Western Victorian Transmission Network Project

High-Level HVDC Alternative Scoping Report

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Executive Summary

Amplitude consultants were engaged by Moorabool Shire Council to investigate an alternative HVDC option utilising underground cable to the AEMO preferred Western Victoria Transmission Network Project (WVTNP) Option C2, which includes erection of new 220 kV and 500 kV overhead transmission lines (OHTL).

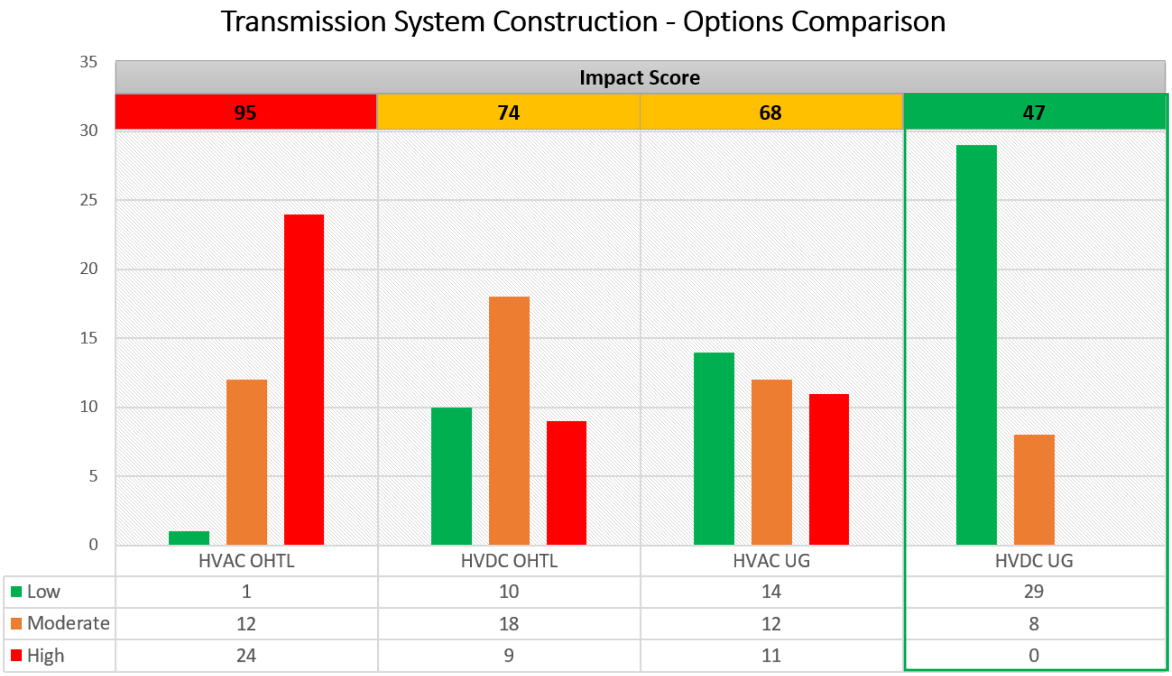
It was determined that not only is a HVDC system utilising underground cables a technically feasible alternative, but it is also likely to be more reliable and efficient for the movement of renewable energy to major centres whilst presenting significantly reduced impact to social and environmental factors.

A high-level comparison of AC and HVDC transmission options was performed in relation to the WVTNP to ascertain which transmission technology and overhead or underground construction method would present the least impact when considering a variety of criteria including technical, environmental and other risks.

The key points pertaining to the HVDC underground option being the lowest impact solution are as follows:

- Little to no risk of underground cables causing bush fires.
- Little to no risk of interruption to power transmission, or underground cables being affected, during bush fires or severe weather events. Power does not need to be switched off during bush fires to aid firefighting, and is highly unlikely to be disrupted due to smoke causing flashovers and potentially tripping the line.
- Little to no impact to access e.g. for emergency services or aviation operations.
- Minimal impact to private land or current land use once construction is completed as the easement could be designed to fit within existing road reserves.
- Significantly reduced impact to flora and fauna due to the possible location of the cable along roadways.
- No visual impact concerning the transmission line as the cables are buried underground.
- Equivalent or reduced visual and land-use impact from the converter station as it would be expected to occupy a relatively similar area as a typical AC terminal station with much of the equipment being housed indoors.
- No audible noise along the transmission line.
- Little to no electromagnetic field impacts.

The assessment results are presented in the figure below, which shows that the HVDC underground cable option carries the lowest impact out of the four options considered.

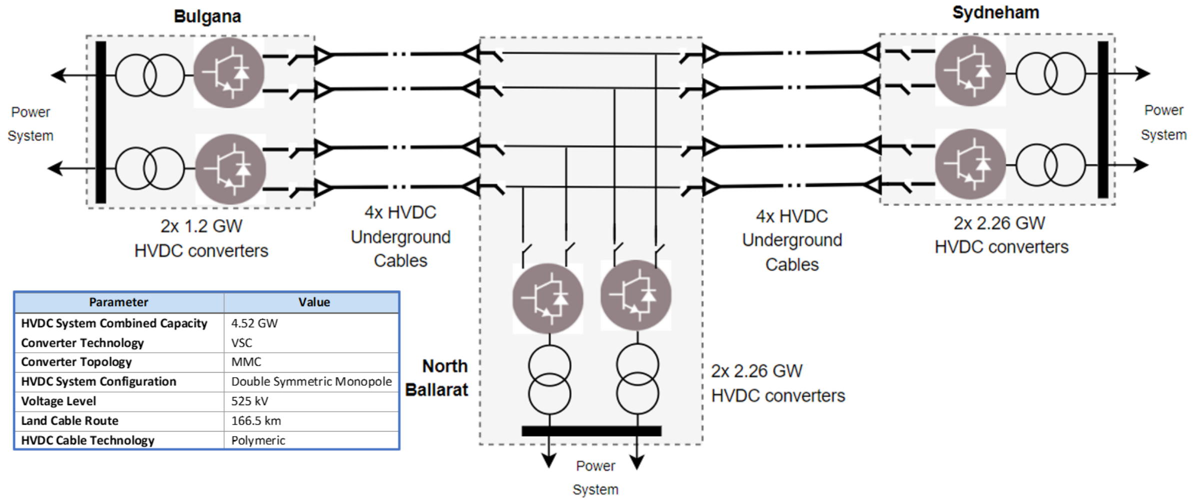


	HVAC OHTL	HVDC OHTL	HVAC UG	HVDC UG
🟩 Low	1	10	14	29
🟧 Moderate	12	18	12	8
🟥 High	24	9	11	0

Amplitude reviewed the publicly available information and information that was provided by the Moorabool Shire Council to ascertain the parameters of the WVTNP Option C2. Amplitude then developed an alternative Base Case Concept HVDC System which could replace the proposed 220 kV and 500 kV AC overhead transmission lines between Bulgana Terminal Station and Sydenham Terminal Station with an entirely underground HVDC transmission system. The following points summarise some of the considerations and assumptions applied to the development of this option:

- Converter station locations were assumed to be close to the 220 kV lines near Bulgana, north of Ballarat, and in close proximity to the Sydenham Terminal Station.
- The underground cable transmission route from Bulgana to North Ballarat was assumed to predominantly follow the existing 220 kV overhead transmission line that runs from Bulgana Terminal Station to Ballarat Terminal Station. The route length was estimated to be approximately 88.5 km in length.
- An underground cable transmission route was estimated from North Ballarat to Sydenham, for the purpose of estimating cable route length and costs, using prudent avoidance techniques and routed mainly alongside existing roads and highways between Ballarat and Sydenham. The cable trench was estimated to be three meters wide and the route length to be approximately 78 km.

A summary of key technical aspects of the option utilising HVDC technology and underground cables are presented in the figure and table below.



Parameter	Value
HVDC System Combined Capacity	4.52 GW
Converter Technology	VSC
Converter Topology	MMC
HVDC System Configuration	Double Symmetric Monopole
Voltage Level	525 kV
Land Cable Route	166.5 km
HVDC Cable Technology	Polymeric

Amplitude developed a high-level cost estimate of this underground solution using publicly available sources, which came to circa $2.7Bn. This compares to around 5.7 times the cost of the AEMO preferred AC overhead WVTNP Option C2, rather than the up to 10 times more referenced by the AEMO Western Victoria Renewable Integration Project Assessment Draft Report (PADR). This cost estimate includes the overall engineer, procure and construct (EPC) cost of the HVDC converters and cables.

This option is considered to be rated in excess for the required transfer capacity, as it follows the N-1 reliability typical planning criteria and the 500 kV AC OHTL capacity of Option C2 proposed by AEMO, which carries a large capital expenditure and leaves a significantly more reliable HVDC system underutilised. Therefore, two additional HVDC options were developed that offered lower capital costs of $1.75Bn and $1.49Bn for a redundant bipole of lower capacity and a non-redundant single symmetric monopole respectively. These costs compare to around 3.7 times and 3.2 the cost of the AEMO preferred AC overhead WVTNP Option C2 respectively. These are only very high-level estimates and Amplitude are of the view that further system optimisation may be able to reduce this cost further.

During the initial investigation into the WVTNP, it was noted that the maximum transfer capacity of the WVTNP as a stand-alone project is described in the AEMO Western Victoria Renewable Integration Project Assessment Conclusions Report (PACR) to be a maximum of 2,000 MVA. This is estimated to be approximately 40% of the capacity of the new 500 kV AC transmission line. The remainder of the WVTNP overhead line capacity is to be utilised on completion of the planned VNI West connection into the North Ballarat Terminal Station which would increase the transfer capacity between Victoria and New South Wales, via either the AEMO proposed Kerrang or Shepparton link. This indicates that a staged development approach for the Concept HVDC System may also be possible.

In this report, Amplitude has considered an extension option for the Base Case Concept HVDC System that involves an additional terminal to be built at Wagga-Wagga (i.e. the same connection point as the VNI West), which would connect to the North Ballarat TS via a HVDC overhead transmission line, over an estimated 450 km route. This solution could be within 45% of the combined AC options of the AEMO preferred WVTNP Option C2 and VNI West Shepparton link. The HVDC option however will come with the various non-financial benefits over the AC option as described in this report, such as increased network support and flexibility, electrical separation of AC transmission networks, ease of undergrounding, bushfire resilience and lessened visual impact.

Amplitude is of the view that a HVDC system which considers the scope of both the AEMO preferred WVTNP Option C2 and the VNI West Shepparton link could be a cost competitive and technically superior alternative, pending a detailed scoping study and cost estimation.

1 Purpose

This report is prepared by Amplitude Consultants Pty Ltd (Amplitude), on behalf of Moorabool Shire Council (the Council), to investigate an alternative HVDC underground option to the Australian Energy Market Operator (AEMO) proposed transmission network upgrade for the Western Victoria Transmission Network Project (WVTNP). AEMO identified Option C2 as the preferred transmission augmentation solution which proposes the installation of new 500 kV and 220 kV AC overhead transmission lines (OHTL) between Bulgana and Sydenham, Victoria (VIC).

The purpose of this high-level study is to investigate and propose an alternative HVDC underground cable solution ("Concept HVDC System") that would meet the current and future objectives of the AEMO preferred Option C2.

2 Authors

The primary Amplitude team members that took part in performing this high-level study and authors of this report are Les Brand, Matt Gnad 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 27 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 2022. 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 is a joint recipient of the National Professional Electrical Engineer of the Year award with Engineers Australia for 2020.

2.2 Matt Gnad – Manager Projects Engineering and Delivery

Matt is an experienced electrical engineer with over 15 years of experience in the electricity industry with the last 12 years operating exclusively in the HVDC and FACTs industry in Australia, New Zealand and Canada. Matt has significant hands-on experience in the construction, installation, commissioning, operation and maintenance of HVDC, FACTS, and high voltage systems. These include new projects and upgrade works.

Some key activities that Matt has undertaken during his career include the preliminary and planning works for control and protection upgrade works on the New Zealand HVDC system, the management of operation and maintenance activities and project works for the Benmore HVDC converter station, South Island FACTS (SVC/STATCOM) equipment, and Inter Island Subsea HVDC power cables (New Zealand) and site construction and commissioning of the Eastern Alberta Transmission Line (EATL) HVDC project (Canada). Matt also held project management and site engineer roles for the New Zealand Pole 3 HVDC project and has led failure investigations for HVDC and FACTs, including the investigation of SVC capacitor bank fire and project manager for the restoration project.

Since joining Amplitude, Matt has held lead or principal level roles in HVDC-related projects, including Directlink and Murraylink control and protection replacements (Australia) in a shared Owner's Engineer and Commissioning Manager role, a number of HVDC projects under development in Australia, support on a HVDC project in Canada as well as various AC vs HVDC and HVDC framing/scoping studies for proposed projects in Australia and the UK. Matt is a regular member of the new CIGRE working group B4.90 "Operation and Maintenance of HVDC and FACTS Facilities" and a contributor to Section 7 "Implementation of HVDC schemes" for the proposed CIGRE Green Book on High Voltage DC Power Transmission Systems (HVDC).

2.3 Alexander Kayrin – Senior Consultant

Alexander Kayrin is an electrical engineer with over eight years of experience in utility distribution networks, industrial high voltage systems, renewable energy projects and HVDC projects. He is a specialist in the application of AS2067, lightning protection, earthing, power, lighting and high voltage equipment to 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. 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 AAPL and other proposed HVDC projects in Australia and overseas.

3 Abbreviations

The terms and abbreviations provided in Table 3-1 have been used throughout this report.

Table 3-1 – Terms and Abbreviations

Term / Abbreviation	Definition
AC	Alternating Current
AEMO	Australian Energy Market Operator
APR	Annual Planning Report
AUD	Australian Dollar
EPC	Engineer, Procure and Construct
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
ISP	Integrated System Plan
kV	Kilo-Volt (measurement of voltage)
LCC	Line Commutated Converter
MVAr	Mega-Volt-Ampere reactive (measurement of reactive power)
MW	Mega Watt (measurement of active power)
NEM	National Electricity Market
NSW	New South Wales
NTNDP	National Transmission Network Development Plan
PACR	Project Assessment Conclusion Report
PADR	Project Assessment Draft Report
PSCR	Project Specification Consultation Report
PV	Photo-Voltaic (Solar Generation Technology)
RBA	Reserve Bank of Australia
VRET	Victorian Government Renewable Energy Target
RIT-T	Regulatory Investment Test for Transmission
ROW	Right of Way
SA	South Australia
TAPR	Tasmanian Annual Planning Report
TB	CIGRE Technical Brochure
TAS	Tasmania
TNSP	Transmission Network Service Provider
VAPR	Victorian Annual Planning Report
VIC	Victoria
VSC	Voltage Source Converter
WA	Western Australia
WEM	Wholesale Electricity Market
Western Victoria	Western Victoria Region
WVTNP	Western Victoria Transmission Network Project

4 Introduction and Background

The transition to renewable energy sources has made Western Victoria an attractive location for new electricity generation due to the quality of its renewable energy resources. AEMO has assessed that the transmission infrastructure in this region is insufficient to allow efficient access to all the new and committed Renewable Energy Zones (REZ) seeking to connect to it [1].

It was identified in the AEMO PSCR [1] that around 2,000 megawatts (MW) of committed new renewable generation was to either be built or be in the process of commissioning in the Western Victoria region by 2020. AEMO also projected that a further 3,000 MW of new generation will be constructed in the region by 2025, and a further 1,000 MW by 2030, based on proposed new connections in the region and the increase required to achieve the Victorian Government's Victorian Renewable Energy Target (VRET) of 50% by 2030 [2].

AEMO expects generators connecting to the existing 66 kV and 220 kV transmission systems in Western Victoria to be heavily constrained by the thermal capacity of that network, while those proposing to connect to the existing 500 kV transmission system are not expected to be constrained.

The WVTNP underwent the Regulatory Investment Test for Transmission (RIT-T) over 2017-19. The preferred option proposed is Option C2 utilising overhead AC transmission [3].

Amplitude were engaged by the Council to investigate how an alternative transmission solution utilising HVDC technology and underground cables could be applied instead of the proposed overhead AC transmission lines for the WVTNP. Additionally, the Council requested for Amplitude to undertake a qualitative and comparative assessment of other non-market benefits of the transmission construction options including the use of HVDC and AC technology and overhead and underground construction for each.

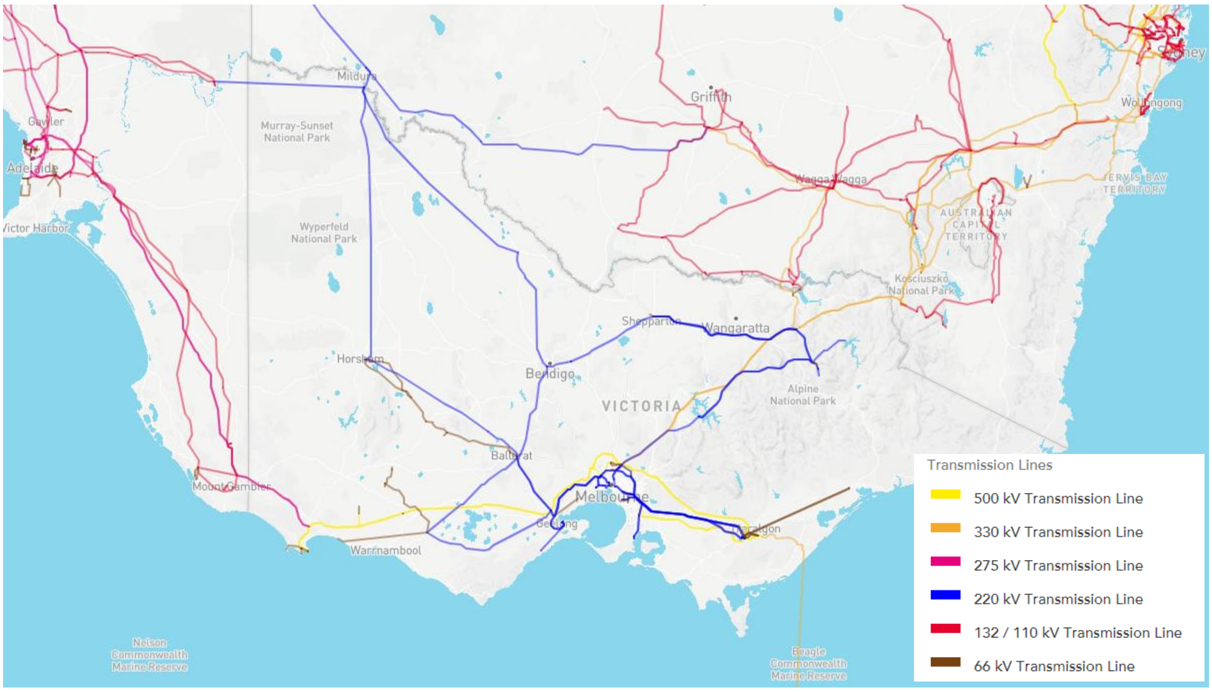
5 Western Victorian AC System Considerations

5.1 Existing AC Network

The Western Victoria region extends to include Central Highlands, Wimmera Southern Mallee, Mallee, Loddon Campaspe, and parts of the Great South Coast as defined in the context of the RIT-T [1].

The transmission network consists predominantly of 66 kV, 220 kV and 500 kV transmission lines and is connected to the rest of the National Electricity Market (NEM) via AC and HVDC transmission lines. The transmission lines in the Western Victoria region are shown in Figure 5-1. The generation from the Western Victoria region accounts for approximately 10% of the state's electricity demand, while the average peak demand in the region is expected to remain flat over the next five-year period [1].

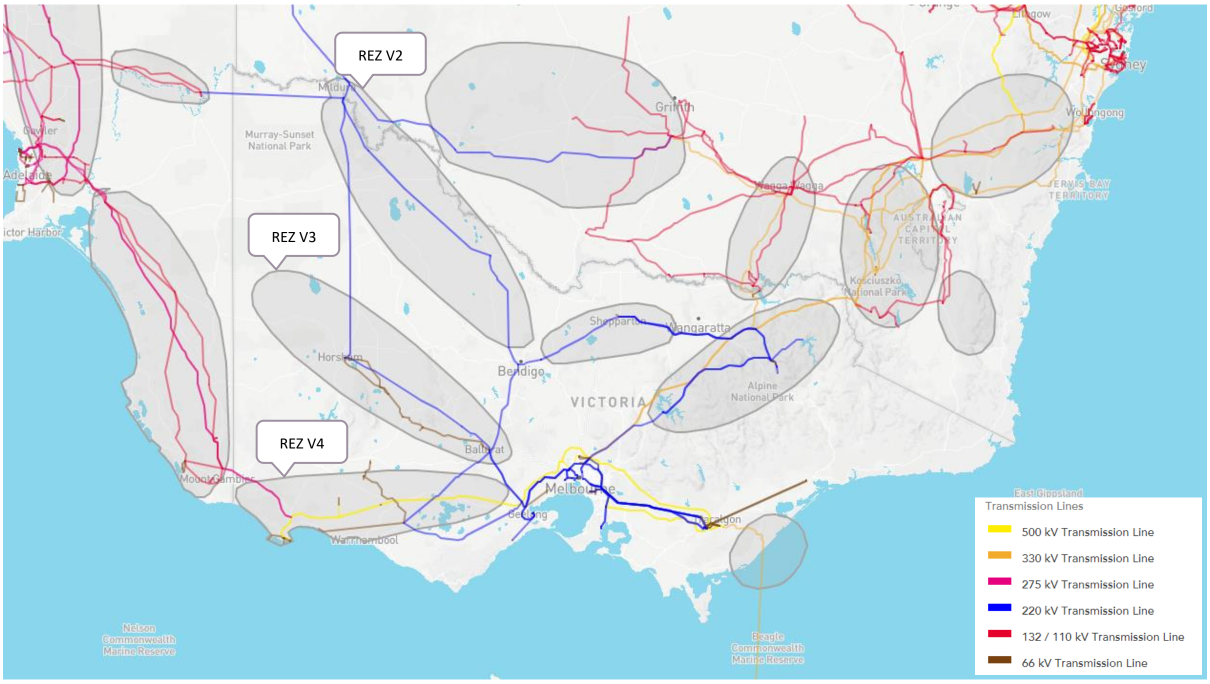
Figure 5-1 – Western Victoria Transmission Network



5.1.1 Renewable Energy Zones in the Western Victoria Region

The Integrated System Plan (ISP) published by AEMO has identified a number of REZs within the Western Victoria region with “good” to “excellent” quality [1] of renewable energy resources – predominantly being high levels of wind energy or solar irradiance. The REZs in Western Victoria region are shown in Figure 5-2.

Figure 5-2 – REZs in Western Victoria Region



The type of renewable generation and installed capacity forecast by AEMO to be developed in the indentified REZs by year 2030 are summarised in Table 5-1.

Table 5-1 – Renewable Generation Summary in Western Victoria Region [4]

REZ Area	Solar			Wind			Total Forecast[1] (MW)	Total Potential (MW)
	Forecast (MW)	Potential (MW)	Quality	Forecast (MW)	Potential (MW)	Quality[2]		
REZ V2	400	4,700	C	-	-	D	400	4,700
REZ V3	100	400	D	700	2,800	B	800	3,200
REZ V4	-	-	E	750	3,900	C	750	3,900

Notes:

1 Forecast generation by year 2030 excluding current installed generation and committed projects.

2 AEMO defined solar and wind average capacity factor based on nine reference years, refer to ISP 2020 **[4]**.

5.1.2 Congestion on Existing AC Network

The identified REZs in Western Victoria region as described in Section 5.1.1 are attractive to developers due to the quality of the resources and the relatively low cost of land in the area. Renewable generation developers are proposing to connect to the existing 66 kV and 220 kV transmission lines and/or associated local substations. The majority of the power generated in the Western Victoria REZs during peak times, that is in excess of the region’s local demand, would flow to the main load centre of Melbourne city via the Moorabool Terminal Station (TS) [1].

In their initial assessment in the PSCR released in 2017 [1], AEMO has reported shortages of available capacity on these transmission lines. When shortages of capacity on the transmission lines occur, generation typically needs to be constrained, or turned off, in order to maintain system stability and/or prevent overloading of the lines during contingencies, faults, or outages on the network. With the increasing development and connection of renewable generation in the Western Victoria region, AEMO has forecast increasing levels and durations of transmission capacity shortages and generation needing to be constrained. As such, they have identified the need for augmentation of the existing network in order to accommodate the increasing amount of connection of renewable generation.

The PSCR identified limitations of the existing network related to both thermal limits and system strength. These are summarised below (refer to [1] for further details):

- **Thermal limits:**
    - Refers to physical limitations of the transmission lines to be able to transfer power, which cannot be exceeded to avoid failure of the conductors.
    - The proponents applying to connect to the existing 220 kV network in 2017 exceeded the combined available capacity of the connection points by 70%.
- **System Strength**:
    - Refers to the available fault current or the short circuit ratio, driven by factors such as transmission distance between terminal stations and the amount of synchronous generation (i.e. conventional power stations) connected to the network.
    - The network in Western Victoria region is of low system strength as it has long distances between terminal stations and limited amount of synchronous generation connected. Additional non-synchronous generation (wind and solar farms) contribute to lowering system strength which can degrade the power system performance and security.

- The connection of renewable generators onto a system of low strength can result in these generators being constrained, meaning that they would not be able to supply all the available power being generated.

6 AEMO Preferred WVTNP Option – C2

6.1 Overview

AEMO has performed an analysis of the different network augmentation options to facilitate the connection of renewable energy generators, as presented in the Western Victoria Renewable Integration PADR published in 2018 [5]. The preferred option for the augmentation of the Western Victoria network which is stated to provide the highest market benefit is Option C2. It is noted that:

a) Only market costs and benefits are evaluated as part of the RIT-T process and that non-market benefits are not taken into consideration; and

b) No underground options were considered as part of the RIT-T analysis.

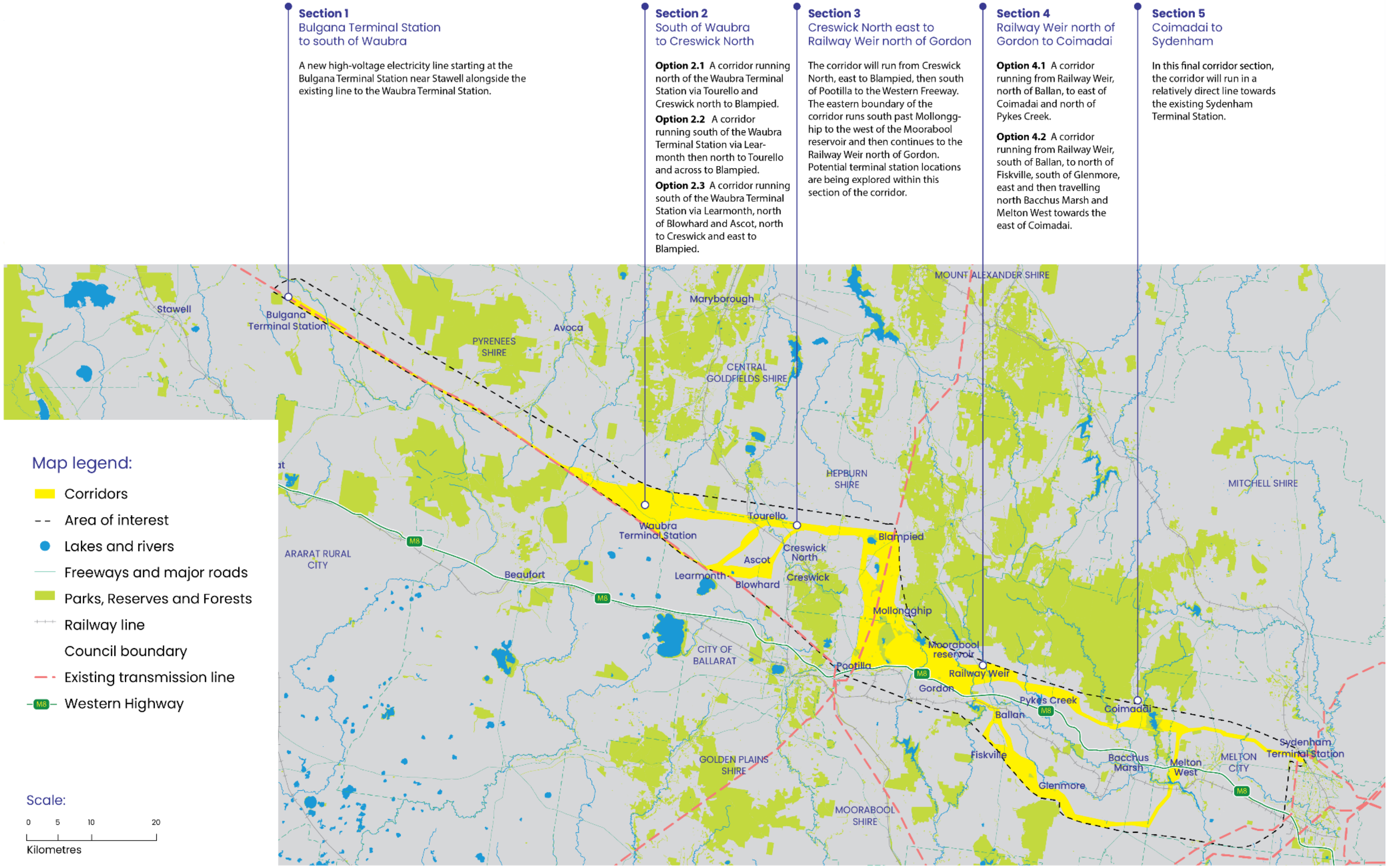
The scope of the Option C2 includes:

1. Minor transmission line augmentations for the Red Cliffs to Wemen to Kerang to Bendigo, and Moorabool to Terang to Ballarat 220 kV transmission lines. The scope for this includes the installation of wind monitoring systems and upgrading limiting equipment at the terminal stations.
2. Construction of a new North Ballarat TS with 2x 1,000 MVA 500/220 kV transformers.
3. Connecting North Ballarat TS to the existing Ballarat to Bendigo 220 kV single circuit transmission line.
4. Construction of a new 500 kV double circuit line from Sydenham to North Ballarat, with a summer rating of 2,700 MVA per circuit, and 50 MVAr reactors on each end of each circuit. Figure 6-1 shows the corridors for further investigation by the AusNet and Mondo WVTNP Project team for the placement of the AC OHTL. This transmission line is estimated to span approximately 118 km based on the estimated route [6].
    - Amplitude notes that the PACR presents the line rating as both 2,700 MVA (at 40^{O}C) and 2,700 MW. OHTL ratings are dependent on ambient temperature and wind movement. A typical line rating for a 500 kV AC OHTL is between 2,500 MVA and 3,000 MVA [3].

      Therefore, a rating of 2,700 MVA was used in this report as it is both mentioned in the PACR and is a reasonable average rating of a single circuit on a 500 kV OHTL.
5. Construction of a new 220 kV double circuit OHTL from North Ballarat to Bulgana with a summer rating of 750 MVA per circuit. Figure 6-1 shows the corridors for further investigation by the AusNet and Mondo WVTNP Project team for the placement of the AC OHTL. This transmission line is estimated to span approximately 90 km based on the estimated route. A potential further upgrade of this line to 500 kV is also being proposed by the Victoria State Government [6], however this is outside of the scope of this report.

6. Connecting one of the new 220 kV transmission circuits from North Ballarat to Bulgana to the existing Waubra Terminal Station.
7. Disconnecting the existing Waubra TS from the existing Ballarat to Waubra to Ararat 220 kV transmission line.
8. Cutting in the Ballarat to Moorabool 220 kV circuit No. 2 at Elaine Terminal Station.
9. Install additional circuit breakers at Ballarat Terminal Station to establish a bus splitting control scheme following a critical contingency.

Figure 6-1 – Transmission Route Corridors Under Investigation by the WVTNP Project [7]



Section 1
Bulgana Terminal Station to south of Waubra

A new high-voltage electricity line starting at the Bulgana Terminal Station near Stawell alongside the existing line to the Waubra Terminal Station.

Section 2
South of Waubra to Creswick North

Option 2.1 A corridor running north of the Waubra Terminal Station via Tourello and Creswick north to Blampied.

Option 2.2 A corridor running south of the Waubra Terminal Station via Learmonth then north to Tourello and across to Blampied.

Option 2.3 A corridor running south of the Waubra Terminal Station via Learmonth, north of Blowhard and Ascot, north to Creswick and east to Blampied.

Section 3
Creswick North east to Railway Weir north of Gordon

The corridor will run from Creswick North, east to Blampied, then south of Pootilla to the Western Freeway. The eastern boundary of the corridor runs south past Mollongghip to the west of the Moorabool reservoir and then continues to the Railway Weir north of Gordon. Potential terminal station locations are being explored within this section of the corridor.

Section 4
Railway Weir north of Gordon to Coimadai

Option 4.1 A corridor running from Railway Weir, north of Ballan, to east of Coimadai and north of Pykes Creek.

Option 4.2 A corridor running from Railway Weir, south of Ballan, to north of Fiskville, south of Glenmore, east and then travelling north Bacchus Marsh and Melton West towards the east of Coimadai.

Section 5
Coimadai to Sydenham

In this final corridor section, the corridor will run in a relatively direct line towards the existing Sydenham Terminal Station.

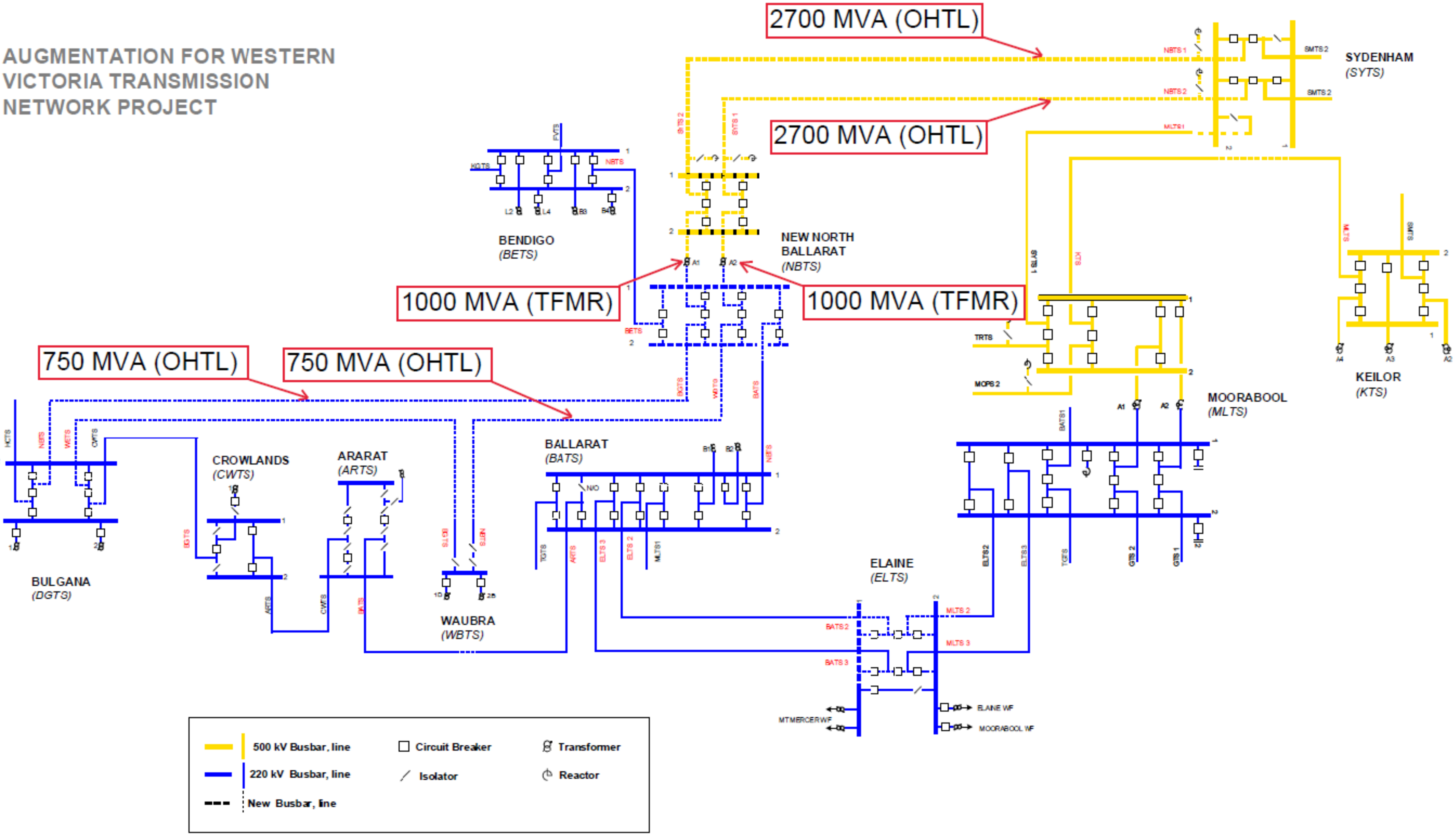
Map legend:

- 🟨 Corridors
- -- Area of interest
- ● Lakes and rivers
- Freeways and major roads
- 🟩 Parks, Reserves and Forests
- Railway line
- Council boundary
- Existing transmission line
- M8 Western Highway

Scale:

The single line diagram for Option C2 is shown in Figure 6-2, which includes Amplitude's interpretation of design capacities of the new lines and transformers based on information supplied and available in the public domain.

Figure 6-2 – Option C2 Single Line Diagram [3]



From the further assessment presented in the Western Victoria Renewables Integration PACR published in 2019, AEMO states that this option has the highest projected net market benefits under all assessed scenarios and sensitivities [3].

The preferred Option C2 is stated by AEMO to provide the following benefits [3]:

- Minimise network congestion;
- Reduce the capital cost of new generation by enabling more efficient generation connections;
- Improve the generation dispatch efficiency;
- Increase the Victoria to New South Wales interconnector capacity;
- Enable future transmission network expansion from Victoria to New South Wales, consistent with the 2018 ISP;
- Support future efficient development of the national transmission network; and
- Help to reduce the cost of electricity for consumers in the long term.

6.2 Option C2 Costs

The latest estimated costs of Option C2 for the 220 kV and 500 kV portions of the option are presented in the PACR [3]. The PACR report also shows the estimates obtained from AusNet and three different vendors, as shown in Table 6-1. The average values of the estimates will be used for comparative purposes in this study.

Table 6-1 – Option C2 Cost Estimates [1]

Portion	Cost Estimate in AUD$ (M)					
	AEMO	AusNet	Vendor 1	Vendor 2	Vendor 3	Average
220 kV	188	200	182	168	202	**188**
500 kV	285	321	283	250	287	**285.2**
Total	473	521	465	418	489	**473.2**

6.3 VNI West Project

The WVTNP is part of a greater plan to develop the transmission network in the Western Victoria region and South-East New South Wales, which is comprised of a number of other projects that are either committed or actionable ISP projects as defined by AEMO.

One such project which is related to the WVTNP is the VNI West interconnector. This project is proposed to connect to the new North Ballarat TS, which is part of the WVTNP, via a new 500 kV line from either Dinawan or Wagga Wagga TS, referred to as the Kerang Link and Shepparton Link, respectively. The decision on the selection of link to be built is currently being investigated by AEMO through the RIT-T process [8].

The VNI West project is expected to bring an additional 2,000 MVA of transmission capacity through the new North Ballarat TS with the ability to channel that power through the WVTNP 500 kV OHTL to Sydenham TS. Early works are expected to commence in late 2024 and completion is anticipated to be in 2027-2028 [8].

Refer to Figure 6-3 for VNI West project overview and Figure 6-4 for the single line diagram of the VNI West connection to the new North Ballarat TS.

Figure 6-3 – VNI West Overview [8]

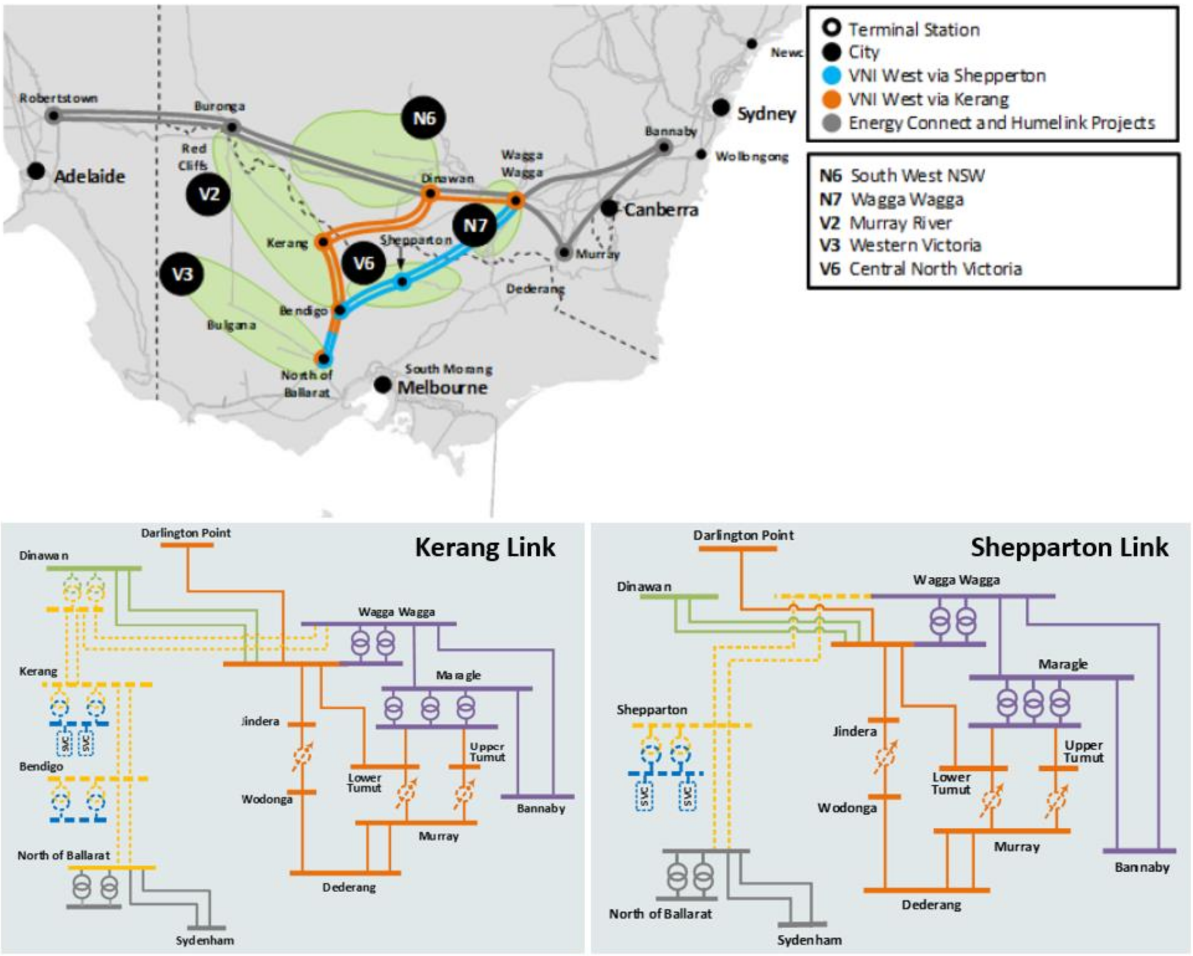
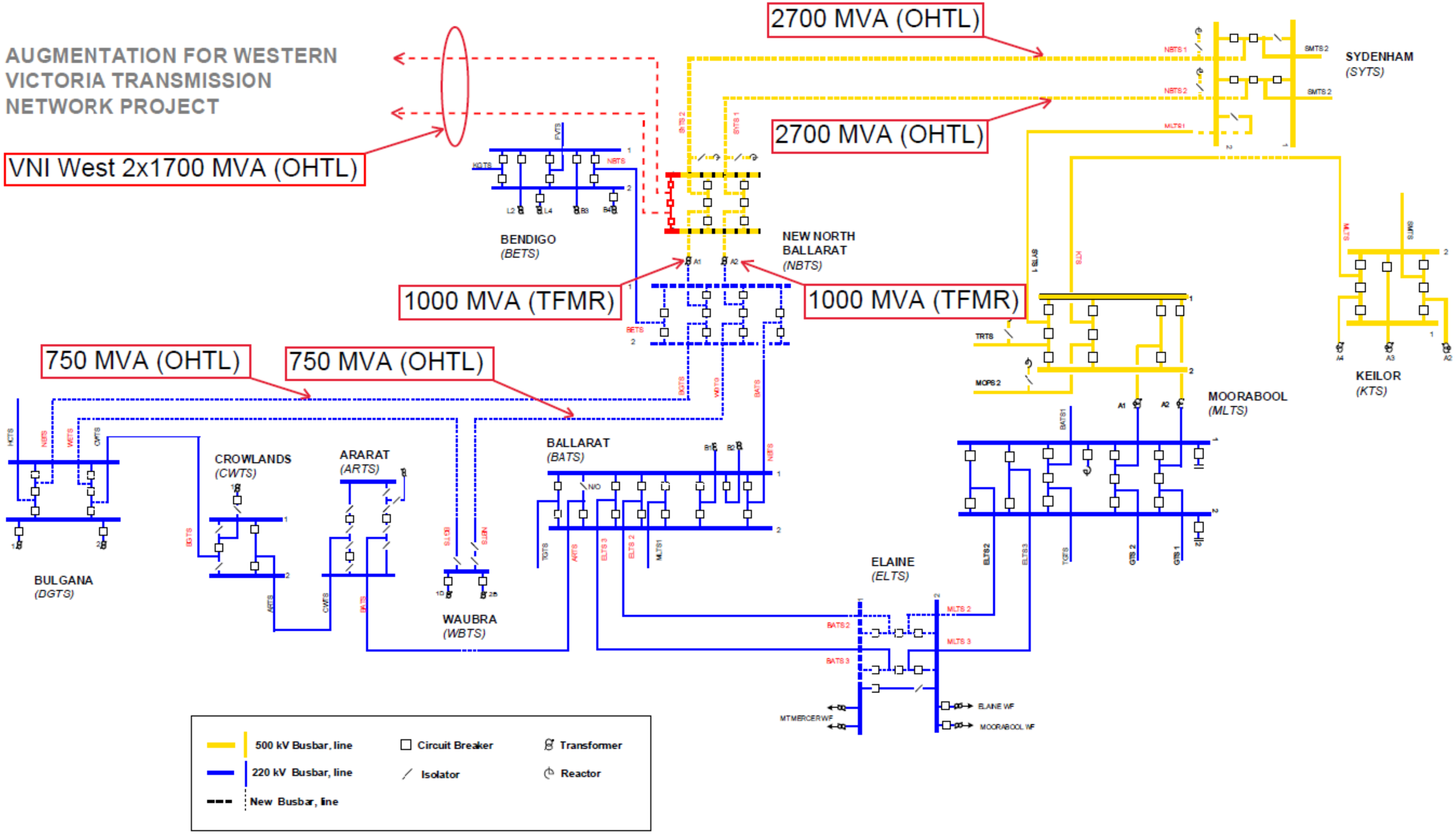


Figure 6-4 – VNI West Connection to New North Ballarat TS [3]



7 AC vs. HVDC Transmission

Amplitude were engaged to explore an alternative HVDC underground option to the AEMO proposed AC solution (Option C2) for the WVTNP. This Section presents some high-level comparisons of some of the key differences between AC and HVDC transmission technology.

There are pros and cons with the use of both AC and HVDC technology for high power transmission interconnection. The best technology to select is often dependent on the specific application. For the HVDC transmission system, voltage source converter (VSC) technology was selected for the WVTNP alternative due to anticipated lower system strength at the connection points and its suitability for the power transmission requirements. Further details of the technology and the justification for its use is provided in Appendix A of this report. Table 7-1 provides a summary of key pros and cons when comparing AC and VSC HVDC technologies for the purpose of power transmission.

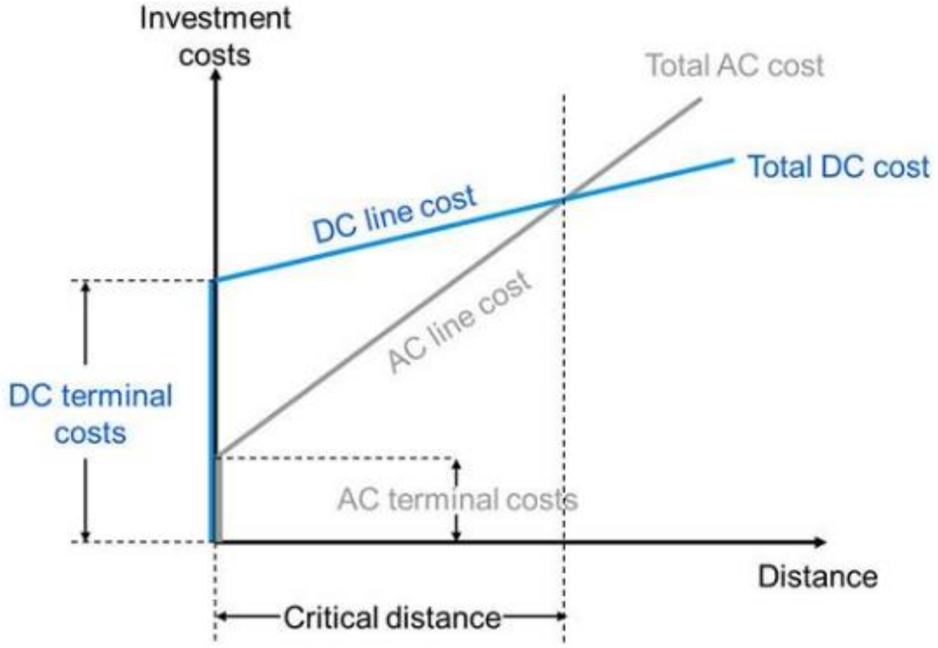
Table 7-1 – Pros and Cons of AC and VSC HVDC Technology for Power Transmission

Parameter	AC	VSC HVDC
Controllability	No	High
Losses – Substation/Converters	Lower	Higher
Losses – Lines/Cables	Higher	Lower
Inherent Voltage Support Capability	Not Available	Available
Inherent Damping Control Capability	Not Available	Available
Overhead Line	Larger Conductors, More Conductors, Larger Towers	Smaller Conductors, Fewer Conductors, Smaller Towers
Underground Cable Capability	At a distance >50km and at higher voltage, requires substantial reactive compensation	No Practical Limit on Distance, Fewer Cables
Tap Off Points Along Route	Unlimited, relatively low cost	Limited to a few and preferably known in advance, high cost
Substation/Converter Station Footprint	Smaller	Larger
Easement Width for Overhead Lines	Larger	Smaller
Visual Impact of Overhead Lines	Greater	Lesser

VSC HVDC transmission has a number of technical advantages over AC transmission, including controllability, lower losses on the transmission lines, voltage support and damping control capability. Conversely, AC transmission will have lower losses in the terminals (substations). For the same power transfer level, the VSC HVDC transmission can be superior in terms of environmental impact and aesthetics where the use of underground cables becomes more viable.

In terms of cost of AC versus HVDC, in general, the total cost per MW of an HVDC interconnector becomes more competitive against an AC option as the route length of the interconnector increases and once a “breakeven distance” is exceeded. This is often represented generically in the form of Figure 7-1, which also shows the effect of the high terminal and converter cost versus the relatively lower AC substation cost. The slope of the lines in this graph indicates that the cost per kilometre of the transmission circuits i.e. the lines or cables, is generally much less for HVDC systems due the fewer conductors or cables required for the same MW level of power transmission.

Figure 7-1 – Comparison of AC and HVDC cost vs Distance[1]



8 Comparison of Overhead and Underground Transmission

Amplitude has performed a further comparison between the two transmission types with a focus on the design of the transmission system construction, where underground (UG) and overhead transmission line (OHTL) options for the WVTNP were compared for both AC and HVDC. Thirty-seven different criteria were used to assess the four different options (AC and HVDC OHTL, AC underground and HVDC underground). The criteria used included technical, environmental, land use/disturbance and risk aspects. Refer to Appendix A for the detailed comparison that was performed.

To aid in the comparison, a traffic light ranking system was applied to identify how each of the four options faired against the considered criteria in terms of being the option with the highest (red), moderate (yellow) and lowest (green) impact. It should be noted that this comparison was performed at a very high level and was based on the information that was available in the public domain at the time of writing this report and what is known to Amplitude from previous HVDC projects and industry experience.

The comparison is also tailored to the general parameters of the WVTNP project, meaning that the rankings and outcomes of the comparison could be different when considering a project with different parameters, such as route length, power capacity requirements, voltage levels, etc. The assessment and ranking results are presented in Figure 8-1.

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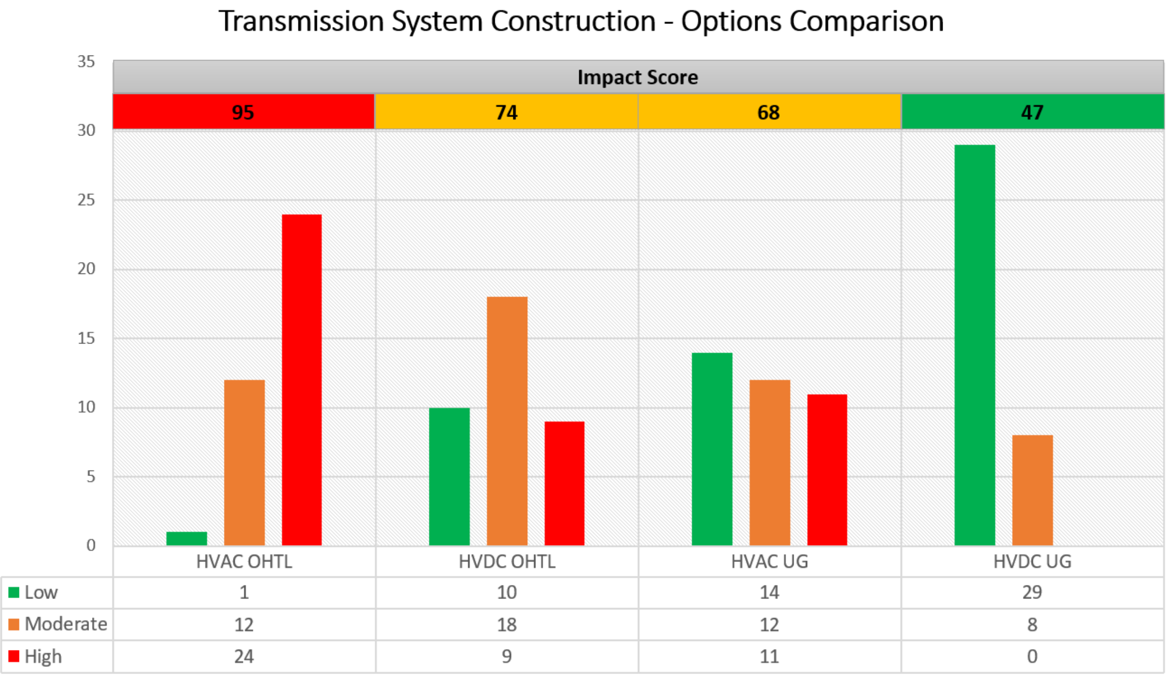
[1] *Image from medium.com/predict/future-of-electricity-transmission-is-hvdc-9800a545cd18.*

Figure 8-1 – Transmission System Construction Comparison Ranking Results



	HVAC OHTL	HVDC OHTL	HVAC UG	HVDC UG
🟩 Low	1	10	14	29
🟧 Moderate	12	18	12	8
🟥 High	24	9	11	0

It can be seen from Figure 8-1 that the HVDC underground option has the least impact against all other options based on the assessment criteria, while the AC OHTL has the highest number of high impact scores. The key reasons for this are as follows:

- HVDC underground cables are technically feasible for this distance, whereas the AC underground cables will be subject to very large charging current beyond a 50 km route length at a high voltage level requiring significant reactive compensation and design considerations.
- The HVDC underground option requires less cables to transmit the same amount of power, and the cables themselves are most likely to be smaller. Therefore, the required trench width to accommodate the cables is expected to be significantly less than for the AC underground option.
- Due to the smaller trench size requirement for the HVDC underground option it is expected that the cables can be installed along or near to the existing road reserves for the majority of the route. By using existing road reserves, ready access to the proposed trenching locations and joining pits is generally expected to be available for construction access and therefore will have the least impact on farmlands and land disturbance in terms of existing agricultural activities.
- The impact to the surrounding environment is greatly reduced for the HVDC underground option compared to all others, as there are significantly reduced electro-magnetic fields (EMF), no noise pollution, impact to visual amenity or risk of causing bush fires.
- The HVDC underground option will also not be impacted by bush fires. Power does not need to be switched off during bush fires to aid firefighting, and the power transmission is highly unlikely to be disrupted due to smoke causing flashovers and potentially tripping breakers.

- HVDC systems have active power flow control and can provide reactive power depending on the HVDC technology selected together with frequency and damping support. Furthermore, HVDC systems can electrically isolate two networks, or parts of larger networks, so that a fault in one part of the network is not substantially transferred to another part of the network which can help to prevent system collapse for large disturbances.
- Other technical advantages also attributed to the HVDC underground option as shown in Table 7-1.

9 Concept HVDC System

Amplitude has developed a number of Concept HVDC System options that could fit the requirements of the WVTNP Option C2, based on a high-level assessment. An overview of the options is shown below:

- **Option 1 (Base Case – 100% Redundancy):** a HVDC system that matches the transfer capacities of the AEMO preferred Option C2, for both the 220 kV AC OHTL between Bulgana and North Ballarat and the 500 kV double circuit line between North Ballarat and Sydenham. This system provides an N-1 redundancy level.
- **Option 2 (50% Redundancy):** an alternative option to the base case that maintains the maximum transfer capacity of a single 500 kV AC OHTL and still provides some redundancy, albeit at a reduced level. This reduces the complexity of the system and the resulting capital costs.
- **Option 3 (No Redundancy):** similar to Option 2 in terms of transfer capacity but with no redundancy in the system, which further reduces the complexity of the system and results in lower capital costs.

The key parameters common to all of the options are summarised in Table 9-1. The more detailed technical description of the parameters and discussion on why they were selected can be found in Appendix A of this report.

Table 9-1 – Key Common Parameters of the Concept HVDC System

Parameter	Value	Reasoning and Discussion
Converter Technology	VSC	VSC technology is more suitable for the power transfer capacity and after consideration of other factors when compared to LCC technology.
Converter Topology	MMC	This topology is 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. MCC topology also results in lower converter losses.
Voltage Level	525 kV	For the required power transfer capacity, this voltage would keep the current at a level to allow for reasonable cable sizing. Further analysis of cable sizing and system voltage will need to be performed if the HVDC option were to proceed.

Parameter	Value	Reasoning and Discussion
Land Cable Route	167 km	Estimated to be the most direct route from Bulgana TS to the new North Ballarat TS and then to Sydenham TS. This route was estimated with the use of prudent avoidance techniques, utilising right of way corridors of existing transmission lines and routing of cables along the existing road reserves. Actual proposed routes require further detailed investigation.
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 and other benefits as discussed in Section A.2.1.

The options are further presented in the following subsections.

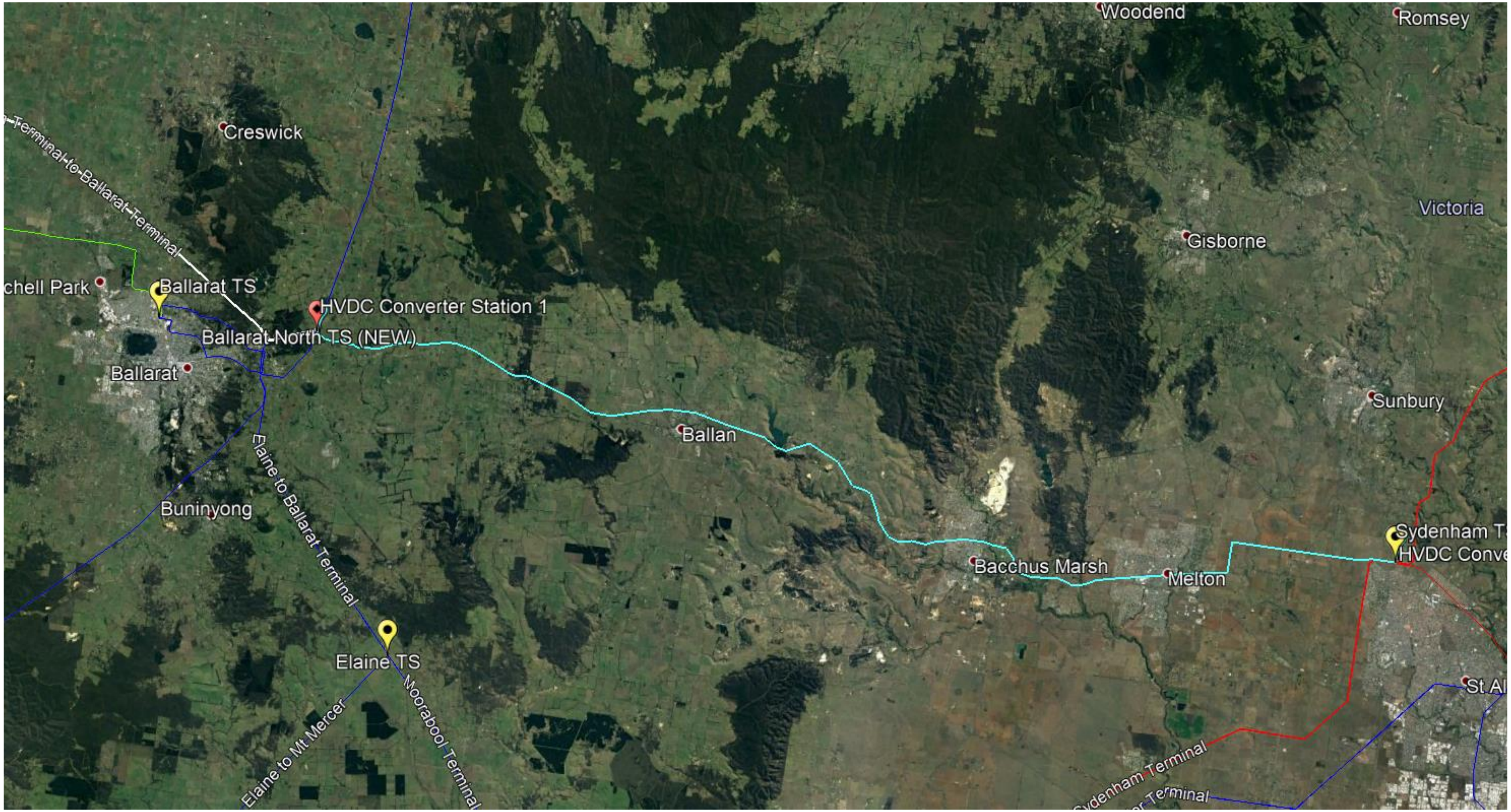
9.1 HVDC Underground Cable Transmission Route and Connection Points

For the purpose of developing a Concept HVDC System as an alternative for WVTNP Option C2, Amplitude have estimated a land cable route for the HVDC underground cable by applying prudent avoidance techniques and routing the cables mainly along roadways, existing transmission line right of way corridors and away from farmlands, nature or conservation reserves as much as possible. This is assumed to be practically feasible as a cable trench of approximately three meters wide should be able to fit in the fire break zone of the existing roadways and would not require a significant extension of the transmission line corridors. The conceptual route and converter station locations are shown in Figure 9-1 and Figure 9-2. The total route length is approximately 88.5 km between Bulgana and North Ballarat and 78 km between North Ballarat and Sydenham.

The converter station at Bulgana was assumed to connect to, and be located in close proximity to, the existing Bulgana TS. The converter station location at North Ballarat was assumed to be next to the existing 220 kV line that runs from Ballarat TS to Bendigo TS and would cut into the OHTL on the AC side. The converter station at Sydenham was assumed to connect to, and be located in close proximity to, the Sydenham TS.

Figure 9-1 – HVDC Underground Cable Route, Bulgana to North Ballarat (White Line)

Figure 9-2 – HVDC Underground Cable Route, North Ballarat to Sydenham (Teal Line)



9.2 Concept HVDC Option 1 – Base Case

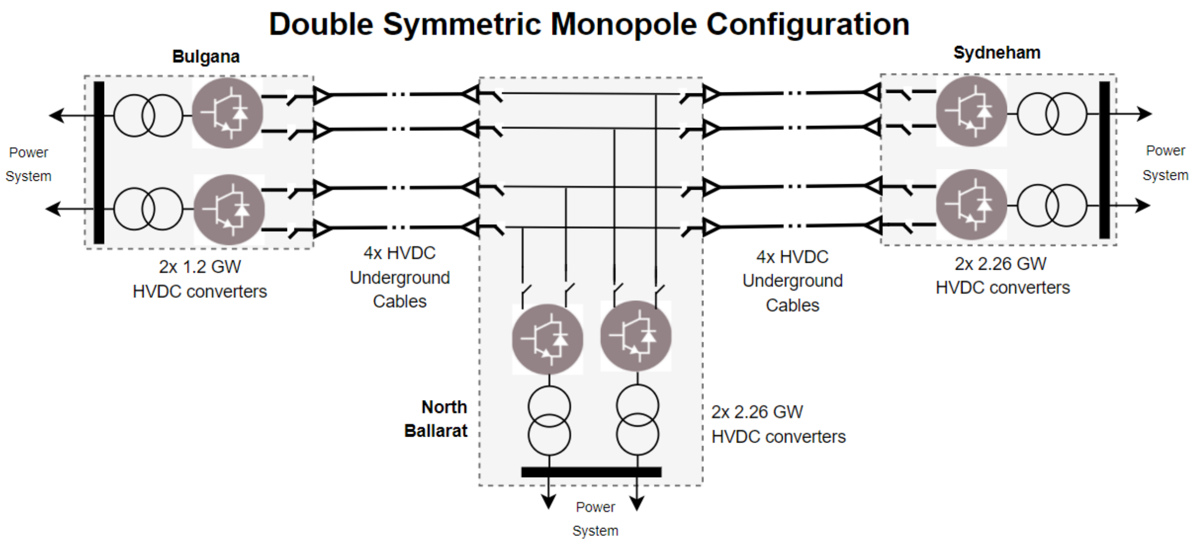
The Base Case Concept HVDC System proposes a three-terminal double symmetric monopole system with parameters as shown in Table 9-2. This is a robust option that is equivalent to the AEMO preferred Option C2, in terms of power transfer capacity and full system redundancy.

Table 9-2 – Base Case Option Concept HVDC System Parameters

Parameter	Description
Configuration	Double Symmetric Monopole
Redundancy	100% - this means that for a fault on either one cable or one converter, the second system can continue operating at its maximum system rated capacity. i.e. instead of splitting 2.26 GW across two systems, one "healthy" system will take the full load.
Converter Station 1 - Bulgana	Two converters rated at 1.2 GW each
Converter Station 2 - North Ballarat	Two converters rated at 2.26 GW each
Converter Station 3 - Sydenham	Two converters rated at 2.26 GW each
Transmission Line 1 - Bulgana to North Ballarat	Four underground cables with a combined maximum transfer capacity of 2.4 GW. Required trench is estimated to be approx. 2 m wide and 1.25 m deep.
Transmission Line 2 - North Ballarat to Sydenham	Four underground cables with a combined maximum transfer capacity of 4.52 GW. Required trench is estimated to be approx. 3 m wide and 1.25 m deep.

The Base Case Concept HVDC System is shown diagrammatically in Figure 9-3.

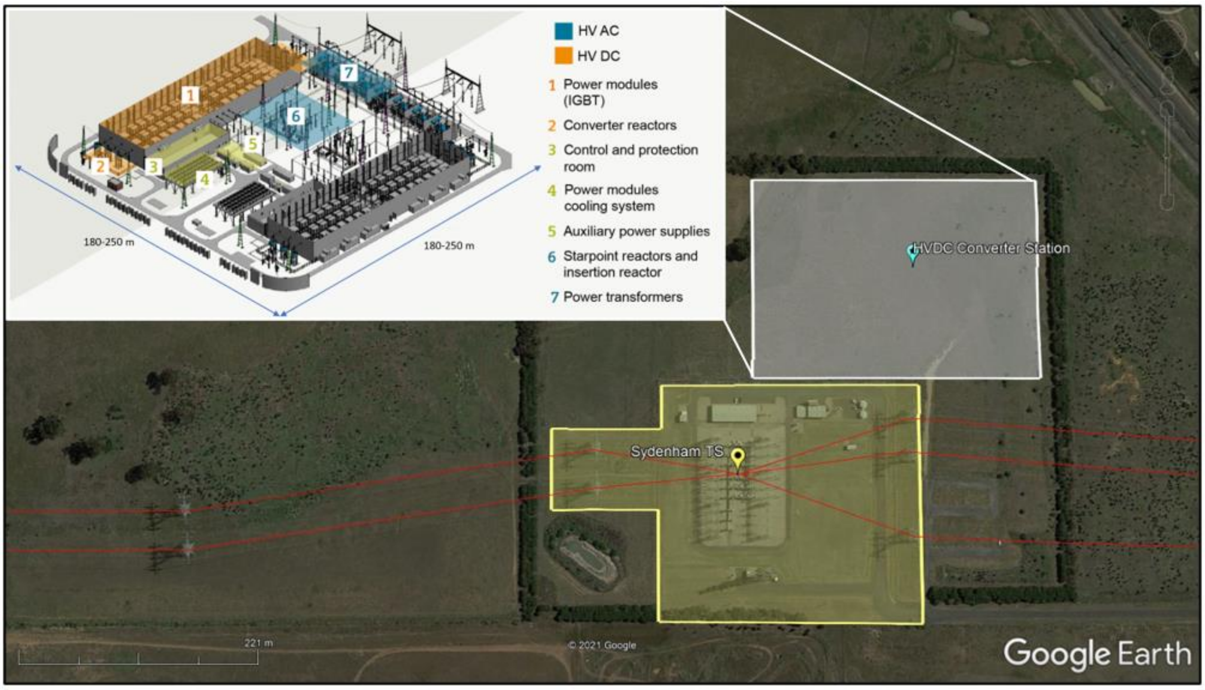
Figure 9-3 – Option 1: Diagrammatic Representation of Base Case Concept HVDC System



9.3 Converter Station Typical Layout and Land Footprint

A typical converter station layout and dimensions are shown in Figure 9-4. The footprint of a converter station can be influenced by factors such as land availability, terrain and system design. It is also possible to construct HVDC systems in different arrangements and configurations, which will affect the converter stations' footprint. For the case of the HVDC converter stations at each end of the Base Case option, footprints are expected to be in the range of 50,000 m^2 to 65,000 m^2. By comparison, and as shown in Figure 9-4, this footprint is expected to be comparable to the footprint required for an existing 500 kV AC terminal station.

Figure 9-4 – Typical Converter Station Layout [9]



9.4 HVDC Underground Cables and Installation

This section describes the selected parameters and installation of the underground cables for the Concept HVDC System. The cable parameters are selected based on the ratings of the Concept HVDC System Base Case option and the parameters described in Section 9.1. The scope of the final installation will need to take into account the following aspects:

- Route selection;
- Trench width and depth determination to suit the number of cables to be installed;
- Vegetation and tree clearance;
- Soil excavation types;
- Cable layout; and
- Backfilling materials.

9.4.1 HVDC Cable Parameters

Various physical parameters determine the size of HVDC cables, such as burial depth, configuration in which the cables are installed in and temperature related aspects, which would need to be ascertained during the design phase with the aid of survey information. In the absence of detailed information, Amplitude used the following assumptions to estimate the cables sizes to meet the requirements of the Concept HVDC System design:

- Burial depth (to top of cable): 1.0 m.

- Conductor Spacing: Bundled, 0.5m, 1 m, 1.5 m, 2 m.
- Thermal Resistivity (TR) of soil: 1.2 K.m/W.
- Soil Temperature: 20^{O}C.

Amplitude applied the methodology presented in IEC 60287 for the required system ratings for a double symmetric monopole configuration to develop a range of expected cable sizes. The options for the concept cable design suitable for the WVTNP project based on the parameters above and the Concept HVDC System parameters are shown in Table 9-3.

Table 9-3 – Concept HVDC System Cable Sizing Options

Spacing Between Cables [1]	Required Conductor Diameter			
	Bulgana to North Ballarat (1.2 GW)		North Ballarat to Sydenham (2.26 GW)	
	Cu (mm^2)	Al (mm^2)	Cu (mm^2)	Al (mm^2)
Bundled	649	1,100	2,301	N/A [2]
0.5 m	507	796	1,800	N/A [2]
1 m	445	698	1,578	2,475
1.5 m	414	650	1,470	2,305
2 m	397	623	1,408	2,209

1 *Measured between centre point of the cable.*

2 *For practical purposes, a limit of 2,500 mm^2 was applied to cable sizes.*

From the cable sizes presented in Table 9-3, Amplitude are of the view that the bundled 1,100 mm^2 aluminium cables are suitable for the Bulgana to North Ballarat line and the 1,800 mm^2 copper cables with a spacing of 0.5 m would be a suitable option for the North Ballarat to Sydenham transmission line for this option. The selection of these cable sizes is expected to keep the trench sizes relatively narrow, which would allow for ease of installation (more cable per drum, reduced drum weight etc) and keep the conductor at size which is also not beyond or too close to the limit of available cable sizes on the market. Further analysis would be required to optimise the cable size and the overall HVDC system parameters if the HVDC option were to be pursued further.

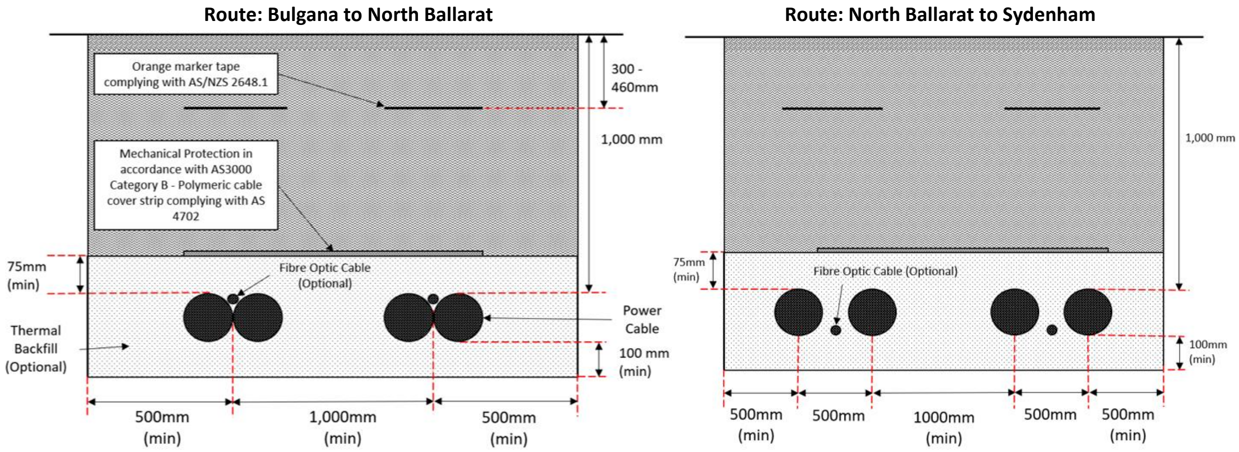
9.4.2 HVDC Underground Cable Trench Profile and Installation

Amplitude developed two concept cable trench profiles based on the cable parameters and spacing selected as described in Section 9.4.1. The two trenches vary in width due to the spacing requirements between cables, which are estimated to be as follows:

- **Bulgana to North Ballarat Route:** cable pairs are laid in bundles in a 2 m wide and 1.25 m deep trench.
- **North Ballarat to Sydenham Route:** within each cable pair, the two cables are spaced apart by 0.5 m in a 3 m wide and 1.25 m deep trench.

Conceptual trench profiles are shown in Figure 9-5.

Figure 9-5 – Cable Trench Profiles (LHS - Bulgana to North Ballarat; RHS - North Ballarat to Sydenham)



Cable trenching requires the use of heavy excavation machinery to dig up the soil to an appropriate depth and apply the required bedding layers and heavy haul transport to remove the excess soil from site. Once the trench is prepared, cables are delivered to the installation site(s) on cable drums by crane trucks, where an installation team will slowly pull the cables in one section at a time, which is assumed in this report to be one kilometre in length for each section. These sections are connected by a cable joint which is installed by a separate, specialist jointing team.

Depending on the type of soil in the region of installation, a different type of backfill material with defined thermal characteristics may need to be imported to cover the cables. This may be required to prevent overheating of the cables in the case where the native soil is determined to not be suitable for drawing heat away from the cables. Cable identification and warning and/or protective layers would also be installed.

Crossings across rivers, ditches, drains may be performed by attaching to existing infrastructure such as bridges or be installed underneath using methods such as horizontal directional drilling. Each crossing typically requires a site-specific design.

9.5 AC vs HVDC Losses

9.5.1 HVDC Underground Option

HVDC systems have inherent losses due to various factors, the two most prominent being losses due to the switching of the IGBTs in the converter submodules and DC resistive losses on the cable systems.

The total losses accounted for by the HVDC converters, including the converter stations at both ends and assuming the use of a half-bridge MMC topology, is expected to be no more than 2% of the total peak power output of the HVDC system.

The HVDC underground cable losses were estimated based on parameters defined in Section 9.4.1. The results are presented in Table 9-4. These results are for the transmission underground cables only and do not include the losses in the converters.

Table 9-4 – HVDC Cable Resistive Losses

Item	Bulgana – North Ballarat	North Ballarat - Sydenham
Voltage	525 kV	
Maximum Power Capacity	2,400 MW	4,520 MW
Cable Length (Route Length + 10%)	97.5 km	86 km
DC Resistance	0.033 Ω/km	0.011 Ω/km
Number of Cables	4	
Current Flowing Per Symmetric Monopole	1.143 kA	2.15 kA
DSM Cable Losses	**16.78 MW**	**17.53 MW**
DSM Converter Losses (assumed 2%)	**48 MW**	**90.5 MW**
Total Losses as % of Total Max. Capacity	**2.49%**	
Notes: *A 10% length increase has been assumed to account for route deviations and required additional length during installation. This is an estimate only, the final route and required cable length is determined during detailed design.*		

The complete HVDC system losses (combined converter and cable losses) are expected to be approximately 2.49% of the maximum power output. It can be seen that the larger portion of losses in the HVDC system comes from the converter stations and not the underground cables.

9.5.2 AC OHTL Option Losses

For comparative purposes, Amplitude has estimated what the equivalent AC transmission losses would be expected to be, at a high-level.

AC systems have electrical losses associated with both the power transmission equipment in substations as well as the OHTL. The substation losses by comparison to the converter station losses are typically the much smaller component, with the OHTL being responsible for the major losses of the AC system. For this high-level estimation, substation losses for the AC option have been assumed to be 0.5%. This value is considered typical based on Amplitude’s experience in the industry but is heavily dependent on the final design of the AC substations and associated transformers.

The losses for the 500 kV AC OHTL for WVTNP Option C2 were estimated based on the following assumptions:

- Four conductor bundles per phase are assumed as is typical for 500 kV AC transmission.
- The conductor size and resistance was determined based on the required current carrying capacity, from which a resistance value of 0.096 Ω/km was used, based on publicly available information [10].
- The route length for the AC OHTL is as described in Section 6 with an assumed 10% increase to account for variations in tower placement and micro-sighting.
- A power factor of 0.93 is the value used for generator automatic access standard in the National Electricity Rules (NER) [11].

The AC OHTL resistive losses were estimated as 5.96% of the maximum power transfer capacity. The complete AC system losses (considering losses associated with three substations and OHTL) are expected to be approximately 7.5 % of the maximum power output considering three substations and the complete circuit length of 231 km from Bulgana to Sydenham.

9.5.3 HVDC and AC Losses Comparison

The estimated system losses for the AC and HVDC systems presented in the previous sections are 7.5% and 2.49% at maximum power output, respectively. It can be seen that the AC option is higher than the HVDC option. An even larger difference in losses would be expected if the transmission route were longer than that of the WVTNP. As the losses here are calculated based on the maximum power output, it should be noted that the losses will vary for both the AC and HVDC systems at different power levels.

9.6 HVDC Project Option Costs

9.6.1 Base Case Option – Cost Estimate

Amplitude have prepared a high-level cost estimate for the WVTNP Base Case Concept HVDC System described in this report which is presented in Table 9-5. The following cost estimate assumptions were applied:

1. This high-level assessment has been developed for the purpose of comparing the AC and HVDC options only.
2. The capital cost estimates therefore are limited to the costs directly related to the engineering, procurement, manufacture, construction, installation, testing and commissioning of the proposed HVDC transmission system. Other costs associated with the project are assumed to be the same or similar for both AC and HVDC options.
3. The cost estimates exclude such items as:
    i. Land or easement purchase and associated ongoing costs;
    ii. Environmental planning, permitting, or cultural heritage and associated mitigations (if required);
    iii. Site preparation or demolition works and civil engineering risk items such as rock or soil contamination risk;
    iv. Internal project management and overheads;
    v. Local taxes, import and other taxes or duties;
    vi. Insurances, interest during construction (IDC), or contingency costs or allowances; and
    vii. Exchange rate or commodity price fluctuations, inflation or future market supply and demand-based risks or adjustments.
4. Other assumptions, exclusions, and details of the level of accuracy of the cost estimates are as described in this report.
5. The cost estimates for this high-level assessment have been based on high level unit rates for the converters (per MW) and transmission lines (either overhead or underground cable on a per

kilometre basis), which have been derived from costing information from publicly available sources, including:

i. Published feasibility and technology reports;
ii. Announcements and press releases from HVDC converter and HVDC cable suppliers;
iii. AEMO Input and Assumptions workbook;
iv. CIGRE technical brochures and papers; and
v. Rawlinson's 2019 Construction Guide.

Table 9-5 – WVTNP Base Case Concept HVDC System High-Level Cost Estimate

#	Item	Estimated Costs $M AUD
1	**Connection Bays**	
1.1	2x 500 kV Conn. Bays/Circuits [12] (North Ballarat and Sydenham)	$22.4
1.2	1x 220 kV Conn. Bays/Circuits [12] (Bulgana)	$4.3
2	**Transmission System**	
2.1	**Bulgana to North Ballarat:** Supply and Install DC Cable 525 kV DC Al 1,100 mm^2	$340.0
2.2	**North Ballarat to Sydenham:** Supply and Install DC Cable 525 kV DC Cu 1,800 mm^2	$375.0
3	**HVDC Converter Stations**	
3.1	**Bulgana Terminal:** 2x 1.2 GW double symmetric monopole terminal	$535.5
3.2	**North Ballarat Terminal:** 2x 2.26 GW double symmetric monopole terminal	$709.5
3.3	**Sydenham Terminal:** 2x 2.26 GW double symmetric monopole terminal	$709.5
	TOTAL	**$2,696.2**

9.6.2 Operation and Maintenance Costs

HVDC systems utilising underground cables mainly require operation and maintenance (O&M) of the converter stations, as the cables themselves are buried below ground and in ideal conditions do not need significant regular maintenance aside from regular inspection of the route.

Each converter station will require specialist personnel to operate and maintain the facilities and equipment contained within. Costs will include personnel wages (operations team, engineering, contractors, specialists), cost of materials and equipment and any replacement equipment or the replenishment of spares. The cost of this maintenance is typically assumed to be 0.5% per annum [13] of the converter costs, which (based on the high-level estimate presented in Section 9.6.1) is estimated to be circa $6.5M per annum.

The O&M for HVDC systems generally incur higher costs at the beginning, middle and towards the "end of life" of the project for the following reasons:

- **Early life O&M costs:** A new HVDC system is expected to incur higher early life O&M cost than AC equivalent due to introduction of new technology to the company or region requiring the introduction of specialist skills, maintenance strategy setup, personnel training, spares acquisition, etc.

- **Mid-life O&M costs:** High mid-life costs are expected due to the need for refurbishment of obsolete equipment, generally associated with electronics and microprocessor based equipment, typically after 15-20 years. Based on published costs for recent VSC HVDC control and protection system replacements, we anticipate the cost for this work, for a double symmetric monopole system, to be in the range of $35M to $45M [14].
- **End-of-life O&M:** End-of-life costs are difficult to estimate but are expected to be higher for HVDC systems because of the number of components and equipment involved.

9.6.3 Risk Mitigation Costs

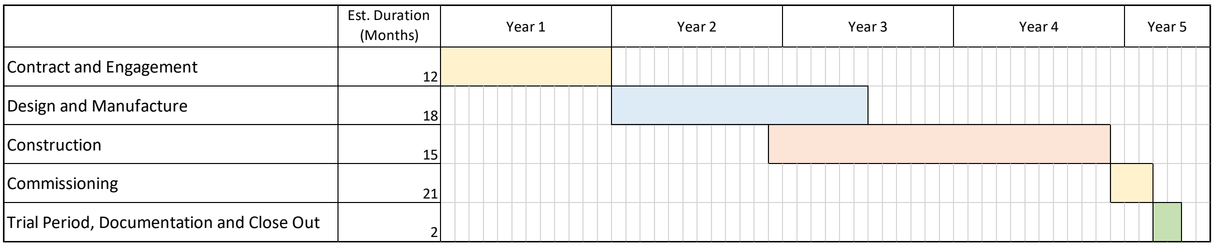
When comparing the cost of the AEMO preferred WVTNP Option C2 versus that of the similar HVDC underground solutions that have been developed in this report, a direct comparison cannot be made without also considering the risks associated with each. For instance, the cost of the proposed AC overhead solution does not capture the cost of mitigating risks outlined in Appendix B to the same extent as what could be considered to have been inherently incorporated or mitigated against by the HVDC underground options. For the AC overhead solution to be engineered to achieve the same level of risk and/or performance as the HVDC underground solutions, where this is even possible, significant additional costs may need to be factored in or a higher level of risk, or lower level of performance, accepted.

Tangibly quantifying these risk differences can be difficult and it is unknown what consideration or allowances might have been made for these as part of the AC overhead solution's cost estimate in the RIT-T. If the costs of these mitigations were to be fully considered and addressed in the AC overhead solution, then the total AC overhead solution cost could be much more expensive than is currently estimated.

9.7 High-Level Project Schedule

A HVDC transmission project involves similar implementation phases as an AC transmission project and is anticipated to take approximately 4 - 4.5 years from inception to start of commercial operation. A conceptual and typical high-level schedule is presented in Figure 9-6.

Figure 9-6 – Concept HVDC System High-Level Schedule



At present the demand for HVDC technology and associated cables is high and there are signs that this demand is increasing. The signs are looking positive for new entrants in the VSC HVDC technology and HVDC cables, particularly out of Asia, that may provide some relief. Even so, it is expected that the high demand combined with the limited number of companies and facilities offering HVDC VSC technology and HVDC cables will limit opportunities to compress the schedule going forward.

That said, the following strategies can be considered and one or both of these could be applied to potentially compress the project schedule:

1. **Early contractor engagement:** This involves engaging the contractor as early in the “contract and engagement” process as possible. This could involve an early expression of interest or tender process followed by a period of engineering and design with the selected vendor. Such arrangements can also lead to discussion of “early works”, where manufacturing slots can be secured, long lead time materials and equipment ordered and/or a start can be made on detailed engineering to compress the schedule.
2. **Multi-vendor contracting strategy:** In the case of the HVDC cables, it is possible to have multiple vendors supply the cables. An example would be a DSM system where two vendors could each provide one pair of cables for a symmetric monopole. This strategy is particularly useful where the critical path is related to lack of manufacturing capacity and available manufacturing slots for one or more HVDC cable vendors.

The impact of these strategies will vary greatly between projects and depend heavily on the factors driving the critical path items.

In comparison to the timeframes and schedule of AC OHTL system construction, the AEMO WVTNP Option C2 suggests in the PACR [3] that the medium term works pertaining to the major construction of the project is anticipated to begin in 2021 and be commissioned in 2025. This means that duration is approximately 4-5 years, which is not much different from the HVDC schedule that is shown in Figure 9-6.

Other AC OHTL projects of similar scale, such as the Energy Connect [15] and CopperString [16], suggest a project implementation schedule akin to the AEMO WTNP Option C2. For example, the CopperString project schedule indicated a period of approximately five years from start of design until final commissioning.

In summary, the HVDC project may take a similar amount of time to implement if not marginally quicker, if the strategies suggested in this Section are applied successfully.

9.8 Options Based on Alternative Availability and Reliability Criteria

Typically, AC transmission networks with double circuit or parallel transmission lines are designed to operate on an N-1 basis, where the power transfer across the transmission line is managed such that an unexpected outage of one of the parallel lines will not overload the other “healthy” line. For HVDC systems, where the converter stations at each end are a much higher portion of the overall transmission cost, providing such a level of reliability (i.e. a fully redundant systems) means building two poles or HVDC systems in parallel. The Base Case presented in Section 9.1 presents a HVDC solution that provides N-1 reliability, and where each symmetric monopole of the double symmetric monopole system is rated near to the full expected transmission capacity of a single AC 500 kV transmission circuit. To provide N-1 reliability, such a system will be required to operate at 50% of capacity most of the time, to allow enough headroom for one symmetric monopole to take 100% of its own capacity in the event of a failure of the other symmetric monopole. Therefore, for the vast majority of the time more than half (>50%) of the system’s transmission capacity goes unused. Due to the relative cost differences between HVDC converter stations and AC terminal substations, adding this extra level of redundancy makes the HVDC option significantly more expensive than the AC option. This extra redundancy/transmission capacity becomes difficult to justify the additional costs associated with providing this.

In some cases, the consideration of a HVDC system as part of a larger, meshed transmission network may drive a rethink of the requirement for that segment of the meshed network to require N-1 redundancy. Suitably sized bipole and double symmetric monopole HVDC systems inherently provide 50% redundancy, where the trip of a pole or symmetric monopole leaves 50% capacity still in service, with fast control of this power transfer to avoid overloading the healthy pole. At the converter station end, two symmetric monopoles of a double symmetric monopole system can be designed to greatly minimise, if not eliminate, the likelihood of both symmetric monopoles tripping at the same time. The underground cables are known to have significantly better availability and reliability performance compared to equivalent overhead transmission lines, and the outage of a single symmetric monopole due to a fault on a properly designed and installed cable is expected to be very rare, potentially once every 10-20 years, making such an incident non-credible. The underground HVDC system will also have controllability benefits not readily available in AC transmission systems, which means the implementation of run-back schemes may allow better utilisation of other parallel AC transmission lines.

A relaxation of the N-1 criteria in the consideration of the alternative Concept HVDC System will have a dramatic impact on the capital cost of the HVDC option. Not requiring full N-1 redundancy, and instead designing a system that can handle 50% loss due to a fault on one pole or system (or possibly less if overload is designed into the HVDC system), will reduce the required rating of the HVDC converter stations and underground cables and significantly reduce the capital cost of the HVDC alternative.

Such a relaxation will require the performance of studies and investigations by the transmission planning authorities. These studies and investigations should consider the impact of a complete loss of the HVDC system, or the loss of a single pole or system with 50% capacity remaining, while also taking into account the benefits to the reliability of the overall transmission network by utilising some controllability aspects of the HVDC system and consideration of the expected lower incidence of outages due to the cables being installed underground.

The following sections explore two alternatives to the Base Case, which consider a reduced N-1 criteria where a loss of either 50% or 100% of the HVDC system capacity due to a fault in the converter stations or the underground cables is deemed acceptable.

9.8.1 Concept HVDC Option 2

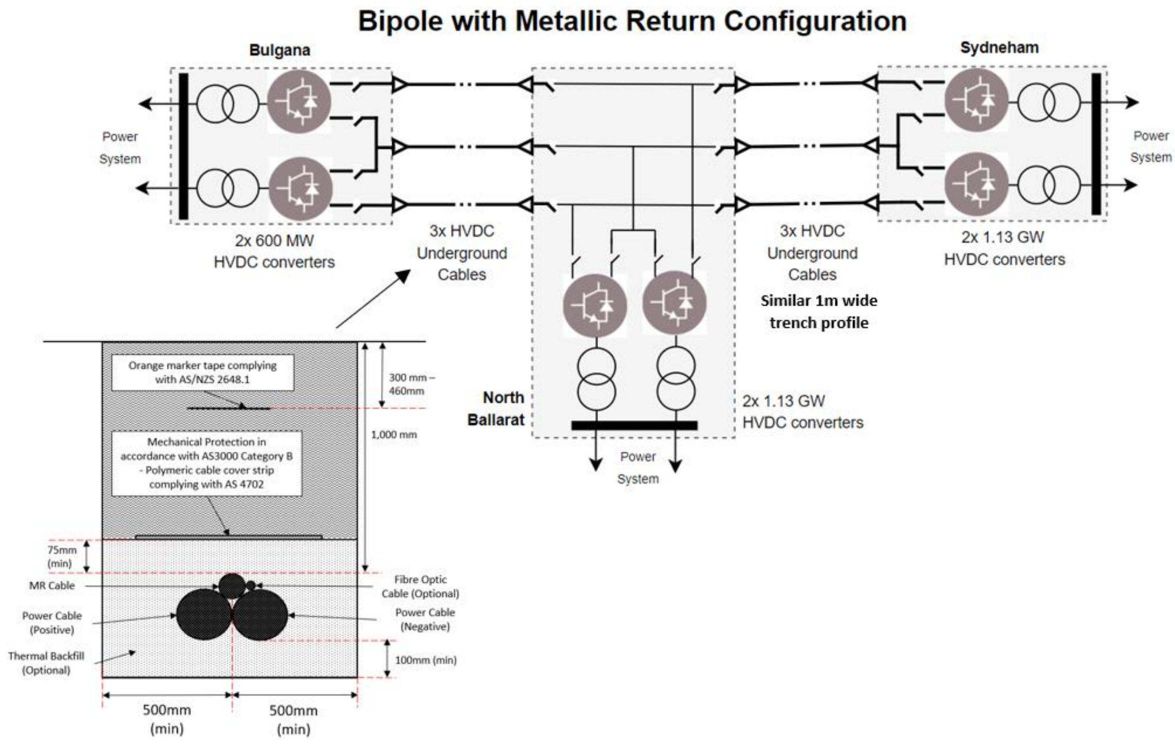
Option 2 of the Concept HVDC System proposes a three-terminal bipole with a metallic return system which would have parameters as shown in Table 9-6. This system rating is equivalent to one AC circuit proposed by the AEMO preferred Option C2. While this system has half of the maximum transfer capacity of the AC double circuit lines, it is expected to be able to facilitate the required power transfer levels and still be able to provide 50% redundancy. This could lead to a much greater utilisation level of the assets.

Table 9-6 – Option 2 Concept HVDC System Parameters

Parameter	Description
Configuration	Bipole with Metallic Return
Redundancy	50% - this means that for a fault on either a cable or a converters, the system can continue operating at half of the converter rated capacity
Converter Station 1 - Bulgana	Two converters rated at 600 MW each
Converter Station 2 - North Ballarat	Two converters rated at 1.13 GW each
Converter Station 3 - Sydenham	Two converters rated at 1.13 GW each
Transmission Line 1 - Bulgana to North Ballarat	Two 1,100 mm^2 aluminium power cables and one metallic return underground cable with a combined maximum transfer capacity of 1.2 GW
Transmission Line 2 - North Ballarat to Sydenham	Two 2,300 mm^2 copper power cables and one metallic return underground cable with a combined maximum transfer capacity of 2.26 GW
Trench Size	Approx. 1 m wide and 1.25 m deep
Combined System Losses	2.49% (86 MW)
Cost	$AUD 1.75Bn

The Concept HVDC System and cable trench profile for this option are shown diagrammatically in Figure 9-7. It should be noted that this option requires a significantly smaller trench width, in both of the routes, i.e. from Bulgana to North Ballarat and from North Ballarat to Sydenham.

Figure 9-7 – Option 2: Diagrammatic Representation of Concept HVDC System



9.8.2 Concept HVDC Option 3

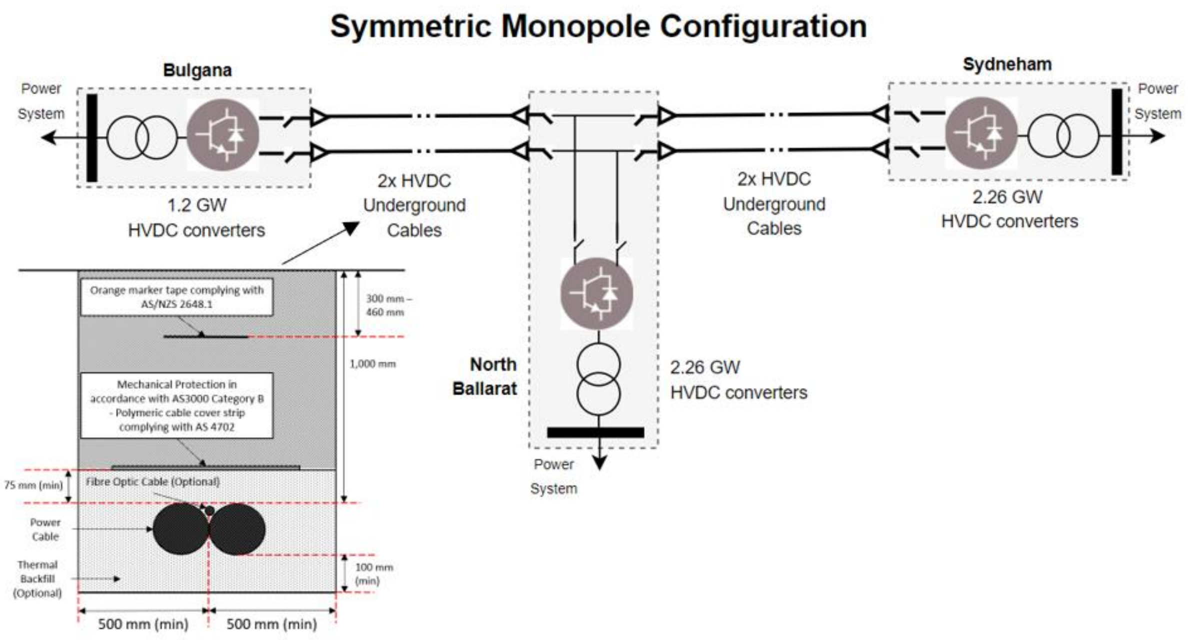
Option 3 of the Concept HVDC system proposes a three-terminal single symmetric monopole system which would have parameters as shown in Table 9-7. While this option has half of the maximum transfer capacity of the AC double circuit lines, it is expected to be able to facilitate the required power transfer levels but will not provide redundancy in the event of a fault or outage on the converter or cable system.

Table 9-7 – Option 3 Concept HVDC System Parameters

Parameter	Description
Configuration	Single Symmetric Monopole
Redundancy	None
Converter Station 1 - Bulgana	One converter rated at 1.2 GW
Converter Station 2 - North Ballarat	One converter rated at 2.26 GW
Converter Station 3 - Sydenham	One converter rated at 2.26 GW
Transmission Line 1 - Bulgana to North Ballarat	Two 1,100mm^2 aluminium underground power cables with a combined maximum transfer capacity of 1.2 GW
Transmission Line 2 - North Ballarat to Sydenham	Two 1,800mm^2 copper underground power cables with a combined maximum transfer capacity of 2.26 GW
Trench Size	Approx. 1m wide and 1.25m deep
Combined System Losses	2.5% (86.5 MW)
Cost	$AUD 1.49Bn

The Concept HVDC System and cable trench profile for this option are shown diagrammatically in Figure 9-8.

Figure 9-8 – Option 3: Diagrammatic Representation of Concept HVDC System



10 Opportunities for Cost Efficiencies

The full capacity of the WVTNP section from North Ballarat to Sydenham is not planned to be utilised until such time as the VNI project from Wagga Wagga is realised and connects to the network at North Ballarat as described in Section 6.3. As such, a HVDC option could be extended to provide additional connection and transmission capacity all the way through to Wagga Wagga. Therefore, the initial Base

Case option for the Concept HVDC System can be implemented in a staged approach and subsequently provide a connection to Wagga Wagga, as described in the below subsections.

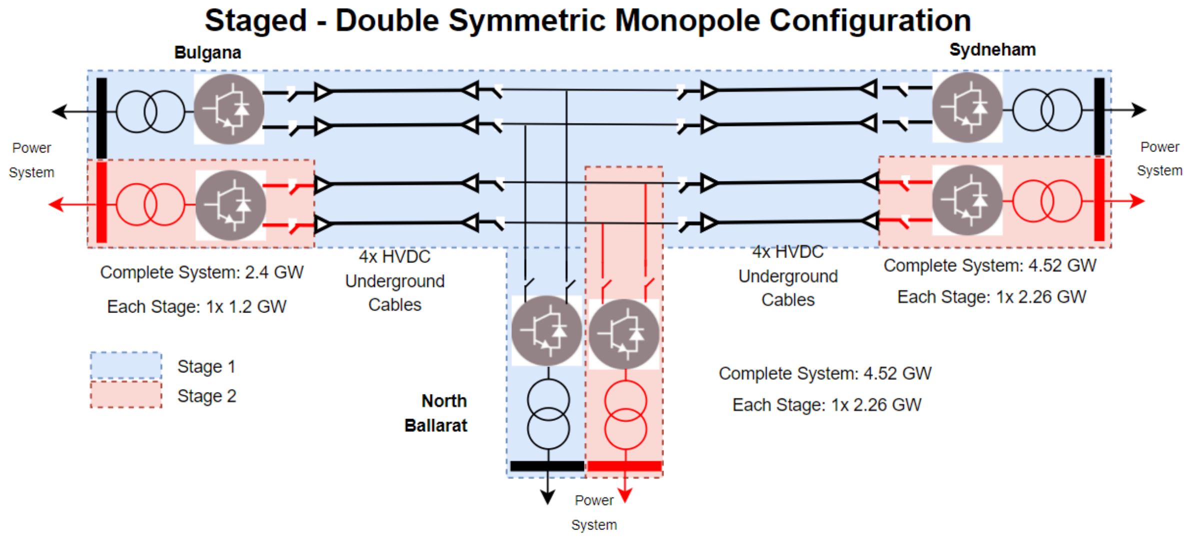
10.1 Staging of Base Case Option

Staging of the Base Case option is also possible and would ultimately result in a system with parameters and ratings identical to that which is presented in Section 9.1, but is constructed in two separate stages to enable half the transfer capacity earlier at a smaller initial capital expenditure. The scope of the two stages is as follows:

- **Stage 1:** The scope of this stage is constructed and put into operation prior to VNI connection at North Ballarat (shown in blue in Figure 10-1).
    - Construction of one HVDC converter at each of the three locations - Bulgana, North Ballarat and Sydenham.
    - Four cables would be installed at the same time along the transmission routes, but only two cables are utilised for this stage during normal operation. The remaining two cables can be used for redundancy in case of a fault on an operating cable or operated in parallel to reduce losses. Construction of the complete cable system (four cables in total) at the same time is necessary for both practical and economic reasons.
- **Stage 2:** The scope of this stage is constructed in time to connect the new VNI project at north Ballarat (shown in red in Figure 10-1).
    - Construction of one additional HVDC converter at each station.
    - Connection of new converters to two of the cables that were installed as part of previous stage and to the AC network.

The Concept HVDC System for this option is shown diagrammatically in Figure 10-1. Alternative combinations and timings would also be possible.

Figure 10-1 – Staged Diagrammatic Representation of Concept HVDC System

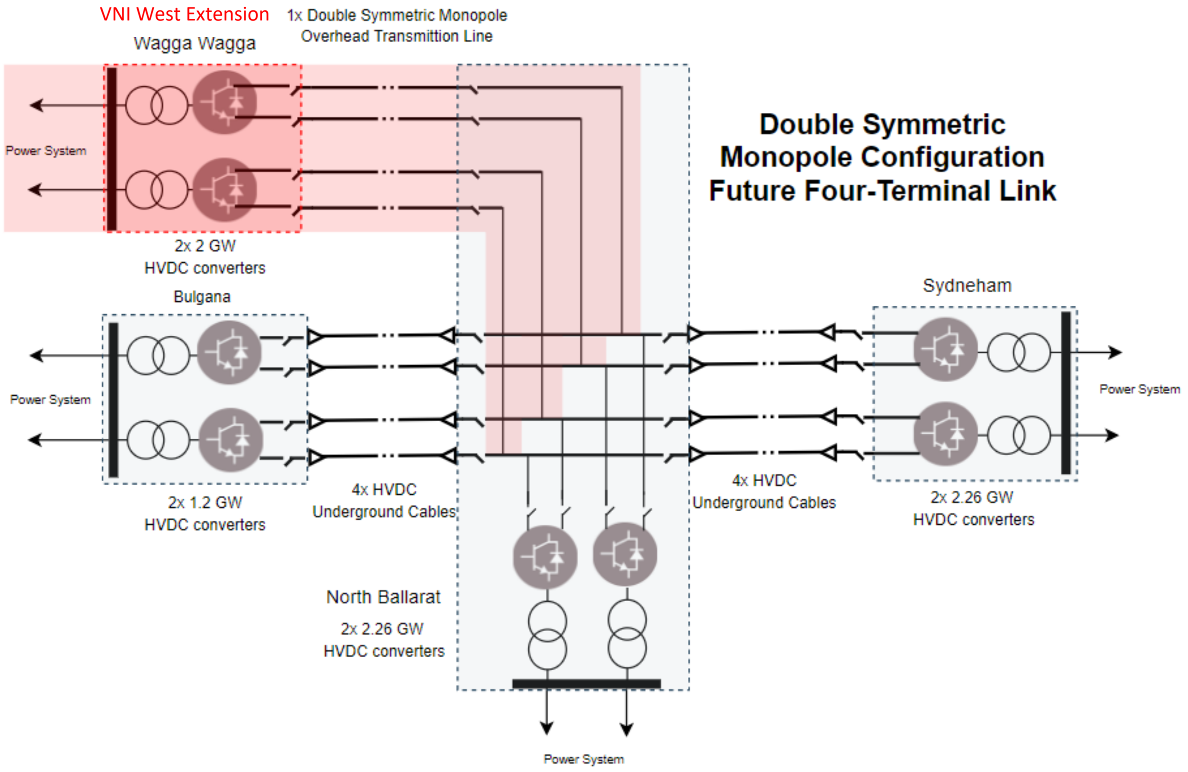


10.2 WVTNP and VNI West HVDC Future Staging Options

A simplified diagram of a possible HVDC four-terminal system is provided in Figure 10-2, with the VNI West extension shown in red which is to connect to the North Ballarat terminal.

There are a number of options for HVDC converter station placement. For example, it may be more beneficial from a network and cost perspective to locate the northern terminal near to Shepparton and/or locate the North Ballarat terminal further west near Waubra or Ararat to create a renewable energy hub with the existing and/or new AC lines or cables feeding in. A more strategically placed HVDC converter station near Waubra for example could remove the need for one of the HVDC converter stations thereby reducing the cost of the Concept HVDC System considerably. Additional converter stations could be added along the line, but this would likely be at a considerable additional cost, depending on rating and configuration. For Future staging configurations would ideally be known from the outset so this can be incorporated into the design and controls for the HVDC system.

Figure 10-2 – Possible HVDC Multi-terminal System for WVTNP and VNI West



Optimised converter station locations, configurations, and ratings would need to be studied in more detail to be able to provide the required transmission capacities and optimise the cost and locations of such an extended multi-terminal HVDC option. The HVDC converter station and connection at North Ballarat for example would only need to be rated for the 2x 1,000 MVA, equivalent to that proposed for the WVTNP project.

Underground cables are assumed for the North Ballarat to Sydenham section as described in Section 9 of this report. An overhead HVDC line with two HVDC circuits could be implemented for the North Ballarat to Wagga Wagga section, making the option more economical if sufficient social license was attained. Double symmetric monopole OHTL towers are estimated to be approximately 10-20%

shorter in height than an equivalent 500 kV double circuit AC line due to the HVDC OHTL only requiring four conductor bundles when compared to six for the AC line. Underground HVDC cables could technically also be used for this section but due to the lengths involved this would be at significant additional cost if it were to be for the whole length. Underground cables may be instead used for strategic sections within the line if required, for example passing through sections of national parks, reserves or other sensitive locations. These transitions would however require additional transition compounds where the transmission line changes from overhead to underground and vice versa and therefore the number of underground sections should be limited.

The additional cost for adding 450 km of HVDC OHTL and an additional HVDC converter station at Wagga Wagga is expected to be of the order of $1,240 M. Some cost reduction may be available if this development path is known such that the converter stations at North Ballarat can be sized appropriately. As there are no double symmetric monopole HVDC OHTLs constructed at the time of writing of this report, the cost of this overhead line using self-supporting structures has been developed using assumptions based on experience. Cost estimates are subject to the provisions and assumptions noted in Section 9.6.

Based on the future staged option presented here, a cost comparison can be made between this option and the combination of the AEMO preferred WVTNP Option C2 and VNI West Shepparton option. The costs are presented in Table 10-1.

Table 10-1 – High-level Cost Comparison AC vs. HVDC Future Staging Options

AEMO Project Cost Estimates (AC) (AUD$ M)		HVDC Alternative Costs Estimates (AUD$ M)	
WVTNP Option C2	470	**WVTNP HVDC Base Case Option**	2,696
VNI West Shepparton Option [4]	1,730	**Wagga-Wagga HVDC OHTL Extension**	1,240
Total	**2,200**	**Total**	**3,936**
Notes: ***The VNI West cost estimate was taken as the average of the minimum and maximum costs estimates presented in the AEMO ISP 2020* [4].**			

The cost comparison in Table 10-1 shows that the HVDC option for the WVTNP by itself is estimated to be around five times more expensive than that the proposed AC option. However, when considering the larger transmission development plan including VNI West, a four terminal HVDC system could be more cost competitive and within 45% of the combined AC options. The HVDC option presented here however will come with potentially significant various non-financial benefits over the AC option as described in Sections 7 and 8.

11 HVDC System Reliability and Availability

11.1 Reliability

The reliability of an HVDC system is affected by the frequency of both forced and scheduled outages. In this context, a forced outage is an unplanned or unexpected outage caused by the failure of equipment within the HVDC system i.e. excluding outages caused by issues on the connected AC network. A scheduled outage is one which is planned or expected that is scheduled to undertake routine maintenance or other planned works.

The reliability of a HVDC system is driven by the number of times a trip of a converter occurs, either through failure or mis-operation of equipment within the converter station or due to a HVDC cable fault.

The most common source of data on the reliability (and availability) of HVDC systems is published by CIGRE every two years, which is based on data submitted by HVDC asset owners and collated and analysed by CIGRE representatives [17]. To date, there has been minimal reporting in terms of actual reliability figures for VSC-based HVDC systems.

Reliability requirements (e.g. maximum number of trips per year) are often specified and/or included as a performance warranty in the construction contract documents. The overall reliability can be accounted for in the design, including application of redundancy concepts to minimise the likelihood and impact of trips due to equipment failure or mis-operation. This includes the selection of converter station technology, topology and configuration.

11.1.1 Converter Stations

There are a number of reasons why an HVDC converter station will trip. The most common causes include failures in the AC equipment (within the converter station), valves (IGBT submodules and associated equipment), valve cooling systems and the control and protection systems. In many cases, an outage may be of short duration, requiring a relatively easy fix or reset, and although the outage duration is low, it will still contribute to the overall frequency of failures.

HVDC systems can be designed with resilience to minimise the impact of equipment failure or mis-operation. Some common or often standard design principles applied to HVDC converter stations include redundancy in the selected HVDC configuration, the control, protection, and auxiliary systems, and the submodules.

Based on the two VSC systems that were reported in the latest published CIGRE report, the number of forced outages of VSC converter stations varied between 1 and 11 per year between 2017 and 2018 [18]. Both of these facilities are over 10 years in operation. In Amplitude’s experience, typical design requirements for reliability are to be less than a maximum of 4-5 trips per year, per pole caused by HVDC converter equipment.

11.1.2 HVDC Cables

At a high level, there are two types of cable failure:

- Internal or Intrinsic – a failure not caused by an external interaction and typically associated with a design or manufacturing defect or damage during transportation.
- External - typically caused by an external interaction or impact, such a human interaction (third-party damage) or natural events.

Published statistics show that internal or intrinsic failures are much less likely than external failures. The general causes of internal or intrinsic failures include design errors, manufacturing defects, mishandling of the cable during transportation and installation and premature ageing. Statistics show such failures to be more common on older systems. With improvements in cable design, both in terms of knowledge and understanding and the availability of powerful design software, improvements in field and factory testing and a strong focus on quality control in cable manufacturing over recent decades, it is expected that the likelihood of internal or intrinsic failures for newer cables will be significantly less than for these older cables.

While some statistical information related to external failures is available, the expected occurrence of external failures will be strongly dependent on the management of risks associated with the particular project. External failures can be caused by mechanical interaction with the cable (e.g. excavation), damage during installation, abrasion or chafing of the cable, geological or natural events or cable joints. With prudent installation and protection methods, most if not all of these factors can be mitigated to a certain extent.

11.2 Availability

In a similar way to reliability, the availability of the HVDC system is affected by the duration of forced and scheduled outages. For forced outages, the duration will depend on the cause of the trip and whether it can be resolved simply by restart or if it requires equipment replacement. In the event of equipment replacement, the duration is increased in the event of the failure of larger items of equipment (e.g. transformers, reactors) or equipment difficult to replace, such as large numbers of submodules. For scheduled outages, longer and extended outages (such as annual scheduled maintenance) will impact availability more than short duration outages to address one or a few small items.

Overall, the impact of availability of the overall system can be addressed through the selection of a HVDC configuration with redundancy or alternatively a high degree of preparedness including having spare parts on-hand. To demonstrate the impact of the HVDC configuration, one reference provides typical performance values for monopole HVDC systems to have energy availability of up to 98.5% [19]. These numbers align closely to the two monopolar VSC schemes that reported for 2015-2016 in the CIGRE paper. The bipole values provided show that at least 50% power can be made available for 99.9% of the time [20].

Similar figures for rigid bipole systems are not available, mostly because one has not yet been put into operation. However, we expect similar availability levels as for the bipole system, although slightly lower to account for the system being completely out of service for a significant period of time in the event of a cable fault.

11.2.1 Converter Stations

Availability is driven by the duration of outages caused for the same reasons as described in Section 11.1.1. Similarly, the design principles for improving reliability as described in Section 11.1.1 will also serve to improve availability.

With a view to reduce outage durations for certain types of failures, in addition to consideration of the HVDC configuration, design principles and/or strategies can be applied such as equipment redundancy, sufficient spares holdings and response procedures to enable replacement, repair, or maintenance works to be effectively scheduled.

11.2.2 HVDC Cables

There is limited statistical failure data available for HVDC XLPE cables in the public domain, therefore the failure rates of AC cables can be assumed to be relatively similar for a high-level comparative purpose of this report. The failure rates for cables of different voltages are presented in Table 11-1.

Table 11-1 – Cable Failure Rated (per 100 km)

Voltage	Average failure rate per 100 km		
	Internal Fault	External	Combined Average
60-109 kV	0.0702	0.0211	0.04565
110-219 kV	0.0199	0.0717	0.0458
220-314 kV	0.229	0.0403	0.13465
315-499 kV	0.0511	0.0511	0.0511
500kV and above	0.00	0.00	0
Average of All Voltages	0.0686	0.0368	**0.05544**

In the event of a system outage due to a cable fault, the outage duration is directly related to the time it takes to locate and repair the fault, which is directly influenced by the technologies applied for cable fault finding, the level of preparedness of the asset owner or operator and the availability of the right personnel and equipment. Other factors outside of the owner's control may also influence the outage duration including adverse weather, the resistance of the fault (high resistance faults take longer to locate) and unexpected issues with the availability of equipment and personnel.

Depending on arrangements put in place so that cable repair equipment and experienced personnel can be mobilised in the time required to confidently locate and pinpoint the fault, typical cable repair times for land-based cables can be 2-4 weeks. This duration may be able to be shortened but at additional up-front and ongoing cost to ensure a high-level of preparedness.

11.2.3 Overhead Transmission Line Reliability

The reliability of OHTLs, for both AC and HVDC, is affected by multiple factors associated with climatic, human, fauna and flora aspects within the vicinity of their construction location. Some of these factors may include:

- Lightning strikes;
- Strong winds, cyclones and bush fires;
- Interaction with fallen or overgrown trees (if regular maintenance is not performed);
- Wildlife interaction (e.g. birds);
- Vehicle accidents;
- Vandalism and accidental human interaction; and
- Untimely detection of defects.

The above listed points result in either damage to the insulators, conductors, tower structures and/or general operation of the transmission line which in turn typically results in an outage either immediately or in due time, which has a detrimental effect on the reliability of the OHTL system. It should be noted here that OHTL towers are generally the least impacted items in terms of frequency of occurrence, but in the event of one collapsed tower the impact on the transmission line is catastrophic, as one fallen tower will usually also take down a number of others. The vast majority of the listed items attest to the fact that the OHTLs are obviously built aboveground and are therefore more prone and susceptible to these types of interactions than direct-buried cable systems. One paper [21] reports failure statistics for 500 kV OHTLs as shown in Table 11-2.

Table 11-2 – OHTL Failure Statistics [21]

Year	Average failure rate per 100 km
2011	0.19
2012	0.27
2013	0.29
2014	0.33
2015	0.14
2016	0.14
2017	0.16
2018	0.12
Average of All Years	**0.20**

From the failure data shown in Table 11-2 and Table 11-1, the failure rates for AC OHTL and HV cables are 0.2 and 0.055 per year per 100 km, respectively. This gives a clear indication that faults on overhead transmission lines are more frequent than for buried cable system, although they can often be cleared by automatic reclosers which depends on the severity of the impact. For example, a fallen branch may short circuit the system but can be cleared immediately if no substantial physical damage is caused. It should also be added that if the fault is significant then the repair of a fallen conductor can be repaired relatively quickly compared to a cable fault. Even though a cable fault may be expected to happen much less frequently the time for repair is much longer, as described in Section 11.2.2.

Overall, it is our view that OHTL transmission systems experience a higher frequency of faults than the cable counterpart and therefore have a lesser reliability.

12 New Connections into a HVDC Transmission System

For a new connection to be established to an existing HVDC system, it would require either:

a) Construction of an AC transmission line to the location of the nearest HVDC converter station (AC side); or
b) Construction of a new HVDC converter terminal and installation of either cables or HVDC OHTL to connect onto the existing HVDC transmission circuits.

Depending on the power wanting to be “teed-in” or “tapped-off”, the associated transmission capacities and distances, the costs of building such infrastructure to add an additional terminal would be significantly higher than the equivalent infrastructure requirements of an AC substation to “cut-in” to an existing AC line.

The incremental costs for the additional HVDC terminals along a line can make multi-terminal HVDC system cost-prohibitive. However, when incorporating HVDC transmission into an existing network the HVDC system may be better conceived and designed as a bypass of the existing network for shunting or transfer of bulk power more directly from generation source to the main load centres thereby alleviating constraints on the existing network that can then be better utilised for connection of localised generation, thereby making better or more efficient use of the existing AC network.

If additional connections onto an HVDC system are proposed, then this is best if known and planned at the time of the specification and design of the initial base system. This is so that the system and the controls for the scheme can be designed and optimised for accepting additional connections.

13 Broader Applicability of HVDC in NEM Transmission Needs

HVDC has been implemented, and continues to be considered, for applications within the National Electricity Market (NEM). Some examples where HVDC has been implemented in the NEM in the past include:

1. Directlink and Murraylink Interconnectors – these projects were developed as high voltage underground cable projects to expedite the permitting and approvals process and to allow installation through environmentally sensitive areas. The distances between converter stations (i.e. length of cable) made HVDC a viable and preferred technical option once the decision to go underground was made. These were a few of the first VSC HVDC systems installed in the world. Directlink and Murraylink were put into service in 2000 and 2002, respectively.
2. Basslink Interconnector – With over 300 km of the Bass Strait between Northern Tasmania and the Australian mainland, a HVDC connection is considered the only technically viable option to provide interconnection to Tasmania.

HVDC continues to be a viable technology option for the interconnection of the state transmission networks within the NEM. For example, HVDC is the chosen technology for the proposed second interconnector between the Australian mainland and Tasmania (Marinus link). In other cases, both HVDC and AC interconnection options may be technically viable, in which case the relative merits and advantages of HVDC over AC transmission, including lower losses, power controllability, inherent reactive power capability and the avoidance of transferring of transient stability issues from one network to the other, should be taken into consideration. More detailed description of these aspects is coved in Sections 7 and 8 of this report.

A general rule when comparing the cost of AC and HVDC transmission options is that the longer the distance and the larger the required power transfer capacity, the more viable HVDC becomes in terms of capital cost. This effect is even greater where lifetime costs are considered due to the lower losses on long-distance HVDC lines compared to AC. This concept is shown diagrammatically in Figure 7-1 in Section 7 of this report. The figure shows the relative difference in cost between the AC and DC terminals as well as AC and DC losses. The lower cost of DC transmission circuits is evident by the DC line having a smaller gradient than the AC line. The “breakeven distance” will depend on the required power transfer capacity, and other project-specific factors. It will also depend on whether underground or overhead options are being compared. When comparing AC and HVDC underground options, the breakeven distances can be much shorter than when comparing AC and HVDC overhead options.

The differences in losses between HVDC and AC may also be advantageous to the operation of the NEM. The line losses for HVDC cables and overhead lines are significantly lower than the equivalent AC cables or lines, although the losses within the HVDC converter stations at each end will be higher than for the AC substations/transformers at each end of the AC equivalent. This means, the greater the distance, the less "lossy" the HVDC transmission line will be compared to the AC equivalent. In the context of the National Electricity Objective (NEO), which includes the "*efficient investment in, and efficient operation and use of, electricity services for the long-term interests of consumers of electricity*"[2], it is our view that efficiency in operation (such as lower losses) should be considered when comparing interconnection options as well as capital cost.

Another potential application for HVDC in the NEM is to provide a high capacity "shunt" between remote renewable energy zones (REZs) and the locations for the bulk of the load (typically major and capital cities). Issues are being experienced with congestion on existing AC transmission networks between these points, while more and more projects are being proposed to capture the renewable energy sources at these REZs, further exasperating the problem and driving the need for AC transmission network reinforcement. HVDC options could be employed to take the bulk of this power and shunt it directly to the loads, bypassing the existing AC transmission network at relatively lower cost than doing something similar using AC transmission. If one considers the recent trend of converting existing AC transmission lines to HVDC, the possibility of installing such a "shunt" at relatively lower cost opens becomes even more attractive. Such solutions can also encourage connections in between by relieving congestion on the existing parallel AC transmission lines and allowing connection of renewable energy onto the existing AC transmission lines at locations between the two HVDC converter stations.

In addition to these key points, other factors which should be taken into account when considering HVDC options instead of the more traditional AC transmission development include:

- Increased network support and flexibility – the active and reactive power controllability of the HVDC systems can be used to implement a number of different control modes which can be used to support and stabilise the AC network to which it is connected. This can include AC voltage control, frequency control, and controlled black start.
- Electrical separation of AC transmission networks – where two AC transmission networks are connected together through an HVDC system, transient stability issues experienced in one of these AC networks will not be transferred through the HVDC link to the other AC network.
- Ease of undergrounding – the "breakeven distance" for HVDC systems utilising underground or subsea cables will be much shorter when compared to AC underground cable options. HVDC systems make undergrounding of long-distance transmission more affordable than the equivalent AC transmission systems.
- Bushfire resilience – overhead HVDC transmission systems will have features that make the system more resilient to bushfires, including the ability to operate in "reduced voltage" mode, and may be able to utilise more sensitive and faster operating protection systems to reduce the likelihood of electrical faults remaining undetected for significant durations.

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[2] https://www.aemc.gov.au/regulation/regulation#:~:text=The%20National%20Electricity%20Objective%20(NEO,Electricity%20Law%20(NEL)%20is%3A&text=price%2C%20quality%2C%20safety%20and%20reliability,of%20the%20national%20electricity%20system.%22

Where HVDC systems have made undergrounding possible, the underground cables will significantly reduce the impact of bushfire on the system and eliminate the potential for the HVDC system to start fires.

- Improved visual amenity – visual amenity is significantly improved in cases where HVDC systems have made undergrounding of the transmission line viable. However even in cases where HVDC overhead lines are used instead of cables, for the same power transfer, the HVDC overhead towers will be significantly smaller than their AC equivalents, and typically require smaller easement widths.

14 HVDC vs AC International Trends in Transmission Designs

Global interest in, and demand for, HVDC systems has dramatically increased over recent years. In Australia, a number of HVDC projects have been proposed, mostly to facilitate the long distance transmission of remote renewable energy sources. Globally, there is a significant increase in interest for HVDC projects for the same reasons, plus an increase in interconnection between countries, states and provinces.

Some key and relevant observations are provided here, based on the author’s exposure to HVDC projects worldwide and through active participation and contribution to international CIGRE activities.

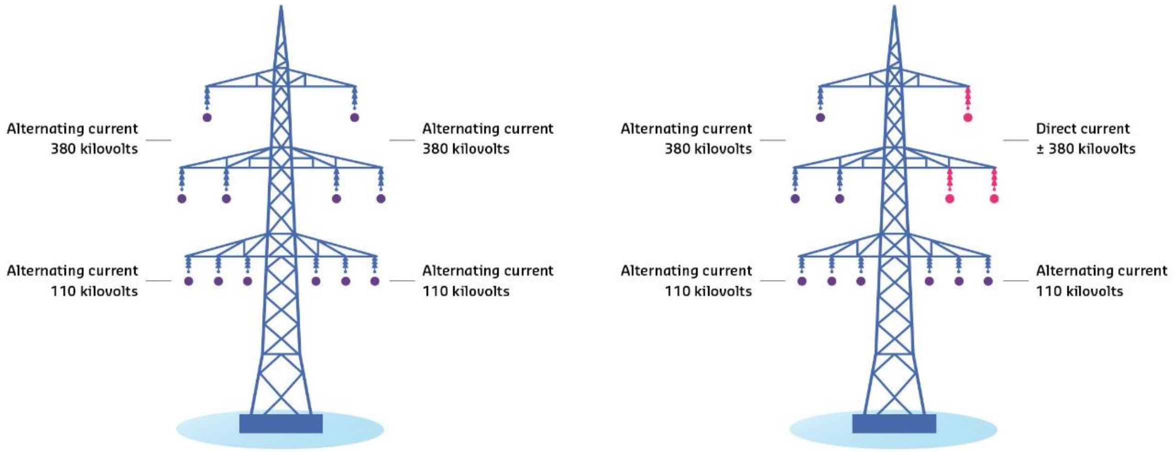
Some key observations on international trends in HVDC projects that may have some relevance to Western Victoria include:

- An increased preference for VSC technology and increasing power capacity requirements for VSC projects. A number of VSC projects at or above 2 GW are under development. One is already in-service (INELFE, which connects Spain and France), although more are under development including (along with their anticipated commissioning date) the EuroAsia Interconnector (Israel-Greece, 2023), SuedOstLink (Germany, 2025), Biscay Gulf (France-Spain, 2025), LEG1 (Libya-Greece, 2025) and Suedlink (Germany, 2026). Within the timeframe of the WVTNP, a number of VSC HVDC projects at or above 2 GW are expected to be in-service.
- Multi-terminal VSC HVDC systems on the increase. A four terminal VSC HVDC system (Zhangbei HVDC project) was put into service in China in December 2020. The scope of this project included converter stations ranging from 1,500 MW to 3,000 MW utilising a bipole with metallic return configuration [22]. Prior to that, the Nao’ao Island HVDC project in China was put into service in 2013, which is a three terminal VSC system utilising symmetric monopole configuration and a combination of underground and subsea cables [23]. The Caithness Moray HVDC link in Scotland is designed to be a three terminal HVDC link, with the first two terminals, rated at 800 MW and 1,200 MW, commissioned in 2018 [24] .These projects demonstrate the technical viability of multi-terminal VSC HVDC systems as well as an increase interest in the implementation of such systems.
- More HVDC projects with long-distance underground land cables are being developed and installed. The SouthWest Link in Sweden has 190 km of its 250 km DC route length using underground HVDC cables [25]. Two of the German HVDC projects mentioned above, SuedOstLink and Suedlink, will have route lengths using underground HVDC cables of approximately 500 km [26] and 750 km [27] respectively, both using 525 kV underground HVDC cables. While underground HVDC projects are more expensive than their overhead equivalents

(AC or DC), it is clear that there is increasing interest in utilising underground cables for long distance power transmission and in such cases, HVDC technology is being selected.

- More VSC HVDC systems using long distance DC overhead transmission lines. The first VSC overhead transmission line project, the Zambezi Link in Africa, was commissioned in October 2010. The 300 MW monopole link are connected by 925 km of DC overhead transmission line. This link reports a return to power transmission following an intermittent fault of about 1.5 seconds [28]. Since then, more VSC HVDC links using DC overhead lines have been installed, including the Zhangbei HVDC link described above and the UltraNet project described below. The Maritime HVDC link in Canada is a VSC project with a combination of DC overhead line, submarine cable and underground cable. The project includes 187 km of DC overhead line (about 52% of total route length) and was commissioned in 2019 [29]. Depending on application and vendor, intermittent faults on the DC overhead line and the fast restart of the HVDC system after such a fault can be managed through the either the implementation of a full-bridge VSC topology or a DC circuit breaker. The Zhangbei HVDC project described above has implemented a 535 kV DC circuit breaker [28].
- There is also an increased interest in the conversion of existing AC transmission lines to HVDC. The benefits are clear – significant increase in power transmission capacity could be obtained without having to install any new transmission lines or cables. The work required to make this happen will include, as a minimum, the installation of the HVDC converter stations at each end and likely the replacement of the insulators on the existing AC transmission line. There have been studies performed looking closely at various conversion scenarios, with some reports concluding that active power transmission capacity levels of between 50% and 150% [30] may be possible, depending on the design of the existing AC transmission line to be converted. A project currently under construction is the UltraNet project in Germany. The new HVDC link and converted AC transmission lines will transmit 2 GW over 340 km [31], and is scheduled for commissioning in 2023 [32]. Figure 14-1 shows how UltraNet will utilise one of the two 380 kV circuits on the existing transmission line to converter to a bipole with metallic return arrangement.

Figure 14-1 – Conversion of Existing AC Transmission circuit to HVDC - UltraNet, Germany [31]



15 Conclusion

Amplitude has performed a high-level scoping study for a HVDC option utilising underground cables as an alternative to the AEMO preferred WVTNP Option C2, which includes the erection of new 220 kV and 500 kV overhead transmission lines.

The Concept HVDC System presented in this report is based on the information provided by the Council and that which is available in the public domain as well as the Amplitude’s industry experience with HVDC projects in Australia and overseas. This scoping study presents a number of options that would be able to meet similar technical requirements of the AEMO preferred WVTNP Option C2. The Base Case Concept HVDC System was estimated to have a capital cost of circa $AUD 2.7Bn, which is approximately five times the cost of the equivalent AC option (based on the option that includes both the 220 kV and 500 kV AC OHTLs).

This capital cost of the Concept HVDC System is tied to the rating of the cables and converters, which were based on the capacity of the 220 kV and 500 kV AC OHTLs between Bulgana, North Ballarat TS and Sydenham TS that meet the typical N-1 redundancy planning criteria. Other options with reduced redundancy were also presented as alternatives which have a significantly reduced capital expenditure to the Base Case option that can be considered if a reduction in redundancy can be accepted given the expected higher reliability of an underground transmission system.

Amplitude has also performed a qualitative comparison between underground and OHTL options for both AC and HVDC transmission. Thirty-seven different criteria were used to assess the four different options. The HVDC underground option showed the least adverse impact against all other options based on the assessment criteria, while the AC OHTL has the highest adverse impact in total.

In this report, Amplitude has considered an extension and/or future staging option for the Concept HVDC System that involves another terminal to be built at Wagga-Wagga (i.e. the same connection point as the VNI West), which would connect to the North Ballarat converter station via a HVDC overhead transmission line, over an estimated 450 km route. A four terminal HVDC system could be within 45% of the combined AC options of the AEMO preferred WVTNP Option C2 and VNI West Shepparton link. The HVDC option however will come with significant various non-financial benefits over the AC option as described in this report, such as increased network support and flexibility, electrical separation of AC transmission networks, ease of undergrounding, bushfire resilience and improved visual amenity and social license.

Amplitude is of the view that a HVDC system which considers the scope of both the AEMO preferred WVTNP Option C2 and the VNI West Shepparton link could be a cost competitive and technically superior alternative, pending a detailed scoping study and cost estimation.

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Appendix A. HVDC Concepts and Technology

This section provides an overview of the concepts and technology for HVDC systems that were considered when developing a Concept HVDC System as an alternative to the AEMO preferred AC Option C2 for the WVTNP.

A.1. HVDC Converter Technologies

A.1.1. Overview

For applications involving long distance power transmission, there are two HVDC technology options available in the market:

- Line Commutated Converters (LCC); and
- Voltage Source Converters (VSC).

The description and comparison of the two technologies is presented in the following sections.

Line Commutated Converters (LCC): 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).

Voltage Source Converters (VSC): 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.

A comparison table of these two technologies is provided in Table 16-1.

Table 16-1 – Comparison of LCC and VSC HVDC Technologies

Parameter	LCC	VSC
Switching Technology	Thyristors	IGBT
Harmonic Filtering Requirements	High	Low to Zero
Converter Requires Reactive Power Compensation	Yes	No
AC Network Strength	Strong	Weak - Strong
Passive Network Capability	No	Yes
Black Start Capability	No	Yes
Control of Waveform to Reduce Harmonic Issues	No	Yes
Independent Reactive Power Control	Limited	Yes

Parameter	LCC	VSC
Automatic AC Voltage Control	Limited	Yes
Comparative Converter Losses	Lower	Higher
Footprint Size of Converter Station	Large	Small
Additional Short-term Rated (Overload) Capability	Yes	Limited
Overhead DC Line Fault Ride-through Capability	Yes	Yes, at additional cost
Applicable DC Cable Systems	MI Cables Only	MI or Polymer Cables
Active Power “Dead-band”	Yes	No
DC Fault Tolerance	High	Low

A.1.1.1. Suitable HVDC Converter Technology

In the determination of HVDC alternatives for the WVTNP, VSC Technology is assumed most suitable for the following reasons:

- **Network Strength:**
    - LCC systems require a synchronous voltage source (provided by the AC network) to operate and requires a relatively strong AC network to avoid “commutation” issues.
    - The network at the potential connection point in Western Victoria is expected to be a relatively weak network, which may become weaker as more non-synchronous generation connects in the future. Therefore, VSC technology is assumed to be better suited as it is not as dependent on high system strength for stable operation.
- **Power Transfer:**
    - Modern LCC systems are more suited for very large power transfers (i.e. up to 12 GW) and have traditionally been used for long overhead transmission lines. VSC systems are generally preferred for lower power transmission levels and are commonly now used for HVDC systems connected with underground or submarine cables.
    - The WVTNP is not expected to have a higher rating than approximately 2.26 GW per converter system and is proposed to be connected using underground cables.
- **Power Dead-Band:**
    - LCC systems have a dead-band of approximately 10% of the power rating in each direction which results in a minimum power transfer level. VSC technology allows continuous power transfer levels in either direction, even at these lower levels.
- **Visual and Environmental:**
    - VSC converters require a smaller land footprint than LCC converters with much of the equipment housed indoors, improving visual amenity and reducing environmental disturbance and impact. Audible noise is also reduced as the need for harmonic filtering is typically much less for VSC converters compared to LCC converters.
- **Other:**

  - VSC technology can also provide other benefits at the connection point, including accurate AC voltage control or frequency control. Consequently, VSC technology is favoured for connections to remote parts of networks, for supplying islanded loads and for the connection of remote offshore wind farms or remote inverter connected generation (i.e. weak systems).

A.1.2. HVDC Converter Topologies

VSC converters are generally available in two main topologies, as listed below:

- HVDC two-level converter; and
- HVDC modular multilevel converter (MMC).

These topologies are discussed and compared in the following sections. Other topologies such as the three-level converter and the cascaded two-level converter have also been developed. However, these are less common or not considered to be currently a standard or typically offered solution and therefore have not been considered for the Concept HVDC System.

A.1.2.1. Two-Level Converter

The characteristics of the two-level converter topology can be summarised as follows:

- Commonly used in inverter systems for inverter-based renewable power generation such as solar and wind.
- Uses pulse width modulation (PWM) principles to derive the required AC waveform.
- Employs series connected IGBT modules that switch very fast between the maximum positive and negative DC voltages. The modules are stacked together to achieve the required voltage level.
- Higher switching losses due to the high number of IGBTs and fast switching frequency.
- Harmonic distortion is often present due to the IGBT switching, which would typically require additional AC filters to be installed.

The two-level topology is best suited and is commonly employed for HVDC transmission systems with low power transfer capacity, such as 100 MW or less, which is significantly lower than what is intended for WVTNP.

A.1.2.2. Modular Multi-level Converter (MMC)

The MMC converter topology characteristics can be summarised as follows:

- Uses a number of independently controllable (switchable) submodules, each with its own energy storage capacitor.
- Each module is its own voltage source and is switched in and out independently to build up the required DC voltage and AC voltage waveforms.
- Reduced switching frequency and therefore lower switching losses and harmonics.

- The output voltage from the converter more closely resembles a sine wave, to the point that additional AC filters may not be required which reduces the cost and footprint of the converter station.

A.1.2.3. Selected HVDC Converter Topology

Comparing the two main VSC topologies discussed in this report with respect to their application to WVTNP, the following conclusions have been drawn:

- **Two-level converters:** these are commonly used for lower power transmission applications (e.g. less than 100 MW) than what is proposed for the WVTNP project. Considering this and the higher converter losses (when compared to other available topologies) the two-level converter may not be the best fit for the Concept HVDC System.
- **MMC:** this is the most common type of voltage-source converter for new VSC systems with high power transfer capacity and provide the benefits of reduced switching losses and improved harmonic performance (when compared to a two-level and three-level converters).

From discussion in the above points, the MMC topology is selected for the Concept HVDC System.

A.1.3. HVDC Configuration Options

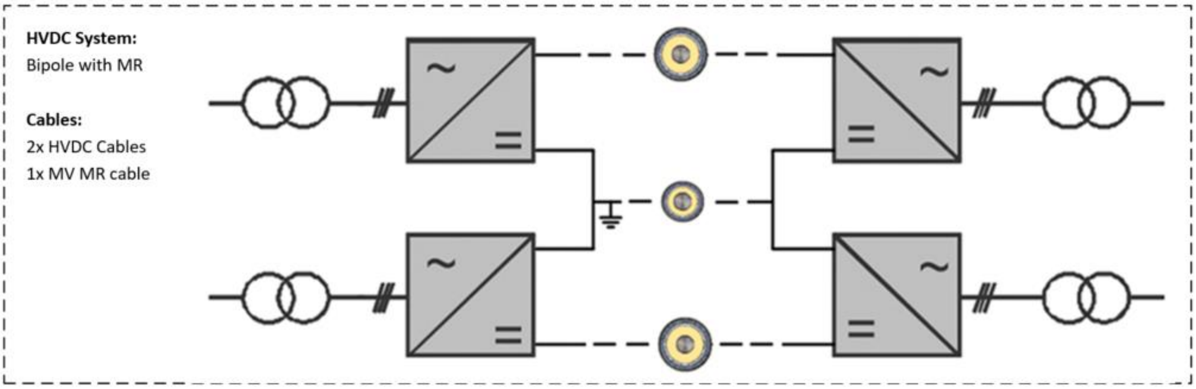
HVDC systems can be installed in a number of different configurations, each with differing technical capabilities and availability levels. This is discussed further in the following sections.

A.1.3.1. Bipole with Metallic Return

A bipole with a metallic return configuration has two converters at each terminal, two main HVDC transmission circuits and one medium voltage (MV) DC metallic return (MR) circuit. The configuration is shown in Figure 16-1.

During normal operation, the current in each HVDC transmission circuit is balanced and only the unbalance or “spill” current flows in the metallic return circuit. At each terminal there are typically two primary high voltage AC connections to the grid. The neutrals of each converter are coupled together and grounded at one end.

Figure 16-1 – Bipole with Metallic Return Configuration



The bipole with metallic return configuration is generally considered to be a redundant HVDC system. Faults on a transmission line or cable or within a single converter will result in a loss of that pole only with continued operation of the healthy pole in monopole configuration. During this time, the HVDC system will operate at approximately 50% capacity. The same level of redundancy applies during planned outages of a single pole. A fault on the metallic return should not result in a loss of transmission capacity if the system can revert into a rigid/balanced bipole mode and/or if a temporary earth path is available.

A bipole configuration is a fairly standard configuration for HVDC systems and provides for a level of “self-cover” that can minimise the impact on the connecting AC network of a pole trip. A bipole trip (simultaneous loss of both converters or cables) remains a possibility with this configuration, but the rarity of bipole trips on properly designed HVDC systems can lead to these events often being considered non-credible.

A.1.3.2. Monopole

A.1.3.2.1. Asymmetric or Symmetric Monopole Configuration

The asymmetric monopole configuration is comprised of a single converter station at each end of the HVDC transmission line or cable where it connects to the AC grid. The HVDC transmission circuit consists of two cables, one HVDC power cable and a second MR cable.

The symmetric monopole configuration is similar, with the key difference being that it has two HVDC power cables (positive and negative voltage terminals), resulting in a larger voltage across the terminals and subsequently a lower current flowing through the cables when compared to the asymmetric monopole. This can result in the use of smaller cables or lines or a lower DC voltage than the asymmetric monopole.

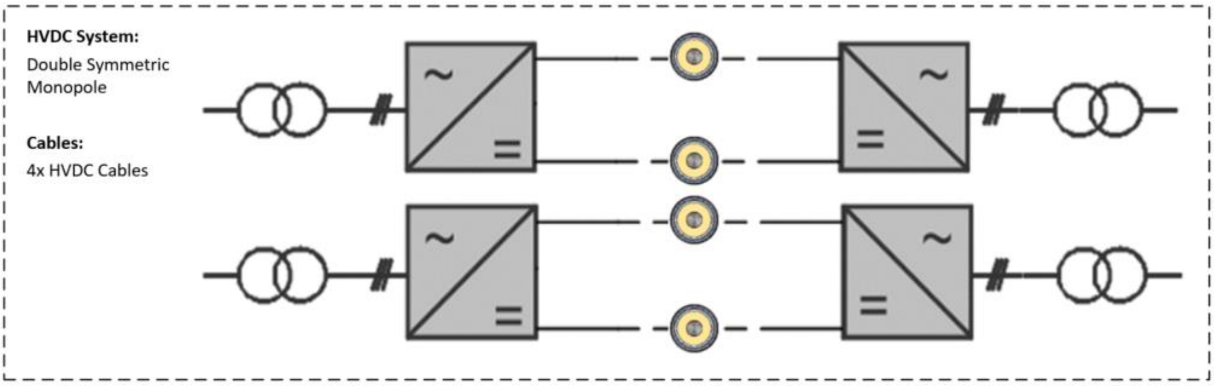
Neither the asymmetric or the symmetric monopole on their own are able to offer redundancy in the case of a converter or a cable fault. The power transmission capacity of over 4 GW required for the Concept HVDC System, is currently not available as a VSC monopole and even if available, it is unlikely the AC network would allow the loss of such a large amount of power in the event of a single credible contingency.

These single asymmetric monopole configuration is not considered viable for Concept HVDC System and will not be assessed further in this report. The single symmetric monopole would be able to provide the required transfer level of over 2 GW but would not be able to provide any redundancy. This system configuration may be considered in the case a non-redundant option is acceptable.

A.1.3.2.2. Double Symmetric Monopole Configuration

As the name suggests, a double symmetric monopole configuration is comprised of two symmetric monopoles each with their own converter at each terminal and two HVDC transmission cables or lines each, installed in parallel to each other. The configuration is shown in Figure 16-2.

Figure 16-2 – Double Symmetric Monopole Configuration



Two symmetric monopoles operating as one HVDC system, i.e. double symmetric monopole, makes it a redundant system. Faults on a transmission line or cable or within the converter of one of the symmetric monopoles will result in a tripping of that symmetric monopole and continued operation of the other symmetric monopole. The same level of redundancy applies during planned outages. When operating with only one symmetric monopole, the total power transfer capacity will be reduced to the rating of the in-service symmetric monopole, which in this case will be 50% of the total transfer capacity of the HVDC system. As both symmetric monopoles are completely independent, a two-system trip caused by a fault within the converter stations is not possible when following good diversity principles.

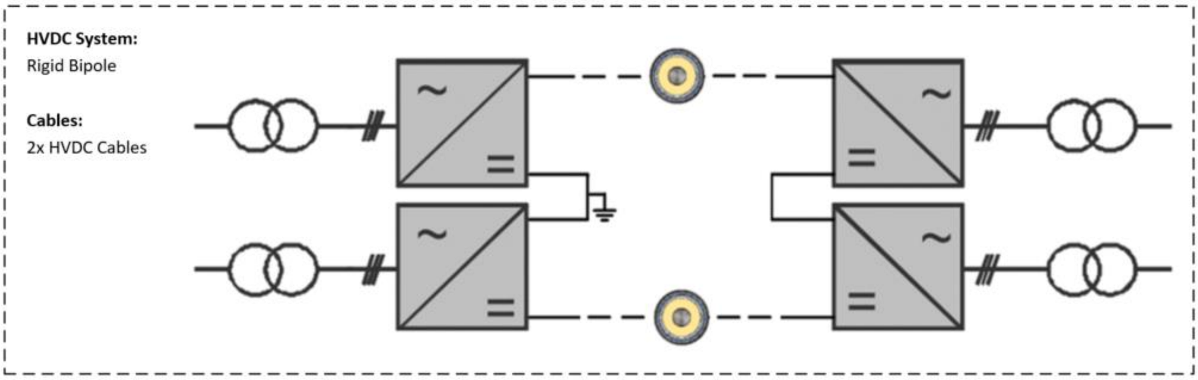
Although additional HVDC transmission circuits are required, the voltage and/or current ratings of the HVDC converters and cables can be reduced for the same total power transfer capacity and/or the current rating of each cable will be much lower (half that of an equivalent bipole configuration).

A.1.3.3. Rigid Bipole

A single rigid bipole system configuration has two converters at each terminal and two main HVDC transmission circuits. At each terminal there are typically two primary high voltage AC connections to the grid. The neutrals of each converter are coupled together and grounded at one end. The configuration is shown in Figure 16-3.

A single rigid bipole can operate at around 50% capacity in the event of a failure or outage of one of the two converter stations at either end but does not have any redundancy on the transmission circuit. This means that a fault on a transmission cables will result in a tripping of the whole HVDC system allowing no power transfer.

Figure 16-3 – Rigid Bipole Configuration



The use of a single rigid bipole configuration is relatively new and has not been commonly implemented mostly due to the single contingency risk that is posed by a fault on the transmission circuit and the impact that this could have on the local power system. However, for longer cable lengths, when compared to a bipole with metallic return, the cost benefit of eliminating one cable may outweigh the risk of a complete loss of the HVDC system due to a cable fault. For lower rated systems, other configurations such as symmetric monopole may be preferable due to a slightly lower cost of the converter stations (less equipment) when compared to rigid bipole.

A.1.3.4. Suitable HVDC System Configuration

A comparison of the technically feasible HVDC system configurations discussed in the previous sections, considered with respect to their application to the Base Case Concept HVDC System for WVTNP, is shown in Table 16-2.

Table 16-2 – HVDC System Configuration Comparison

HVDC System	Bipole w/ MR	Double Symmetric Monopole	Rigid Bipole
Number of converters per end	2	2	2
Number of cables	3	4	2
Redundancy in case of fault or outage on one cable	• Loss of one cable results in system operating at half capacity. • ~50% power capacity remaining.	• Loss of one cable results in system operating at half capacity. • 50% power capacity remaining.	• Loss of one cable results in complete loss of transmission. • 0% power capacity remaining.
Redundancy in case of fault or outage on one converter	• Faulted converter can be bypassed using DC switches. • ~50% power capacity remaining.	• Converter fault results in loss of one monopole system. • 50% power capacity remaining.	• Faulted converter can be bypassed using DC switches. • ~50% power capacity remaining.
General note: The % remaining capacity in this context refers to % of the complete 2.26 GW system i.e. The 50% remaining capacity implies 1.13 GW capacity remaining. This is a simplistic representation and is			

HVDC System	Bipole w/ MR	Double Symmetric Monopole	Rigid Bipole
considered as-referenced at the AC side of the rectifier/sending end, and also excludes losses and any additional short-time ratings that may be available.			

Commentary on the comparison of the different options is as follows:

- **Bipole with Metallic Return:** This configuration offers some redundancy. Half of the capacity will still remain in the event of either a converter or a cable fault. The bipole with metallic return has the second-largest number of cables out of the three options.
- **Double Symmetric Monopole:** This configuration offers good redundancy and the possibility of lowering the DC voltage, thereby lowering the converter power ratings and in turn lowering the DC current which can reduce the cable size requirements. However, even though the cables may be of a smaller rating and size (therefore, comparatively cheaper cost per length of cable), the addition of the extra cable(s) will require wider corridors for the cable route.
- **Rigid Bipole:** This configuration offers some redundancy, meaning that the system will be able to operate at half capacity only in the event of a converter fault but will lose complete power in case of a cable fault. The rigid bipole has the least number of cables. Faults in underground cable systems are comparatively rare due to the level of protection but can still occur in which case the whole system would be out of service until a repair is completed.

From the assessment above, Amplitude are of the opinion that a double symmetric monopole configuration would be suitable to the WVTNP Base Case Concept HVDC System (Option 1 as defined in Section 9.2), due to the redundancy that this system offers and the required power transfer capacity. Opportunities for optimisation of this option are discussed further in Sections 9.8 and 10.

A.2. HVDC Cables

A.2.1. HVDC Cable Types

The two main cable types used for HVDC transmission are mass impregnated (MI) and polymeric cables. The key difference between these two types is the insulation surrounding the main power conductor.

The insulation material used for the MI cable design is layered paper that is impregnated with a high viscosity fluid. MI cables are mainly used with LCC HVDC systems as this type of insulation is less sensitive to polarity reversals than polymeric cables and are qualified up to 525 kV.

Polymeric cables use triple extruded polyethylene as the main insulation system, which is to date has typically been crosslinked polyethylene (XLPE), but new innovations have introduced high performance thermoplastic elastomer (HPTE) in order to achieve higher operational temperature capability. There has been recent development in this technology which qualified these cables up to voltages of 525 kV and 640 kV for extra-long distance transmission at higher power capacities.

Polymeric cable are selected for the Concept HVDC System as they are most commonly used with the VSC technology, easier to install, require less onerous maintenance and present less environmental risks than the MI cables.

A.2.1.1. HVDC Cable Ratings and Capabilities

The electrical characteristics of the HVDC cables and accessories are designed to meet the required active power transfer levels and the switching impulse withstand levels, lightning impulse withstand levels and short circuit levels determined during the technical studies performed for the detailed design phase. 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 system;
    - the rated DC voltage;
    - any required additional short-time ratings and the frequency and duration of the additional loading cycles; and
    - the number of HVDC cables required by the selected HVDC configuration.
- The expected power dispatch and cyclic loading (power transfer) profiles on the cable;
- The thermal resistivity (TR) of the surrounding medium (soil) along the cable route;
- The expected ambient temperature of the soil;
- The maximum conductor temperature allowed by the insulation; and
- Required additional layers, including those required for water blocking and mechanical protection.

Some of these factors require detailed investigation or survey (e.g. thermal resistivity (TR) and soil temperatures) whereas others will depend on the selected manufacture and cable insulation technology (i.e. maximum conductor temperature).

A.2.1.2. HVDC Cable Construction

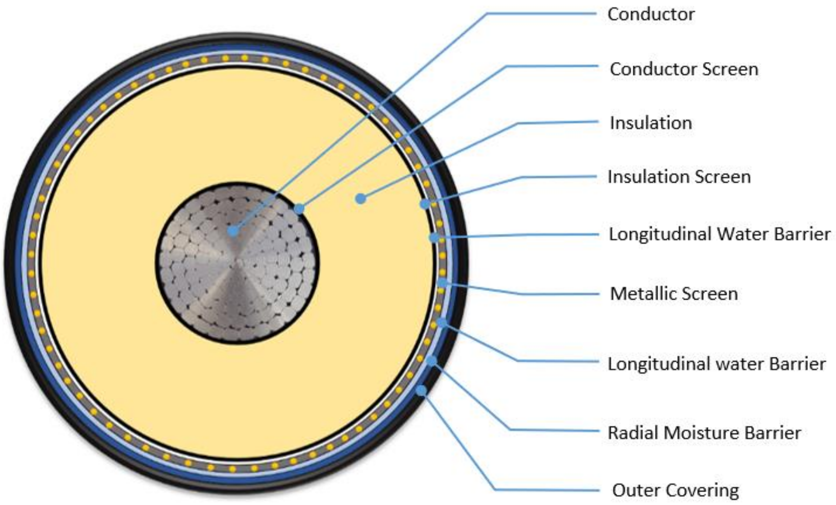
The HVDC cable consists of a conductor with the appropriate layers of insulation, water blocking and protection layers to allow the cable to be buried underground. These various layers are arranged concentrically.

A typical HVDC cable would comprise the following key components/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 16-4.

Figure 16-4 – Typical Land HVDC Cable Construction



For the insulation, a triple extruded polymeric cable core is expected to be the preferred choice for a HVDC option for the WVTNP, mostly because it is of lighter weight which will have benefits in relation to installation activities and is considered to carry less environmental risks than MI cables.

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

A.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.

Appendix B. Comparison of Transmission Options

Amplitude's scope for this activity was to provide our views and some commentary based on our experience on the categories provided by the Council and as listed in this Appendix. This high-level qualitative assessment has been developed for the purposes of relative comparison between the overhead transmission line (OHTL) and underground (UG) transmission construction options as well as between high voltage alternating current (AC) and high voltage direct current (HVDC) transmission technology for each. The following considerations apply:

- It has been developed for relative comparative purposes only and to explore some of the non-cost or market related factors and risks which should or may need to be considered when looking at different transmission development options.
- The comparison has been developed based primarily on experience with references included where these have been readily available.
- The content within should be viewed as a high-level and summary level of the relative pros, cons, risks and main considerations for each.
- It is not an exhaustive comparison and there is much greater level of detail that could be developed for each item.

The comparison below does however cover a large number of factors or considerations that are not otherwise included or evaluated as part of the RIT-T process – the purpose of which is to only *"identify the credible option that maximises the present value of net economic benefit to all those who produce, consume and transport electricity in the market."* [3]

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
1	**Land Disturbance** Total area	**2**	**1**	**3**	**2**
		Lower land disturbance anticipated for this option than the OHTL options [33]. Larger land disturbance than HVDC UG option, due to more cables and of larger size. Trench size estimated to be between 5-7 meters.	Low land disturbance due to fewer cables being needed for equivalent power transfer. Estimated to require a trench width of three meters.	Greater land disturbance by total area is anticipated vs. all other options when also considering access tracks to tower sites [33].	Lower land disturbance anticipated when compared to AC OHTL due to smaller structure sizes.

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[3] https://www.aer.gov.au/system/files/AER%20-%20Regulatory%20investment%20test%20for%20transmission%20-%2025%20August%202020.pdf

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
2a	**Land Disturbance** Type of impact: Soil	3	2	2	1
		Largest volume of soil excavation required when compared to OHTL options and HVDC UG option.	A larger volume of soil will be excavated when compared to OHTL options and less than AC UG option.	Lesser than UG options. Larger towers will require larger foundations, hence greater soil mass excavation requirements than HVDC OHTL option.	Similar to AC OHTL, although the impact is anticipated to be lower due to smaller easement and structure sizes required for equivalent power transfer.
2b	**Land Disturbance** Type of impact: Flora and Fauna	2	1	3	2
		Lesser impact post rehabilitation when compared to AC OHTL due to smaller easement widths. Higher than HVDC UG due to larger easement requirements for cable quantity and size.	Lowest impact post rehabilitation when compared to OHTL options and to AC UG due to smaller easement for fewer cables. Utilisation of road verge or rights of way and smaller trenches means lower disturbance to flora and fauna.	Largest impact than all options due to vegetation clearing and construction activities required for larger easement widths.	Greater impact than UG options due to easement size, but lesser than AC OHTL due to smaller structures.
3a	**Land Disturbance** Permanent structures	1	2	3	2
		There will be limited above ground infrastructure with potentially only cable route markers and link boxes along the route, therefore lower than OHTL options. Below ground structures would include the cables, accessories and ducts (if used). Marginally more infrastructure than the HVDC UG option due to more cables and accessories. Additional equipment may also be needed at terminal stations to support cable operation.	Similar to AC UG except that there would be fewer cable circuits meaning less UG infrastructure and a narrower corridor width for the cables. More permanent structures and larger area required at each end of the link for converter stations than AC.	There will be transmission towers every 250 m – 550 m together with conductors and associated hardware installed above ground. Below ground structures will include tower foundations and earthing systems. A greater number of OH conductors and larger towers when compared to HVDC OHTL will result in larger permanent structures, possibly closer together to account for conductor sag and spacing requirements.	Similar to AC OHTL except that HVDC OHTL structures would be smaller and lighter for equivalent span lengths or alternatively, for structures of equivalent strength longer spans may be used reducing the number of tower structures needed. More permanent structures and larger area required at each end of the link for converter stations than AC.

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
4	**Land Disturbance** Disruption to landowners / community during construction	**3**	**2**	**2**	**1**
		Depends on the chosen cable route but generally during construction there will be obstacles to road use/practicability, disturbance to human activities as well as possible damage to agricultural and wild plantations [33].	Similar impact to AC UG though on a reduced scale due to fewer cables being used and anticipated shorter project duration.	Depends on the chosen OHTL route. Lesser than UG cable options due to less excavation and construction next to roads, but greater than HVDC OHTL option due to larger structures and associated duration of construction. [33]. Duration of impact will likely be shorter than for UG transmission systems due to faster construction rates.	Greater impact than UG options and similar to AC OHTL though on a reduced scale due to smaller tower structures, fewer conductors and anticipated shorter project duration.
5	Land Disturbance Re-use of existing easements or rights of way	**2**	**1**	**3**	**2**
		There is the potential to co-locate UG systems in existing easements however the practicality is highly dependent on the type of adjacent infrastructure. Both normal system operation and electrical disturbance scenario effects must be assessed. Greater number of cables make this option more difficult and onerous than the HVDC UG option.	Smaller easement, low to no electric fields, limited electromagnetic interference and electrical clearance requirements will offer an advantage when compared to OHTL systems. System disturbance effects have to be considered when assessing interactions with adjacent infrastructure. Normal system operation effects are less of a concern than AC.	The size of the structures and permitting process may pose an impediment. Similar to UG systems, interactions between adjacent infrastructure will need to be assessed for feasibility. Both normal system operation and electrical disturbance scenario effects must be assessed.	Similar to AC OHTL with the exception that only the system disturbance condition will have to be studied in detail as the steady state interaction with adjacent infrastructure is likely to be minimal. Structure and easement requirements will be reduced when compared to AC OHTL.

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
6a	**Environmental impact** Visual amenity	**2**	**1**	**3**	**2**
		Negligible visual impact compared to OHTL options. Marginally more impact than HVDC due to larger cable pits and link-box placement between cable sections.	No visual impact, as the cable system is completely buried along the route.	Significantly higher visual impact compared to UG options due to above ground towers. Larger visual impact than HVDC OHTL option as lattice towers are bigger to support more conductors.	Significantly higher visual impact compared to UG options due to above ground towers. Lesser visual impact than AC OHTL option as the towers are smaller to carry less conductors.
6b	**Environmental impact** Construction and excavation and rehabilitation afterwards.	**3**	**2**	**2**	**1**
		Greater construction and significant rehabilitation is required post construction to an acceptable condition compared to OHTL options due to earth works. For most part, public and vehicle traffic returns to normal after works are complete.	Similar to AC UG option with the exception that the reduced easement will need less excavation and rehabilitation work.	Some rehabilitation will be required post construction. Significantly less rehabilitation required due to lower volume of excavation when compared to AC and HVDC UG options. Construction and rehabilitation is marginally more than the HVDC OHTL option due to larger towers and easement requirement.	Similar to AC OHTL except that a smaller footprint will need to be rehabilitated due to smaller towers.
6c	**Environmental impact** Traffic and transportation during construction	**3**	**2**	**2**	**1**
		Larger impact to traffic due to greater earth-works and excavations movements, when compared to OHTL options.	Similar to AC UG except that not as much equipment will need to be transported (cable drums) and reduced excavations due to fewer cables.	Less excavation and faster construction rate than for UG options.	Similar to AC OHTL except requiring less excavation, fewer conductors needing transport and faster construction rate anticipated due to smaller/lighter structures and conductor quantity.

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
7	**Land use** Easement width	**2** Smaller easement than OHTL options. Larger easement to that required for HVDC UG option to accommodate more cables of a larger size.	**1** Smaller easement than OHTL options. Smaller easement to that required for AC UG option due to less cables of a smaller size.	**3** Larger easement than for UG options. The easement for a double circuit 500 kV AC OHTL is estimated to be 60 m wide [34].	**2** Larger than for UG options. Smaller easement for self-supporting lattice towers when compared to AC OHTL option.
8	**Land use** Impact on land use during construction	**3** During construction there will be obstacles to road use/practicability, disturbance to human activities as well as damage to agricultural and wild plantations [33]. Construction zones will place restrictions on egress and access compared to OHTL options.	**2** Similar impact to AC UG though on a reduced scale due to fewer cables being used and anticipated shorter project duration. Construction zones will place restrictions on egress and access compared to OHTL options.	**2** The scale and duration of impact is anticipated to be lesser when compared to the UG options due to reduced earth works, but higher than the HVDC OHTL option due to larger towers. Construction zones will place less restrictions on egress and access than UG options due to less excavation, but more so than the HVDC OHTL option due to larger tower construction.	**1** Similar impact to AC OHTL though on a reduced scale due to smaller tower structures, fewer conductors and anticipated shorter project duration. Construction zones will place less restrictions on egress and access than UG options due to less excavation, and lesser than the AC OHTL option due to smaller tower construction.

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
9	**Land use**	**2**	**1**	**3**	**2**
	Agriculture - general crops, potato growing, Lucerne, grains etc, grazing, burn-offs (smoke impact), operation of large water spray irrigators	The growing of trees directly above a cable easement will likely be prohibited due to the effect this may have on soil moisture level and thermal properties of the soil which can have negative effects on the cable performance. Agricultural activities prohibited directly above the cable circuits as well as additional restrictions to ensure unhindered access by maintenance teams. The routing of the cables can be selected to limit impact by following property boundaries, firebreaks and road reserves. No-Go Zone clearances will have to be adhered to, with clearances being in order of three meters to cable circuits operating at 66 kV and higher [35]. HVDC UG preferred over AC UG and overhead systems due to smaller easement and fewer restrictions. Additionally, HVDC UG has fewer cables which will allow for more flexible routing when compared to AC UG option.		In general, agriculture and grazing may be permitted provided that the activities do not encroach the specified electrical clearances or impede access for maintenance teams. There will be height limitations on the types of trees that may be cultivated and equipment that may be used near to the powerline. Depending on irrigation equipment used, height and encroachment restrictions have the potential to reduce the available irrigated area. For further information on restricted and allowed activities please consult [34]. Burn-offs will likely have to be coordinated with the asset operator and undertaken at an appropriate time to minimise flame height and network risk. No-Go Zone clearances will have to be adhered to, with clearances being in order of eight meters for transmission towers, with a spotter required for works between eight and ten meters to ensure clearances are not breached [36]. The HVDC line may be able to be operated in a reduced voltage mode to allow for burn-offs with lower risk of tripping which is an advantage over the AC OHTL option. Additionally, HVDC OHTL will have a smaller footprint than the equivalent AC OHTL option.	
10	**Land use**	**2**	**1**	**2**	**3**
	Metallic and non-metallic fencing	Installation of metallic and non-metallic fences and structures on the easement will typically require approval to ensure that the risk to the cable system is managed during installation and access is unhindered. This is anticipated to be less of a concern than for OHTL options. Smaller trench width requirement for the HVDC UG option makes it more favourable over the AC UG option as it is easier to route along roadways and reduce interaction with fencing installations.		Installation of metallic and non-metallic fences on the easement will require approval and be subject to height limitations to ensure dangerous voltage and breach of clearances do not occur. Metallic fences, if allowed, will require additional sectionalising, earthing and bonding to avoid transfer potentials during a fault event [34]. Parallel metallic fences should be avoided. AC OHTL is expected to impose marginally less restrictions to HVDC OHTL due to taller construction of the towers reducing risk of fence interaction, dependant on the tower design and circuit configuration.	

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
11	**Land use** Use of large agricultural tractors, harvesters and other machines such as cranes, excavators, etc.	2	1	2	3
		Use of heavy machinery will be negatively impacted and/or restricted, though to a lesser extent when compared to OHTL options. Excavation in proximity to the easement will require permits and/or dial-before-you-dig clearances to be obtained. Depending on cable system construction method, the use of heavy machinery on the easement may be restricted and/or require permitting. No-Go Zone clearances will have to be adhered to, with clearances being in order of 3 m to cable circuits operating at 66 kV and higher [35]. Routing of cables along existing roadways can be possible which would reduce impact to the use of harvesting machinery, tractors, etc. when compared to the OHTL options. HVDC UG is preferred over AC UG and overhead systems due to smaller easement requirement for fewer cables.		Use of equipment will be limited and/or restricted. As an example, equipment will have a height limitation imposed with permits required if equipment exceeds three meters in height and this may only be granted if there is sufficient electrical clearance available [34]. Other prohibited activities on the easement as reported in [34] could include: • Loading, unloading and load adjustment of large trucks. • Operation of large water spray irrigators of the gun type. • Metal pipes (including reinforced concrete), power cables and other electrically conductive materials within 30 metres of any tower steelwork. • Fuelling of and repairs to vehicles, plant and equipment. • Parking of large trucks and caravans. No Go Zone clearances will have to be adhered to, with clearances being in order of eight meters for transmission towers, with a spotter required for works between eight and ten meters to ensure clearances are not breached [36].	
12	**Land use** Commercial, Private, Sports, Emergency or Agricultural Aerial activities	1	1	3	2
		Limited to no impact to activities foreseen.		Low level aerial activities will be impacted and/or restricted. Appropriate precautions and aviation rules will have to be followed in proximity to overhead line structures. Additional risks are anticipated for activities when compared to UG options.	Similar risks and impacts to AC OHTL option though towers are likely to be smaller and lower in height for equivalent power transfer, therefore marginal reduction to the risk may be expected.

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
13	**Land use** Trees exceeding 3m mature growth height	2	1	3	2
		Provided not planted directly above the cable or possessing roots capable of damaging the cables, it is not anticipated that there would be a need to limit the mature growth height of trees planted in proximity to the cable circuits. Restrictions to ensure access to the easement may be required. HVDC UG is preferred over AC UG due to smaller easement requirement for fewer cables.		The height of trees would need to be limited to prevent flashover and risk of trip due to bushfires. Three metres is reported in [34] as the permitted height for trees and shrubs on the easement. HVDC OHTL is the preferred option out of the two, as the towers are expected to be smaller and therefore present less of an impact.	
14	**Land use** Metallic pipes, power cables, antennas, towers and other conductive materials	2	1	3	2
		The impact of magnetic coupling and fault current on infrastructure running in parallel or in proximity to the cable systems will have to be assessed and risks mitigated through appropriate design. Assessment will have to address both normal operation and fault scenarios for the AC UG option.	Similar to AC UG, assessments will have to be undertaken, however interactions during normal operation with adjacent infrastructure are anticipated to be less of a concern with more focus being placed on fault scenarios. Additionally, effects of parallel infrastructure coupling electromagnetically onto the HVDC system will have to be assessed as well.	Installation of structures on the easement will require approval and may be subjected to restrictions in terms of proximity, length, orientation and height. Additional earthing and bonding measures may be required. Electromagnetic interactions will have to be assessed for compatibility.	Less of a concern compared to AC OHTL. HVDC OHTL interactions in normal operation with adjacent infrastructure are anticipated to be less of a concern with more focus being placed on HVDC OHTL fault scenarios. Additionally, effects of parallel infrastructure coupling electromagnetically onto the HVDC system will have to be assessed.
15	**Land use** Operation of and interference to radio, television, communications services, including Amateur (Ham) Radio HF reception	1	1	3	3
		Lower risk when compared to OHTL options as there are no corona discharges along transmission route giving rise to interference. Compliance to standardised interference limits will need to be met through appropriate design and verification methodology.		Higher risk when compared to UG transmission options. Typically, the worst emissions are during bad weather for AC and fair weather for HVDC. Compliance to standardised limits will need to be met through appropriate design and verification methodology.	

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
16	**Technical** Audible noise	1	1	3	3
		UG cables do not produce audible noise [33]. Some audible noise is expected from the HVDC converter stations and AC terminal stations but these are typically located away from main public areas.		Audible noise is generated due to corona on the transmission line conductors and must be considered. Compliance to standardised limits will need to be met through appropriate design and verification methodology. Additional noise can occur from lattice transmission towers and strung conductors in windy weather, which is a factor that does not concern underground cables and is considered as a detriment effect to the OHTL construction in this assessment.	
17	**Technical** EMF Health and Safety (Particularly considering the adverse effect of the electric field (micro-sparks, ozone, etc) - with less focus on the non-intrusive magnetic effects)	2	1	3	2
		Time varying magnetic fields are present and usually higher directly under AC OHTL [33]. Electric field effects are contained within the cable construction and are usually less of a concern when compared to OHTL systems.	Electric fields are contained with only static magnetic fields present. The limits are much less stringent for HVDC for the static component. Compliance to standardised limits will need to be met through appropriate design and verification methodology.	Both time varying electric and magnetic fields are present and compliance to standardised limits will need to be met through appropriate design and verification methodology.	Static electric and magnetic fields present and compliance to standardised limits will need to be met through appropriate design and verification methodology. Limits for static electro-magnetic fields (DC) are less onerous than those for time-varying (AC) fields, and therefore the HVDC OHTL option is preferable over the AC OHTL option.
				High electric field surface gradient on the conductors will give rise to corona which is associated with audible noise, power loss, radio and television interference together with the formation of ozone and nitrogen oxides. Corona performance is a key aspect of the design and designers will have to ensure that the electric field threshold for corona inception is considered and emissions during wet and dry conditions are maintained to below the specified limits. HV OHTLs are known to have an inductive effect on metallic structures that are located within their vicinity, which can result in static charge build up or micro-shocks if appropriate design practices and techniques are not employed. Micro-shocks, if they do occur, are not known to cause any long-term health effects or cause skin damage [37]. This is a phenomena that occurs on OHTLs but not on cable systems, therefore is a detrimental factor to the OHTLs in this assessment, even though minor in its impact.	

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
18	**Technical** Electrical losses - MWh/year	3	1	2	1
		AC UG cables typically have higher low load losses when compared to AC OHTL due to the constant dielectric loss of the cable and lower full load losses due the lower impedance. Additionally, the charging current required for this cable route length would be particularly high, due to the AC capacitance of the cables.	HVDC UG is more efficient than AC UG due to the lower cable impedance for DC and no charging currents, resulting in lower losses.	AC is more efficient at low loads than AC UG but likely less efficient than HVDC OHTL and HVDC UG systems.	HVDC OHTL is more efficient than AC for equivalent conductor type and power transfer levels due to reduced conductor DC resistance.
19	**Technical** Electrical losses - equivalent tons of CO2 emitted/year	3	1	2	1
		See qualifier below. Assumed to be higher for this option as the losses are greater.	See qualifier below. Assumed to be lower for this option as the losses are lower.	See qualifier below. Assumed to be higher for this option as the losses are greater.	See qualifier below. Assumed to be lower for this option as the losses are lower.
		To perform a fair design comparison on transmission lines and cable system, design would be required together with power transfer and loading assumptions. HVDC UG is anticipated to have the lowest equivalent tons of CO2 emitted/year due to higher efficiency.			
20a	**Technical** Power system stability - potential overload	3	2	1	2
		AC UG overload flexibility is typically greater than HVDC UG. The overload capacity is largely determined by the pre-overload power transfer. Although, for this particular solution the technology is limited in terms of cable sizing to accommodate this power transfer over the required cable length therefore overload would not be feasible.	Similar to HVDC OHTL, HVDC UG has the potential for overload capability if catered for in the design for both the converter station and HVDC UG. It is considered better in this particular case than AC UG due to feasibility for the circuit lengths involved, but lesser than the AC OHTL option.	AC OHTL and substations offer more flexibility than HVDC OHTL and UG transmission systems up to the thermal capacity of lines and equipment. The overload capacity is largely determined by the pre-overload power transfer.	HVDC OHTL has the potential for overload capability if catered for in the design for both the converter station and transmission circuit.

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
20b	**Technical** Power system stability - potential damping, reactive power generation / consumption	**3**	**1**	**3**	**1**
		AC systems have lesser controllability when compared to HVDC systems. No notable differences between AC UG and AC OHTL options.	HVDC systems have active power flow control and can provide reactive power depending on HVDC technology selected together with frequency and damping support. No notable differences between HVDC UG and HVDC OHTL options.	AC systems have lesser controllability when compared to HVDC systems. No notable differences between AC UG and AC OHTL options.	HVDC systems have active power flow control and can provide reactive power depending on HVDC technology selected together with frequency and damping support. No notable differences between HVDC UG and HVDC OHTL options.
20c	**Technical** Power system stability - black start services	**1**	**2**	**1**	**2**
		AC systems have a black start capability, which does not need to be specifically catered for in the design, unlike the HVDC systems. No notable differences between AC UG and AC OHTL options.	HVDC systems have the potential to provide black start services, but would have to be specifically catered for in the design. No notable differences between HVDC UG and HVDC OHTL options.	AC systems have a black start capability, which does not need to be specifically catered for in the design, unlike the HVDC systems. No notable differences between AC UG and AC OHTL options.	HVDC systems have the potential to provide black start services, but would have to be specifically catered for in the design. No notable differences between HVDC UG and HVDC OHTL options.

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
21	**Technical** Transmission circuit installation techniques and installation rates	3	2	2	1
		Direct cable burial is a more land intrusive technique compared to all options due to excavation and trench widths to accommodate larger cables and a higher quantity of cables. Lengthier installation campaign anticipated for this option in comparison to HVDC UG option due to larger quantity of cables and greater earth works.	Similar installation techniques to AC UG option. More land intrusive compared to OHTL options due to excavation but less so comparing the AC UG option as a smaller trench width will be required for a reduced cable size and quantity. Shorter installation campaign duration compared to AC UG option only, for the same reasons mentioned.	Foundations, above ground tower installation and aerial conductor stringing requires less earth works than for UG options. Generally limited to tower site locations as well as access tracks. Lengthier installation campaign anticipated for this option due to bigger towers compared to HVDC OHTL option and larger quantity of circuits. Marginally shorter installation campaign duration anticipated than for the both UG options.	Reduced installation campaign anticipated for this option due to smaller towers compared to AC OHTL option and smaller quantity of circuits. Shorter installation campaign duration anticipated than for the UG options and only marginally shorter than that for the AC OHTL option.
				Highly variable and is dependent on structure size, construction methods, crew size, terrain and span length.	
22	**Technical** Maintainability and reliability	1	2	2	3
		Anticipated to have more cable related maintenance and/or higher number of faults due to greater number/total length of installed cables when compared to HVDC UG but lower than compared to OHTL options. Average outage duration (AC extruded 315-499 kV) reported as 23.8 days in [38].	Cable maintenance similar to AC UG option. Converter station maintenance is greater than that for AC substations, due to complex electronics and larger quantity of equipment and sub-systems. Acceptable reliability levels considering both the transmission circuit and converter stations can be achieved through design. Average outage duration (DC extruded 220-314 kV) reported as 21 Days in [38].	AC OHTL system anticipated to be more economical to maintain with respect to cost duration and complexity when compared to DC systems and the requirement of the converter stations. More onerous to maintain than a AC UG option, due to increased number of faults on OHTL and vegetation clearing. Spares and components are supplied by multiple vendors with higher levels of interchangeability when compared to HVDC options.	HVDC OHTL will need fewer or reduced maintenance interventions due to fewer conductors being used when compared to AC OHTL option. Maintenance and operation is more specialised and costs more than an AC options when considering the converter stations and complexity of equipment. Dedicated personnel required to run each converter station. Acceptable reliability levels considering both the transmission circuit and converter stations can be achieved through design.

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
		UG cable faults tend to be permanent and have longer repair times, additional circuits may be necessary to obtain the same level of security as with overhead lines [33].		Majority of overhead line faults are transient with overhead lines being reported to be the most economical and reliable means of high voltage transmission [33]. Overhead lines are subjected to more frequent but shorter outage durations than UG cables which have fewer but longer duration outages [33].	
23	**Technical** Susceptibility to faults caused by bushfires and adverse weather events	1	1	3	3
		UG systems have lower risk of faults when compared to overhead transmission systems.		Overhead transmission systems have a higher risk of faults developing due to their exposure to bushfire and weather events e.g. lightning. For weather related scenarios, the designers will have to ensure that the system is able to withstand events below a specified severity (to meet minimum reliability criteria) and to recover to a healthy state should a failure occur due to an event outside of the design margin. The requirements are further defined in national standards. Bushfire performance, if deemed necessary, can be improved through vegetation management methods, advanced satellite warning systems and/or through the construction of larger towers with greater electrical clearances in fire prone areas. HVDC OHTL can be designed to be able to operate in a reduced voltage mode thereby reducing susceptibility to flashovers during times of increased bushfire risk.	
24	**Technical** Health and safety (working at heights, use of helicopters, etc)	1	1	3	3
		Similar to overhead line maintenance, appropriate practices for cable systems have to be followed to ensure electrocution risk are eliminated. Risks for transport and driving and general construction and maintenance works can be considered to be similar to overhead lines, with the exception of working at heights, working on mechanical loaded structures and aerial maintenance work. Risk is therefore considered to be lower for UG transmission systems.		Working at heights is expected during the construction, operation, and maintenance of overhead transmission systems. Depending on the construction and maintenance philosophy, helicopter work can also be anticipated. Additional measures will have to considered to ensure risks are contained to an acceptable level.	

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
25	**Risks** Transmission Lines causing bushfires (e.g. PG&E Camp Fire Scenario)	**1**	**1**	**3**	**2**
		UG cable options have a low to no risk for causing bush fires compared to OHTL systems as faults are contained below ground [39] away from fuel sources, are protected from the elements, having shorter arcing distances to earth, cable protection system are designed to trip and lock out (as opposed to attempting recovery) [39] and above ground components e.g., cable terminations are usually located in dedicated facilities and are closed off to general public.		AC OHTL lines exhibit a higher risk when compared to UG systems due to the nature of their construction, exposure to the elements, proximity to fuel sources and failure modes when compared to UG options. The AC OHTL option is considered to be at a marginally higher level of risk compared to HVDC OHTL option, due to bigger towers and quantity of circuits.	HVDC OHTL risks are comparable to AC OHTL with the exception that HVDC protection systems operate quicker. It is anticipated that the faster protection times will lead to lower fault/arc energy and that the risks for HVDC OHTL causing a fire will be lower than for AC OHTL. HVDC OHTL risks are greater than UG options.
26	**Risks** Transmission Line susceptibility to damage from bushfires	**1**	**1**	**3**	**3**
		Typically, not much of a concern for the transmission line alone. Some consideration needs to be given to the above ground infrastructure as it may be impacted, such as HVDC converter stations and AC terminal stations.		Fires have the potential to damage conductors, insulators, and transmission line hardware.	
27	**Risks** Increasing bushfire risk to communities (Safe egress, restrictions on aerial firefighting activities, switch offs, restoration downtime), risk to land users and ground based firefighters (overhead lines can remain capacitively charged even when powered off)	**1**	**1**	**3**	**2**
		None or low additional risk is foreseen when compared to overhead lines.		Towers may negatively impact aerial firefighting activities. Restoration times are considered similar between AC and HVDC OHTLs.	The HVDC line may be able to be operated in a reduced voltage mode to allow for a lower risk of tripping which is an advantage over AC OHTL during bushfire periods.

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
28	**Risks** Unavailability of power during bushfire peak periods (due to the need to power down circuits during bushfire risks)	**1**	**1**	**3**	**2**
		Cable circuits are foreseen to be a lower risk of outage during bushfires.		A AC OHTL is susceptible to bushfires leading to faults or requiring the line to be de-energized during periods of risk.	HVDC OHTL are susceptible to bushfires leading to faults. The HVDC line may be able to be operated in a reduced voltage mode to allow for a lower risk of tripping which is an advantage over AC OHTL.
29	**Risks** Impact of unreliable breaker technology in high impedance failure scenarios (fire potential)	**1**	**1**	**3**	**2**
		Cable circuits are anticipated to present a lower risk for causing a fire due to a maloperation protection when compared to overhead lines e.g. during an undetected high impedance fault. This is largely because of the UG construction and cable failure modes usually being definitive and permanent faults until a repair is implemented.		AC OHTL systems are susceptible to protection malfunction e.g. for high impedance faults which have the potential to increase fire ignition risks.	HVDC OHTL systems are susceptible to protection malfunction similar to AC OHTL. The difference being that there are several other protection functions which provide greater levels of redundancy, therefore the risk is lower for a HVDC OHTL option than the AC OHTL option.
30	**Risks** Weather / Climate Change	**1**	**1**	**3**	**3**
		Climate change may reduce soil moisture levels and the thermal transfer capacity of the soil, leading to reduced performance or power transfer. Changes in ground water level may also have a negative impact on cable performance [40]. UG systems have reduced exposure to the elements and hence are preferred to overhead systems which have a greater exposure to the elements and effects of climate change.		Increasing frequency of extreme weather events have the potential to collapse towers, and therefore are at a higher risk than the UG options.	

#	Category	AC UG Option	HVDC UG Option	AC OHTL Option	HVDC OHTL Option
31	**Risks**	**1**	**1**	**2**	**2**
	Susceptibility to risk to supply through accident, malicious intent, terrorism, insulation damage from parrots (cockatoos, corellas)	Burrowing fauna such as rabbits may pose a risk as the removal of soil around a cable will impact heat transfer during operation. In soil infected with termites additional measure may have to be undertaken to protect the cables [41] but this is usually accounted for in the design of the cables, i.e. termite barriers. Lower risk from vandalism and malicious intent, though higher risk of accidents due to excavations when compared to overhead transmission systems which can managed by appropriate maintenance techniques. Cable theft can be a concern in certain countries.		Glass discs are subject to gun-shot damage and vandalism due to their failure mode. Certain bird species are known to chew and damage composite insulators. Theft of tower members leading to collapse can be a concern is certain countries. OHTL options are at a higher risk than the UG options due to ease of accessibility and accidental damage, such as car accidents. All considered – marginally higher risk level rating.	
32	**Risks**	**1**	**1**	**3**	**2**
	Risk to aviation operations (commercial, police, air ambulance, sporting, firefighting and agricultural aerial activities are impacted, particularly VFR non-instrument rated flights in low cloud, smoky or adverse conditions, incidents of wire-strike)	Limited to no risk presented by aerial activities.		Low level aerial activities will be impacted and/or restricted. Appropriate precautions and aviation rules will have to be followed in proximity to OHTL structures. Structures will have to comply with standards for the installation and maintenance of warning markers. Additional risks are anticipated for aviation operations when compared to none for UG transmission systems. It is anticipated that AC OHTL will present a greater risk than HVDC OHTL due to larger size of structures.	