are carefully assessed and selected. However, more accurate cost estimates can only be achieved through engagement with HVDC converter station vendors, the majority of which are located in Europe.

The high-level cost estimates for an EPC cost for each VSC converter station, based on full bridge MMC technology and bipole configuration are presented in Table 5. These cost estimates can be considered to be Class 5 estimates as per the AACE International Recommended Practice No. 56R-08.

Table 5 – Modified 2A-1 Option HVDC Converter Station Capital Cost Estimate

MW Rating	DC Voltage	HVDC Systems Qty.	Converter Qty.	Cost /MW	Converter Estimate ($AUD, 2023)
1,285 MW	±525 kV	3	6	$183,606	**$2.83 billion**

From the values presented in Table 5 the overall capital cost estimate for the converters, for the selected HVDC solution is $2.83 billion ($AUD, 2023). The transmission component cost, being underground cables for the complete length of the route, is described and presented in the following section. These costs are consistent with the GHD Report converter stations costs and include an escalation from the 2022 costs in the GHD Report, to the 2023 costs presented in this review.

5.3 HVDC Cable Costs

5.3.1 HVDC Cable Selection

Amplitude has assessed the expected cable size, cable configuration and spacing to meet the required current carrying capacity for the HVDC system, considering a nominal operating voltage level of ±525 kV as well as the anticipated maximum DC current. The environmental parameters assumed are as shown in Table 6. These are the same parameters that were used in the determination of cable sizes in the GHD Report.

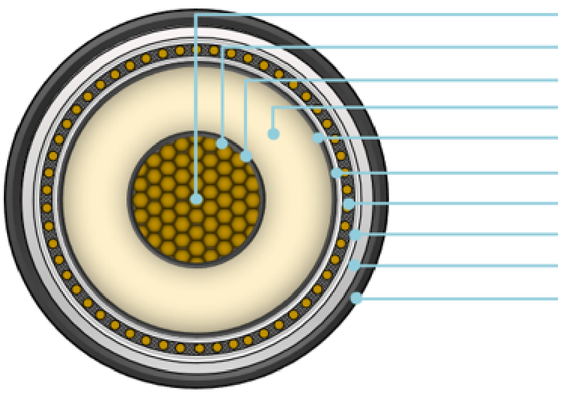
Table 6 – Land Cable Assumed Environmental Parameters

Parameter	Value	Unit
Thermal Resistivity of Soil	1.5	K.m/W
Temperature	25	°C
Burial Depth to Top of Cable	1	meters

It is possible that the thermal resistivity and temperature may be greater than the value shown in Table 6, particularly in some localised areas. In the past, Amplitude have recommended this be managed by measurement of the thermal resistivity during installation and the application of mitigation strategies in the event higher values are experienced, including importing known thermal resistivity backfill or spacing the cables further apart, which may be employed for this project. For the purpose of this high-level assessment, Amplitude have limited the environmental parameters to the ones shown in Table 6 and have assumed that the additional cost of any localised higher thermal resistivity values will be well within the accuracy of the capital cost estimates developed in this assessment.

Amplitude has assessed the approximate size of the HVDC polymeric cables for the required system ratings for a bipole configuration using a cable rating software. An example of the cable model used for this assessment is shown in Figure 4. Note that the cable cross-section diagram is not shown to scale.

Figure 4 – Cable Model for 1,600 mm² Land Cable

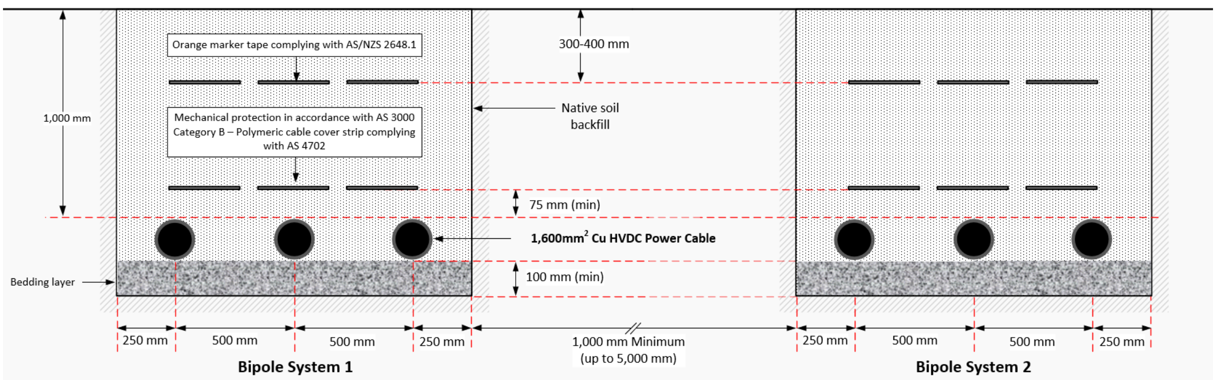


Layer	QTY.	Thickness [mm]
Conductor	1	48.50
Conductor Binder	1	0.50
Conductor Screen	1	1.50
Insulation	1	34.23
Insulation Screen	1	1.40
Longitudinal Water Barrier	1	0.70
Metal Screen	1	1.30
Longitudinal Water Barrier	1	0.70
Radial Water Barrier	1	0.20
Outer Sheath	1	5.50

Overall Diameter:	140.56	mm
Cable Weight:	25.29	t/km

The cable trench profile assumed for this assessment is as shown in Figure 5. Each set of power cables (three per bipole system) will be laid and buried in individual trenches with separation distances of a minimum of 0.5 m between each cable in a system and a minimum of 1 m between each cable trench to maintain thermal and current cable ratings.

Figure 5 – Cable Trench Profile



The minimum required current carrying capacity of the cables for this system is 1,224 Amps so that each HVDC bipole is able to transmit 1,285 MW at ±525 kV. Based on the environmental parameters, installation configuration and cable design the maximum cable current carrying capacity has been modelled to be 1,360 Amps for a HVDC 1,600 mm^2 Cu polymer cable (refer to Figure 4), which is above the required 1,224 Amps for the system.

While the above stated spacing (refer to Figure 5) is for minimum requirements to maintain cable ratings, Amplitude acknowledges that the spacing may need to be increased (in particular between trenches) for practicality reasons for installation, repairs or operations and maintenance purposes.

5.3.2 Cost Estimate Inputs and Assumptions

Amplitude has developed the HVDC cable estimates using the following assumptions when developing the scope and estimates for the HVDC transmission component:

- All cost and size estimates are derived and scaled from publicly available information and are high-level estimates.
- The fibre optic cable is expected to be imbedded into one of the layers of the actual HVDC cable (similarly to the SuedLink project [8]), and therefore the costs of the fibre optic cable is assumed to be included in the overall supply cost of the cable component.
- The cable estimates have been developed for a power transfer level of 1,285 MW continuous.

An estimate for the cost of the ±525 kV 1,600 mm^2 Cu XLPE cable was developed, and determined to be $770,000 per kilometre (AUD, July 2023). The overall installed cable cost is estimated to be $6,239,000/km of route (see Table 8 below). These cost estimates can be considered to be Class 4 estimates as per the AACE International Recommended Practice No. 56R-08.

The installation costs for the cables were estimated using Amplitude's internal calculator which determines the cost of installation based on the estimated cable trench size and profile as well as the amount of effort that goes into laying a specified amount of cables. The calculator applies the 2023 construction and labour costs provided in the Rawlinsons Australian Construction Handbook.

The following scaling factors and assumptions were applied during the development of these estimates:

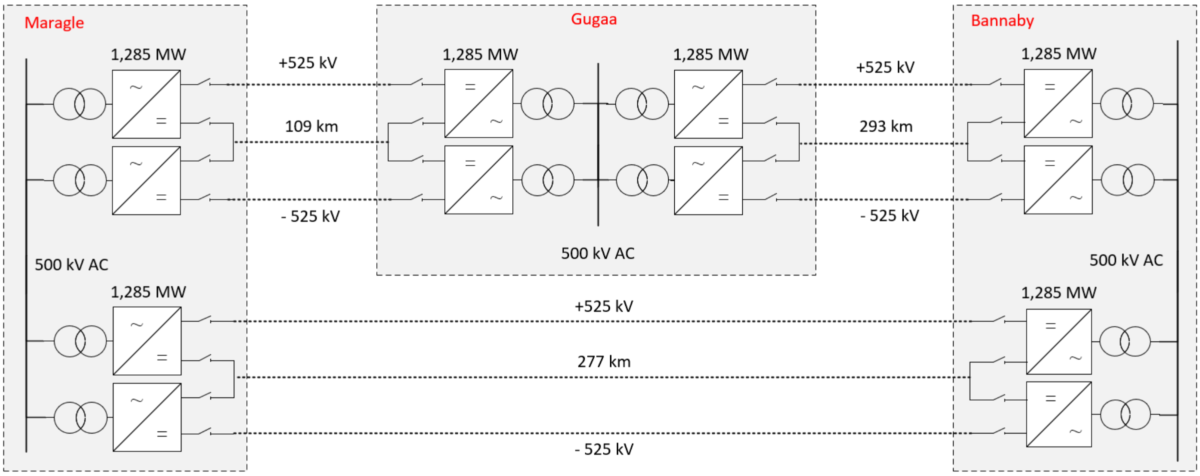
1. Cable cost of manufacture and supply was scaled using the Eurostat Data Browser from year of reference project cable supplier contract announcement to year 2023 [10].
2. The conductor metal component cost was estimated using London Metal Exchange (LME) historical data and calculated as the cost in the year of the HVDC cable contract.
3. The installation was based on the configuration and trench profiles provided in Section 4 and the Rawlinsons Australian Construction Handbook 2023 rates were used in Amplitude's internal trench excavation and cable installation calculator.

5.4 Modified Option 2A-1 HVDC Cost Estimate

5.4.1 System Overview

This is a modification of the option presented in Table 3.2 of the GHD Report (Option 2A-1). In the GHD Report this is a fully N-1 option, where a loss of any pole would not result in less than 2,570 MW transmission into Bannaby. However as noted previously, GHD/Transgrid were advised that a loss of 700 MW in the event of a contingency (i.e., a single pole trip) was acceptable. A single line representation of the modified Option 2A-1 is presented in Figure 6.

Figure 6 – Modified Option 2A-1 Concept Single Line Diagram



It can be noted that this is a replica of the GHD Option 2A-1 HVDC system configuration in terms of quantity of systems, cables, connection points, route lengths, etc. The only difference here is that the power transmission is reduced from 1,713 MW to 1,285 MW. The one other difference that should be noted is that Amplitude determined that a cable size of 1,600 mm^2 is sufficient to transmit this amount of power, as described in Section 5.3.

5.4.2 Cost Estimate

Amplitude has used the information presented in Sections 4 and 5 of this report to develop a high-level cost estimate for the modified option 2A-1 option. This estimate has been prepared as described in the preceding sections. A comparison to the GHD Report estimate for their Option 2A-1 (which does not allow for the loss of 700 MW) is shown in Table 7. The detailed cost estimate is shown in Table 8.

Table 7 – Option 2A-1 Cost Estimate Comparison

Project Variant	GHD 2A-1 Cost Estimate	Amplitude 2A-1 Cost Estimate	Difference ($AUD)	Difference (%)
Capex Total	$11,490,000,000	$7,319,242,000	$4,170,758,000	36.3%
Transmission Line Capex	$7,717,000,000	$4,242,535,000	$3,474,465,000	45.0%
Transmission Line Capex /km	$11,349,000	$6,239,000	$5,110,000	45.0%

Table 8 – HumeLink Option 2A-1 Cost Estimate

Line Design		Maragle to Bannaby	Gugaa to Bannaby	Maragle to Gugaa	Units
HVAC/HVDC		HVDC direct buried cable	HVDC direct buried cable	HVDC direct buried cable	
Circuit configuration		Bipole	Bipole	Bipole	
Voltage		525	525	525	*kV*
Power/Rating		1,285	1,285	1,285	*MW*
TR Value (K.m/W)		1.5	1.5	1.5	*K.m/W*
Soil Temp		25	25	25	*°C*
Cable Size		1,600	1,600	1,600	*mm^2*
Cable Cost /km		$770,000	$770,000	$770,000	*$AUD, 2023*
Route Length		277	293	109	*km*
Number of Converter Stations		2	2	2	
Capital Cost – Transmission Only					
Installed Rate per km of route		$6,239,000	$6,235,000	$6,293,000	*$AUD/km*
Installed Cost per km/MW		$5,000	$5,000	$5,000	*$AUD/km/MW*
Subtotal		**1,726,910,000**	**$1,826,921,000**	**$688,704,000**	***$AUD, 2023***
Capital Cost – Transmission, Converters and All Other					
Installed Rate per km of route		$10,007,000	$9,814,000	$15,296,000	*$AUD/km*
Installed Cost per km/MW		$8,000	$8,000	$12,000	*$AUD/km/MW*
Subtotal		**$2,769,910,000**	**$2,875,444,000**	**$1,673,888,000**	***$AUD***
Cost Basis					
Materials		$691,915,000	$732,391,000	$273,548,000	*$AUD, 2023*
Installation		$716,946,000	$758,018,000	$285,693,000	*$AUD, 2023*
Other		$318,049,000	$336,512,000	$129,463,000	*$AUD, 2023*
Engineering & PM	8%	$116,105,000	$122,791,000	$46,077,000	*$AUD, 2023*
Pre-Construction	7%	$96,543,000	$102,188,000	$38,331,000	*$AUD, 2023*
Distributions	5%	$69,564,000	$73,619,000	$29,736,000	*$AUD, 2023*
Allowances	3%	$35,837,000	$37,914,000	$15,320,000	*$AUD, 2023*
Additional Allowances					
Biodiversity Offset Cost	6%	$80,883,000	$85,377,000	$33,774,000	*$AUD, 2023*
Land Offset Costs	1%	$18,380,000	$19,410,000	$7,674,000	*$AUD, 2023*
Converter Stations		$943,737,000	$943,737,000	$943,737,000	*$AUD, 2023*
Total Transmission Cost:		**$7,319,242,000**			***$AUD, 2023***

5.5 Option 1C-new HVDC Alternative Cost Estimate

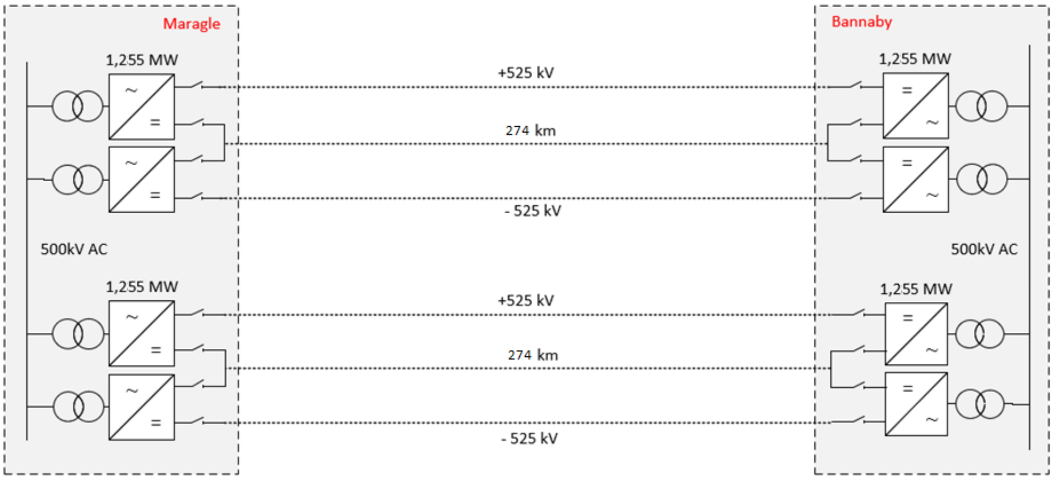
Option 1C-new is from the Addendum to the PACR and is defined as a credible option, which is a direct AC overhead transmission connection between Maragle and Bannaby.

Amplitude was requested to develop an alternative HVDC option and cost estimate for the HumeLink HVDC transmission system as a HVDC underground alternative to Transgrid's Option 1C-new.

5.5.1 System Overview

For this option, the overall rating at Maragle and Bannaby is 1,255 MW per bipole making up a total transmission capacity of 2,510 MW as described in the TransGrid PACR Addendum [2]. This option also includes the loss of 700 MW in the event of a contingency (i.e., a single pole trip). The Maragle to Bannaby direct connection is presented by in TransGrid PACR addendum as 274 km and is shown in Figure 7.

Figure 7 – Option 1C-new HVDC Alternative Concept Single Line Diagram



5.5.2 Cost Estimate

Amplitude has used the information presented in Sections 4 and 5 of this report to develop a high-level cost estimate for the Maragle to Bannaby direct connection option. This estimate has been prepared as described in the preceding sections. The estimated capital cost is presented in Table 9. The detailed cost estimate is shown in Table 10.

Table 9 – Option 1C-new HVDC Alternative Cost Estimate

Project Variant	1C-new (Escalated)[1]	1C-new HVDC Alternative	Difference ($AUD)	Difference (%)
Capex Total	$3,988,000,000	$5,461,768,000	$1,473,168,000	36.9%
Transmission Line Capex	-	$3,417,740,000	-	-
Transmission Line Capex /km	-	$6,237,000	-	-

1. *The costs of the 1C-new option is reported in the TransGrid PACR addendum dated December 2021 to be $2.695 billion, which is a 2020/21 cost. An escalation percentage rate of 48% was used based on the escalation of Option 3C from $3.3 billion (TransGrid PACR, July 2021) to $4.89 billion (Transmission Expansion Cost Report, AEMO, August 2023).*

The breakdown of the TransGrid estimate is not provided in the PACR addendum report, and therefore isolated the transmission line capex costs were not compared.

Table 10 – Option 1C-new HVDC Alternative Cost Estimate

Line Design		Circuit 1	Circuit 2	Units
HVAC/HVDC		HVDC direct buried cable	HVDC direct buried cable	
Circuit configuration		Bipole	Bipole	
Voltage		525	525	*kV*
Power/Rating		1,255	1,255	*MW*
TR Value (K.m/W)		1.5	1.5	*K.m/W*
Soil Temp		25	25	*°C*
Cable Size		1,600	1,600	*mm^2*
Cable Cost /km		$770,000	$770,000	*$AUD, 2023*
Route Length		274	274	*km*
Number of Converter Stations		2	2	
Capital Cost – Transmission Only				
Installed Rate per km of route		$6,237,000	$6,237,000	*$AUD/km*
Installed Cost per km/MW		$4,970	$4,970	*$AUD/km/MW*
Subtotal		**$1,708,870,000**	**$1,708,870,000**	***$AUD, 2023***
Capital Cost – Transmission, Converters and All Other				
Installed Rate per km of route		$9,967,000	$9,967,000	*$AUD/km*
Installed Cost per km/MW		$7,942	$7,942	*$AUD/km/MW*
Subtotal		**$2,730,884,000**	**$2,730,884,000**	***$AUD***
Cost Basis				
Materials		$684,898,000	$684,898,000	*$AUD, 2023*
Installation		$709,245,000	$709,245,000	*$AUD, 2023*
Other		$314,727,000	$314,727,000	*$AUD, 2023*
Engineering & PM	8%	$114,892,000	$114,892,000	*$AUD, 2023*
Pre-Construction	7%	$95,535,000	$95,535,000	*$AUD, 2023*
Distributions	5%	$68,837,000	$68,837,000	*$AUD, 2023*
Allowances	3%	$35,463,000	$35,463,000	*$AUD, 2023*
Additional Allowances				
Biodiversity Offset Cost	6%	$80,038,000	$80,038,000	*$AUD, 2023*
Land Offset Costs	1%	$18,188,000	$18,188,000	*$AUD, 2023*
Converter Stations		$923,788,058	$923,788,058	*$AUD, 2023*
Total Transmission Cost:		**$5,461,768,000**		***$AUD, 2023***

5.6 Comparison to Current HumeLink AC Overhead Cost

Based on the advice from Transgrid in the transcripts of the recent Parliamentary Inquiry of a cost for the AC overhead HumeLink option of $4.89 billion[2] and the estimates presented in this report, the "multiple" for the modified option 2A-1 option is considered to be 1.5 times the cost of the AC overhead line option.

Considering the Transgrid option 1C-new from the PACR addendum escalated by the same factor to bring the cost to present day value from 2020/21 costs, option 1C-new HVDC alternative is 1.37 times the cost of the escalated AC overhead line option.

While these multiples appear low, they may reflect one of the reasons why HVDC underground projects are being favoured by private developers, including offshore wind farm developers. The long duration and amount of work involved in planning, permitting and addressing public opposition will increase the cost and schedule of any long-distance overhead transmission project, and the updated costs announced recently are likely to reflect some of that.

Further, recent and ongoing technical advances are leading to more efficient HVDC underground cables allowing more power to be transmitted and therefore can be expected to reduce the cost of undergrounding. For instance, the recent development of polymeric insulating materials are expected to allow conductor temperatures of up to 90°C, allowing smaller cables for the same power transfer. These technologies may well be in service and current state of the art by the time a HVDC underground Humelink would be under construction.

6 Electrical Loss Estimates

The outcomes of our electrical loss estimates are presented in Table 11 for the modified option 2A-1 and Table 12 for the Maragle-Bannaby direct connection.

These losses are presented at maximum power flow (2,570 MW for option 2A-1 and 2,510 MW for option 1C-new) for comparison purposes only. To use these losses for lifecycle assessment, a transfer/load profile for HumeLink would be needed to establish MWh flows and load factors.

We have also provided a high-level estimate of expected 500 kV AC overhead line equivalents, which are based on certain assumptions including the use of 3 x Mango[3] conductor to meet the power transmission requirements and ensure no corona issues. The 4 x Orange conductor configuration presented in the GHD Report appears to be significantly overrated for the required power transfer, although there may be other reasons for this that we are not aware of.

---

[2] Transmission Expansion Cost Report, AEMO, August 2023.
[3] Conductors (transmission lines) are rated Mango, Orange, etc.

Table 11 – Modified Option 2A-1 – Estimation of Electrical Losses and Comparison

Parameter	HVDC System Losses			AC System Losses		
	Bannaby - Maragle	Bannaby - Gugaa	Gugaa - Maragle	Bannaby - Maragle	Bannaby – Gugaa	Gugaa - Maragle
	5C1	5C2	5C3	5C1	5C2	5C3
Transmission Line Loss (MW_DC/MVA_AC)	9.38	9.92	3.69	34.09	36.06	13.41
Transmission Line Loss (%)	0.730	0.772	0.287	2.47	2.61	0.97
DC Converter Station/AC Transformer Losses (MW_DC/MVA_AC)	20.56	20.56	20.56	11.05	5.53	5.53
Converter Station/AC Transformer Loss (%)	0.8	0.8	0.8	0.4	0.4	0.4
Converter Station/AC Transformer Qty.	2	2	2	4	2	2
Total (MW_DC/MVA_AC)	29.94	30.48	24.25	45.14	41.59	18.94
Total (%)	2.330%	2.372%	1.887%	3.267%	3.010%	1.371%
Combined System Losses (%) at Max. Power	**2.20%**			**2.55%**		

Table 12 – Option 1C-new HVDC Alternative – Estimation of Electrical Losses and Comparison

Parameter	HVDC System Losses		AC System Losses	
	Bannaby - Maragle	Bannaby - Gugaa	Bannaby - Maragle	Bannaby - Gugaa
	5C1	5C2	5C1	5C2
Transmission Line Loss (MW_DC/MVA_AC)	8.85	8.85	32.17	32.17
Transmission Line Loss (%)	0.705	0.705	2.38	2.38
DC Converter Station/AC Transformer Losses (MW_DC/MVA_AC)	20.56	20.56	10.80	10.80
Converter Station/AC Transformer Loss (%)	0.8	0.8	0.4	0.4
Converter Station/AC Transformer Qty.	2	2	4	4
Total (MW_DC/MVA_AC)	29.41	29.41	42.96	42.96
Total (%)	2.288%	2.288%	3.184%	3.184%
Combined System Losses (%) at Max. Power	**2.29%**		**2.91%**	

From Table 11 it can be seen that at full power output levels, the estimated electrical losses on the 500 kV AC overhead transmission option are higher for the longer circuits in the modified option 2A-1 but less for the shorter circuits. This can be expected where HVDC losses tend to be less than their AC equivalents only after a certain length. These calculations tell us that this cross over point is more than 110 km but less than 277 km. Overall, the electrical losses of the HVDC underground option is approximately 13.5% lower than the equivalent AC overhead option at maximum power.

From Table 12, we can see that the electrical losses at maximum power for the HVDC underground option for the direct Maragle to Bannaby alternative is expected to be approximately 21.3% lower than the equivalent AC overhead option at maximum power.

It should be noted that the cables have been sized here to meet the required power transfer, but the cable size for example can be further increased to 2,000 mm^2 (size as per the GHD Report) from

1,600 mm^2 which would lower the losses for the underground solution even further. While increasing the size of the cables will increase the capital cost of the project, it may provide greater savings long term due to lower power losses. The more overall financially feasible option concerning cable size and losses would have to be further assessed during the detailed design phase of the project.

7 Conclusion

In this report, Amplitude has presented the outcomes of a detailed review of the GHD Report and presented high-level technical solution and cost estimates for the proposed modified 2A-1 and the 1C-new HVDC alternative options.

The main concerns with the GHD Report are in the costing of the HVDC underground cables. Comparing the cost per kilometre presented by GHD for the HVDC underground options with our own estimates and other benchmarks such as the AEMO TCD, it is clear that even within the range of accuracy and considering current market cost pressures, the cost per kilometre used by GHD is excessive.

Amplitude's estimates of the two options presented, based on our own estimates of HVDC converter station costs and bottom up of long distance HVDC underground cable cost and installation in Australia, has resulted in multiples (when compared to the latest reported cost of the HumeLink AC overhead line project) of 1.5 times the cost of the 2A-1 AC overhead line option and 1.37 time the cost of the escalated 1C-new AC overhead line option.

References

[1] AEMO, "2023 Transmission Expansion Options Report," AEMO, 2023.

[2] TransGrid, "Reinforcing the NSW Southern Shared Network to increase transfer capacity to demand centres (HumeLink)," TransGrid, 17 Dec 2021.

[3] TransGrid, "PACR," 2021.

[4] TenneT, "T01 - 2 GW HVDC Grid Design and Reliability & Availability," TenneT, 2019.

[5] Sumitomo Electric, "Sumitomo Electric Technical Review," *Expansion of HVDC Cable Application in Response to Growing Demand for Renewable Energy Transmission,* vol. 94, no. April 2022, pp. 34-39, 2022.

[6] NKT, *HVDC Cable Datasheets - Amplitude Consultants Inquiry, Australia,* 2022.

[7] J. H. Jeremy Gordonnat, "Subsea cable key challenges of an intercontinental power link: case study of Australia–Singapore interconnector," Energy Transitions, 2020.

[8] Prysmian, "Prysmian completes perfect hat trick with SuedLink Corridor in Germany," Prysmian, 29 Jun 2020. [Online]. Available: https://www.prysmiangroup.com/en/press-releases/suedlink-corridor-award. [Accessed 17 Jan 2023].

[9] Prysmian, "Prysmian receives the extension of the Suedostlink project in Germany worth approx. €700 mln by tennet," Prysmian, 24 06 2022. [Online]. Available: https://www.prysmiangroup.com/en/media/press-releases/prysmian-receives-the-extension-of-the-suedostlink-project-in-germany-worth-approx-700-mln-by-tennet. [Accessed 17 01 2023].

[10] Eurostat, "Data Browser," Eurostat, [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/STS_INPPND_M__custom_4069197/default/line?lang=en. [Accessed 2023].