Moorabool Shire Council

Comparison of 500 kV Overhead Lines with 500 kV Underground Cables

September 2020

MOORABOOL
SHIRE COUNCIL

Disclaimer

Contents

Abbreviations and Acronyms

Table 1: Abbreviations and acronyms

Item	Description
AC	Alternating Current
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AS/NZS	Australian Standard and New Zealand Standard
DC	Direct Current
DSTN	Declared Shared Transmission Network
CIGRE	International Council on Large Electric
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DELWP	Department of Environment, Land, Water and Planning
EHV	Extra High Voltage
EMC	Electro-Magnetic Compatibility
EMF	Electro-Magnetic Field
EPC	Engineering, Procurement and Construction
HV	High Voltage
IAEA	International Atomic Energy Agency
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-Ionising Radiation Protection
ICRP	International Commission on Radiological Protection
IEC	International Electro-technical Commission
NEAOECD	Nuclear Energy Agency of the Organisation for Economic Co-operation and Development
NEM	National Electricity Market
NER	National Electricity Rules
PACR	Project Assessment Conclusion Report
PADR	Project Assessment Draft Report
PFD	Power Flux Density
PSCR	Project Specification Consultation Report
RIT-T	Regulatory Investment Test for Transmission
TNSP	Transmission Network Service Provider
UHV	Ultra High Voltage
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organisation

Executive Summary

Moorabool Shire Council engaged an independent consultant to conduct a comparison assessment of 500 kV overhead transmission lines with 500 kV underground transmission cables. This report has been prepared to provide an overall perspective based on literature reviews on the impacts of overhead line and underground cables and to assist Moorabool Shire Council in their understanding of these two technologies. All information in this report is based on a literature review with the exception of the EMF modelling which has been conducted by the consultant using typical designs, assumptions and indicative dimensions.

The Western Victoria Renewable Integration Project was initiated in April 2017 by AEMO in accordance with the Regulatory Investment Test for Transmission (RIT-T) to address transmission network limitations in Western Victoria. The driver and benefits of this Project are to unlock up to 6 GW of renewable energy sources, predominantly wind and solar generation, in North West of Victoria. AEMO as the jurisdictional network planner for Victoria conducted an economic cost-benefit analysis that forecasted a gross market benefit of AUD 670 million by investing a capital cost of AUD 370 million.

In December 2019, Mondo (commercial division of AusNet Services) was awarded the Project by AEMO to design, procure, construct, own and operate. The Project has since been renamed to Western Victoria Transmission Network Project with a target completion of the transmission infrastructure in 2025. The scope of work for the entire Project comprises of 75 km of 500 kV double circuit transmission lines, 115 km of 220 kV double circuit transmission lines, a new terminal station at north of Ballarat with 2 x 1,000 MVA 500/220 kV transformers, reconfiguration of existing network with new 220 kV transmission lines at Waubra and Elaine Terminal Stations, and the installation of reactive compensation at Sydenham and the new Terminal Station.

The proposed 75 km of 500 kV double circuit transmission lines are proposed to traverse across Melton City and Moorabool Shire areas. A new terminal station is to be built in north of Ballarat, the location of which has yet to be determined, likely either within Moorabool Shire or Hepburn Shire.

An alternative to the proposed 500 kV double circuit overhead lines could be implemented with 500 kV double circuit underground cables. If it is not commercially viable to install the entire 75 km route underground, certain segments could be installed underground although this would require an aboveground transition station at each end. To install a portion of the route underground is not a simple solution but it is a technically feasible option. Another option is to install some or all of the new overhead line adjacent to the route of the existing overhead line easement (Sydenham-Moorabool-Elaine-Ballarat).

Some of the major differences between overhead and underground options for a 500 kV double circuit transmission connection are:

- Larger visual impact for overhead line due to the above ground infrastructure, reduced visual impact for underground cable, excepting possible need for transition stations. The visual impact of new overhead lines may be reduced by close location with existing overhead lines.
- Indicative EMF modelling results found that the magnetic field level for a person standing directly above the underground cables is higher than when standing below an overhead line. However, underground

cables offer a significant reduction of magnetic field level (even lower than overhead lines) when standing 15 m away.

- During construction, there would be greater ground disturbance for underground cables compared with overhead lines.
- Underground installation of 500kV cables over a 75 km length has not yet been undertaken elsewhere in the world. Theoretically, an effective length of up to 80 km is achievable with significant reactive compensation is required.
- Construction lead time is estimated as 3 times longer for underground cable (6 years) than overhead line (2 years), for a 75 km length. It may be possible to reduce the lead time (potentially by half the estimated time) by increasing resources for working simultaneously at multiple locations along the underground cable route, which may impact on the construction cost.

More detailed differences between overhead lines and underground cables are shown on the next page in Table 2.

Key Differences

Table 2: 500 kV overhead lines versus 500 kV underground cables

No	Description	Overhead lines	Underground cables	Discussion
1.	Effective circuit length	The effective length of a 500 kV AC overhead transmission line can be as long as 2,500 km transferring bulk power from one substation to another. Reactive compensation is required for long length of circuits.	The longest operating 500 kV AC underground transmission cable is approximately 40 km. As technology advances, longer length of cable can be achieved and it is expected that the effective length can be up to 80 km but significant reactive compensation would be required, which adds to the overall capital cost.	Historically, underground cables are only for short length installation but with the advances of technology, longer length of cables are becoming more feasible.
2.	Design and performance	Typical infrastructure designs use steel lattice towers or metal/concrete poles with spans ranging from 400 m to 500m between each tower/pole and terminal stations at both ends of the line. The line consists of bare conductors. The desired capacity for this Project is 3,000 MVA per circuit, totalling 6,000 MVA for a double circuit. Four bundled conductors per phase per circuit are required.	Typical infrastructure designs use transition stations (terminal stations) at both ends of the cable and joint pits along the cable with spans ranging from 400 m to 500 m. The joint pits are located underground and are usually accessible. The cable consists of insulated conductors. In order to meet the approximate desired capacity for this Project, 2,850 MVA per circuit, totalling 5,700 MVA for a double circuit. Two sets of cables per phase per circuit are required.	Both technologies can deliver approximately the same desired performance and capacity to meet the Project's requirements.
3.	Reliability	Susceptible to inclement weather such as high wind, storm, tornadoes, lightning and heat waves. For instance, South Australia and South West Victoria suffered tower collapse and damage incidents in September 2016 and January 2020, respectively. Forced outage rate for the 75 km of double circuit overhead line is calculated as 2.25 incident per annum	Not susceptible to weather conditions. Forced outage rate for the 75 km of double circuit underground cable is calculated as 0.79 incident per annum.	Underground cable systems are not susceptible to weather and have a better forced outage rate.
4.	Easement requirement	For a double circuit line and associated towers, the easement width requirement is between 60 m and 70 m.	For a double circuit underground cable (four sets of cables), the easement width requirement is between 42 m and 48 m.	Depending on the underground cable laying method, easement width for underground cables can be less than overhead lines.

No	Description	Overhead lines	Underground cables	Discussion
			During construction, the corridor swathe of up to 100m is not uncommon.	
5.	Vegetation management	Routine and significant vegetation maintenance is required to prevent bush fire hazards and faults. Trees can overgrow and touching the line, causing a fault. According to AusNet Services [6], the allowable mature height of vegetation on easements is 3 m	Less vegetation maintenance is required. Damage can be caused by flora such as tree roots penetrating or constricting the cable. Damage can be caused by fauna such as rodents and insects eating the surface of the cable.	During normal operations, greater vegetation management activities are required for overhead lines than underground cables.
6.	Ground disturbance	Less ground disturbance during construction. The disturbance is at tower/pole locations where footings will require excavation between 3 m and 10 m depth.	During construction there will be significant ground disturbance as soil will be dug out to build trenches between 1 m and 2 m deep for the entire length of the cable. Nearby areas used for materials storage, temporary haul roads and temporary accommodation will also be disturbed.	Significant ground disturbance during constructions to install underground cables as compared with overhead lines.
7.	Induced voltages	Induced voltages from overhead lines in metallic objects running in parallel or in close proximity such as railway tracks, pipelines, fencing may lead to touch potential issues. Appropriate earthing is required on the metallic objects.	Induced voltages from underground cables to metallic objects running in parallel or in close proximity such as railway tracks, pipelines, fencing may lead to touch potential issues. Appropriate earthing is required on the metallic objects.	Both technologies induce voltages on nearby metallic objects and can result in touch potential issues. The touch potentials can be controlled by implementing appropriate earthing methods.
8.	Audible noise	Audible noise due to corona effects, which sounds like crackling and hissing to human ears. It is expected that 500 kV overhead lines may produce audible noise of up to 45 dB for a person standing 15 m away from the overhead line (closest phase of the circuit).	No (or negligible) audible noise.	Overhead lines emit audible noise whereas underground cables do not (or negligible). Safe Work Australia suggests that a noise levels should be kept below 50 dB if your work requires high concentration or effortless conversation.
9.	Operations and maintenance	Overhead lines system is designed to operate continuously (24 hr, 365 days a year) unless there is threat such as bush fire approaching.	Underground cables system is designed to operate continuously (24 hr, 365 days a year) and generally has no threat from inclement weather.	In comparison, less maintenance activities for underground cables but when there is a damage to the cables, a repair will take significant greater

No	Description	Overhead lines	Underground cables	Discussion
		Routine maintenance is required on the line (patrolling), easement, vegetation, non-invasive inspections and condition assessments.	Routine maintenance is required on the cable (ground patrolling), transition stations and condition assessments.	amount of time as compared with overhead lines. Considering that there are not many applications of 500 kV underground cables installation in the world and none in Australia, specially trained operations and maintenance personnel would be required.
10.	Electro-Magnetic Field (EMF)	Modelling has been conducted to identify the magnetic field exposure for a typical 500 kV double circuit overhead line. For a person standing below the overhead lines, the magnetic field exposure at a height of 1.5 m (typical person's chest or head height) is 2.6 µT. If the person stands 15 m and 30 m away, the magnetic field exposures are 2.3 µT and 1.7 µT, respectively. The results show marginal reduction when standing up to 30 m away from the overhead lines. The magnetic exposure is below the limit of 200 µT defined by ARPANSA.	Modelling has been to identify the magnetic field exposure for a typical 500 kV double circuit underground cable. For a person standing above (assuming peak) the underground cables buried at 1.3m depth, the magnetic field exposure at 0 m (feet height) is 105 µT. If the person stands 15 m and 30 m away, the magnetic field exposures are 0.25 µT and 0.03 µT, respectively. The results show significant reduction when standing 15 m away from the underground cables. The magnetic exposure is below the limit of 200 µT defined by ARPANSA.	Indicative EMF modelling results found that the magnetic field level for a person standing above the underground cables are higher than standing below an overhead line. However, significant reduction of magnetic field level (even lower than overhead lines) when standing 15 m away from the underground cables Modelling results show that both technologies are still within the magnetic exposure limit defined by ARPANSA.
11.	Health and safety	Typical risks have been described in their respective sections such as reliability (tower collapse and fallen conductor that may start a fire). An example within Pacific Gas and Electric (PG&E) power network started a wildfire in California in 2018 and burned down more than 10,000 homes and 153,000 acres, and 84 people lost their lives[1].	The biggest risk is during construction due to massive excavation, materials handling and vehicle movements.	In any infrastructure development there is always a risk as compared to no infrastructure development. The Project shall minimise hazards to an acceptable risk.

1 https://www.bbc.com/news/world-us-canada-53072946

No	Description	Overhead lines	Underground cables	Discussion
				Both technologies are generally safe to operate and maintain and for the general public.
12.	Approvals and standards requirements	In Australia, RIT-T process is required to obtain network planning approvals. Environmental planning assessment is likely to be required. Overhead lines are subject to their own standards, technical requirements and guidelines.	In Australia, RIT-T process is required to obtain network planning approvals. Environmental planning assessment is likely to be required. Underground cables are subject to their own standards, technical requirements and guidelines.	Regardless of overhead lines or underground cables, the Project will need to apply for network planning approvals, environmental planning assessment and adhere to standards, technical requirements and guidelines.
13.	Project timeline	The project timeline for the 75 km length of overhead lines is approximately 5 years, that consists of 3 years for planning and approvals and 2 years for construction.	It is assumed that the planning and approvals would be similar for the Project and the estimated construction timeline for the 75 km length of the underground cables is approximately 6 years.	The construction timeline for underground cable is approximately 3 times longer, 6 years for underground cables and 2 years for overhead lines. It may be possible to reduce the lead time (potentially by half the estimated time) by increasing resources for working simultaneously at multiple locations along the underground cable route, which may impact on the construction cost.

1 Project Background

AEMO initiated a Regulatory Investment Test for Transmission (RIT-T) to address transmission network limitations in Western Victoria known as the Western Victoria Renewable Integration Project in April 2017. The driver and benefit of this Project are to unlock up to 6 GW of renewable energy sources, predominantly wind and solar generation, in the North West of Victoria. AEMO as the jurisdictional network planner for Victoria conducted an economic cost-benefit analysis that forecasted a gross market benefit of AUD 670 million by investing a capital cost of AUD 370 million.

In December 2019, Mondo (commercial division of AusNet Services) was awarded the Project by AEMO to design, procure, construct, own and operate. The Project has since been renamed to the Western Victoria Transmission Network Project with a target completion in 2025. The scope of work for the entire Project comprises of 75 km of 500 kV double circuit transmission line, 115 km of 220 kV double circuit transmission line, a new terminal station at north of Ballarat with 2 x 1,000 MVA 500/220 kV transformer, re-configuration of 220 kV transmission lines at Waubra and Elaine Terminal Stations and the installation of reactive compensation at Sydenham and the new Terminal Station.

In July 2020, Mondo commenced project information sessions for engaging with the community on the various impacts of this Project to the community and stakeholders. The sessions include information in general on timeline, route selection, proposed infrastructure, examples of construction sites and health and safety. The 75 km of 500 kV double circuit transmission line proposed to be erected are expected to traverse across Melton City and Moorabool Shire areas and a new terminal station is to be built in north of Ballarat, the location of which has yet to be determined but expected to be within Moorabool Shire or Hepburn Shire. The proposed transmission corridor is shown in Figure 1.

This report was written for the reader to understand the key differences between 500 kV overhead lines and 500 kV underground cables, and also provide supplementary information of a terminal station (Appendix A). This report has been prepared to provide an overall perspective based on literature reviews on the impacts of overhead line and underground cables and to assist Moorabool Shire Council in their understanding of these two technologies. All information in this report is based on a literature review with the exception of the EMF modelling which has been conducted using typical designs, assumptions and indicative dimensions.

The scope for this report covers topics in relation to the following:

- effective circuit length,
- design and performance,
- reliability,
- easement requirements,
- vegetation management,
- ground disturbance,
- induced voltages,
- audible sound,
- operations and maintenance,
- electromagnetic field,

- general health and safety,
- approvals and standards and
- Project timeline.

Figure 1: Proposed area of interest for the Project

2 Overview of Overhead Transmission Lines and Underground Transmission Cables

2.1 Overhead line

Ultra High Voltage (UHV) AC power transmission can be defined as transmission network operating at voltage levels above 500 kV. At present, there are a number of UHV overhead transmission lines operating around the world and it is common to transmit bulk power over long distances from remote generation sources to the major load centres. The countries that are currently operating transmission network at UHV levels are Ukraine and Poland at 750 kV, South Korea at 765 kV, Brazil at 800 kV, China, Japan and Russia at 1,000 kV. India is currently conducting experiments and planning for transmission network at 1,200 kV.

Extra High Voltage (EHV) AC power transmission can be defined as transmission network operating at voltage levels between 365 kV and 500 kV. EHV transmission lines are common in most countries and have been operating around the world since the 1960s. Regions that are operating transmission network at EHV of 500 kV levels are in North America, South America, Eastern Europe, South East Asia, East Asia and Asia Pacific.

The primary benefits of UHV and EHV transmission are the ability to transmit electricity over long distances with minimal power losses and its cost-effectiveness. The effective length of a transmission line can be as long as 2,500 km transmitting bulk power from one substation to another.

In Australia, the highest power transmission voltage level is in the EHV category, at 500 kV. The development of 500 kV transmission lines began in the state of Victoria. The first 500 kV transmission line was built in 1970 connecting Hazelwood to Melbourne, owned and operated by the State Electricity Commission of Victoria (now AusNet Services). The Victorian 500 kV network traverses across the state, from the east in Latrobe Valley where a cluster of brown coal fired stations are located to central Greater Melbourne then to the west in Portland.

The development of 500 kV lines in New South Wales (NSW) began in the 1980s and the first 500 kV transmission line built was from Eraring Power Station to Kemps Creek, owned and operated by the Electricity Commission of New South Wales (now TransGrid). The NSW 500 kV network is concentrated in the Central and Central-Western part of the state connecting major black coal fired power stations in the Hunter Valley for transmitting bulk power to the major load centres.

Figure 2 and Figure 3 show schematics of New South Wales and Victorian 500 kV transmission network, respectively.

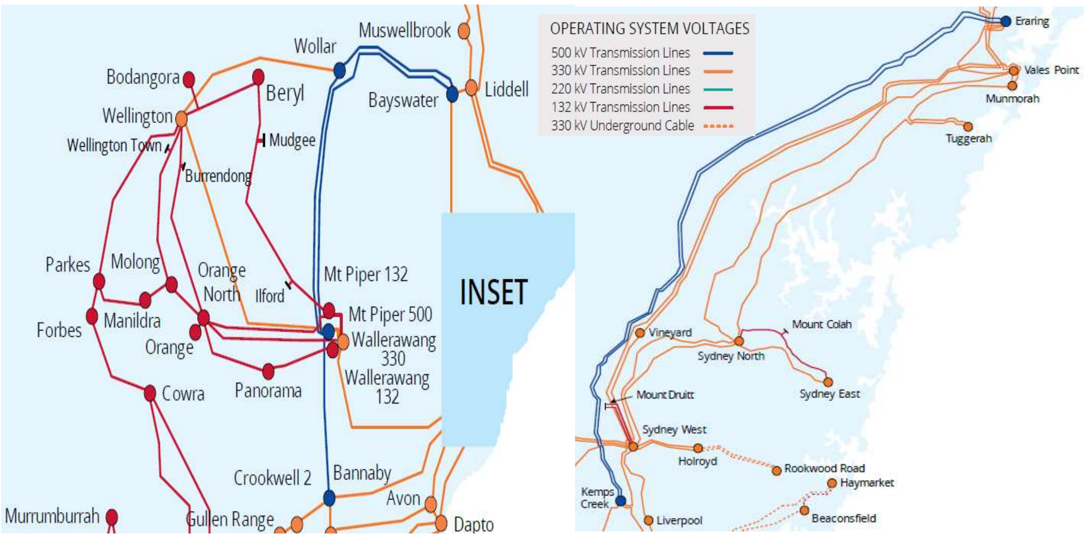

Figure 2: Schematic of New South Wales network showing 500 kV lines[2]

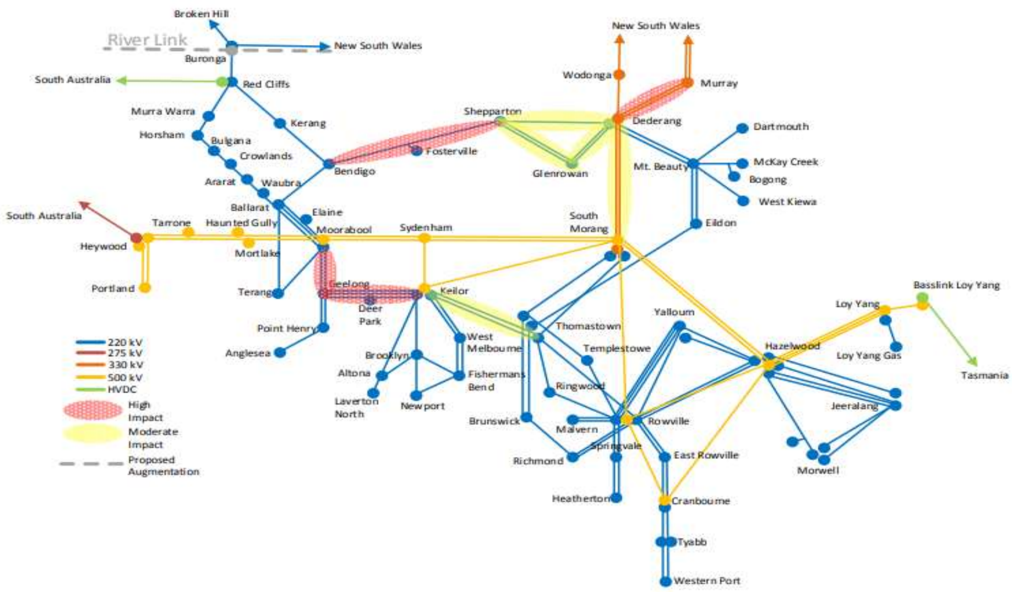

Figure 3: Schematic of Victorian network showing 500 kV lines[3]

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2 https://www.transgrid.com.au/what-we-do/Business-Planning/transmission-annual planning/Documents/2019%20Transmission%20Annual%20Planning%20Report.pdf

3 https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/vapr/2018/2018-victorian-annual-planning-report.pdf?la=en&hash=5AB98F59F8C0AF33F95F8E19D0FADBA5

2.2 Underground cable

There have been significant advances in the development of underground cables at higher voltages especially in the Extra High Voltage (EHV) range. EHV AC power transmission can be defined as transmission network operating at voltage levels between 365 kV and 500 kV. At present, the highest known operating voltage for underground cable in the world is at 500 kV. In Australia, the highest operating voltage for underground cable is at 330 kV.

Below are examples of application of underground cables around the world including Australia.

2.2.1 Japan, Tokyo (Shinkeiyo to Toyosu)

This project is the world's first long distance 40 km of 2 x 500 kV underground cable connecting Shinkeiyo to Toyosu and was completed in year 2000. The double circuit underground cable joined with the overhead transmission lines at Shinkeiyo substation and delivers power the Toyosu substation in the heart of Tokyo city. The cable route and laying method utilised a custom-built cable tunnel, duct installations under bridges and elevated expressways.

Key aspects of the project are shown below [1]:

- Voltage: 500 kV
- Transfer Capacity: 1,800 MW
- Length: 40 km
- Manufacturer: Fujikura (Japan)
- Year of Completion: 2000

2.2.2 China, Shanghai City (Shibo to Sanlin)

This project is the first Shanghai intra city EHV XLPE (cross-linked polyethylene insulated) cable that consisted of 17 km of 500 kV underground cable connecting Shibo to Sanlin and was completed in year 2010. This project was established to meet Shanghai City's constant demand growth for power, with the estimated energy consumption to reach 125 TWh by 2010. The cable route and laying method utilised underground tunnel to carry the 500 kV underground cables. The manufacturer used innovative cable technology for this project, with a metallic screen in smooth laminated aluminum. This is a much lighter solution than the conventional lead or corrugated aluminum sheath for easier cable installation.

Key aspects of the project are shown below[4]:

- Voltage: 500 kV
- Transfer Capacity: 600 MW
- Length: 17 km
- Manufacturer: Nexan (Australia) and Viscas (Japan)
- Year of Completion: 2010

4 https://www.nexans.com/business/High-Voltage---Projects/Power-Networks-Land-High-Voltage/Longest-500-kV-underground-link-between-two-Shanghai-substations.html

2.2.3 USA, Southern California Tehachapi Renewable Transmission Project

This project is the first EHV XLPE (cross-linked polyethylene insulated) cable in North America that consisted of 6 km of 500 kV underground cable joined with 268 km of 500 kV overhead transmission line, and was completed in year 2016. The project was established to deliver renewable energy generation from Kern County heading south towards Los Angeles County and to the east towards the city of Ontario in San Bernadino County. The cable route and laying method utilised duct and manhole systems passing through under the city of Chino Hills.

Key aspects of the project are shown below[5]:

- Voltage: 500 kV
- Transfer Capacity: 1,700 MW
- Length: 6 km
- Manufacturer: Taihan Electric Wires (South Korea)
- Year of Completion: 2016

2.2.4 Denmark, Copenhagen Metropolitan Power Project

This project is the world's first significant XLPE cable that consisted of 36 km of 400 kV underground cables. The project comprised of North and South Link with circuit lengths of 14 km and 22 km, respectively. A total of 123 pre-fabricated splices were established and utilising a direct buried cable route laying method.

Key aspects of the project are shown below [1]:

- Voltage: 400 kV
- Transfer Capacity: 1,000 MW
- Length: 36 km
- Manufacturer: NKT (Denmark)
- Year of Completion: 1998 (North Link) and 1999 (South Link)

2.2.5 United Kingdom (Elstree to St. Johns Wood)

This project is one of the longest and highest capacities of EHV cables in Europe that consisted of 20 km of 2 x 400 kV underground cable connecting Elstree (in northwest London) to St. Johns Wood (in central London). The cable route and laying method are enclosed in a 3 m diameter tunnel with five intermediate tunnel access shafts and head house buildings along the route. The house buildings are required for ventilation and installation of control equipment for the operation of the cables.
Key aspects of the project are shown below [1]:

- Voltage: 400 kV
- Transfer Capacity: 1,200 MW
- Length: 20 km
- Manufacturer: SudKabel (Germany)
- Year of Completion: 2004

5 https://www.tdworld.com/intelligent-undergrounding/article/20969593/engineering-a-500kv-underground-system

2.2.6 Australia, New South Wales (Sydney South to Haymarket)

This project consisted of 28 km of 330 kV underground cable in Sydney City connecting Sydney South to Haymarket. The cable route with a length of 24.5 km was being laid in trenches, mainly beneath public roads, and remaining 3.5 km of the route is via a deep tunnel section under the southern part of the Sydney Central Business District.

Key aspects of the project are shown below [2]:

- Voltage: 330 kV
- Transfer Capacity: 750 MW
- Length: 28 km
- Manufacturer: J-Power System (Subsidiary of Sumitomo, Japan)
- Year of Completion: 2003

2.2.7 Australia, Victoria (Cranbourne to Victorian Desalination Plant)

This project consisted of 88 km of 220 kV underground cable in South East Victoria, connecting Cranbourne to the Victorian Desalination Plant at Wonthaggi. The cable route and laying method are in trenches and cables enclosed in conduits.

Key aspects of the project are shown below[6]:

- Voltage: 220 kV
- Transfer Capacity: 165 MW
- Length: 88 km
- Manufacturer: Nexan (Australia)
- Year of Completion: 2012

6 http://www.jicable.org/TOUT_JICABLE_FIRST_PAGE/2015/2015-E6-2_page1.pdf

3 Design and Performance

3.1 Overhead line design and performance

The Project is proposed to construct 75 km of 500 kV double circuit overhead line with a rating of 3,000 MVA per circuit, totalling 6,000 MVA. In order to meet the capacity requirements, four conductors (bundles) per phase per circuit are required. Reactive compensation is required at both ends of lines at the terminal stations to achieve the desired performance.

The overhead line comprises of above ground infrastructure with conductors strung on steel lattice towers or poles and terminal stations at both ends of the line, which generally considered as high visual impact from ground level. The net visual impact of multiple lines may be reduced by sharing a common route.

Figure 4 shows typical designs of 500 kV double circuit overhead line.

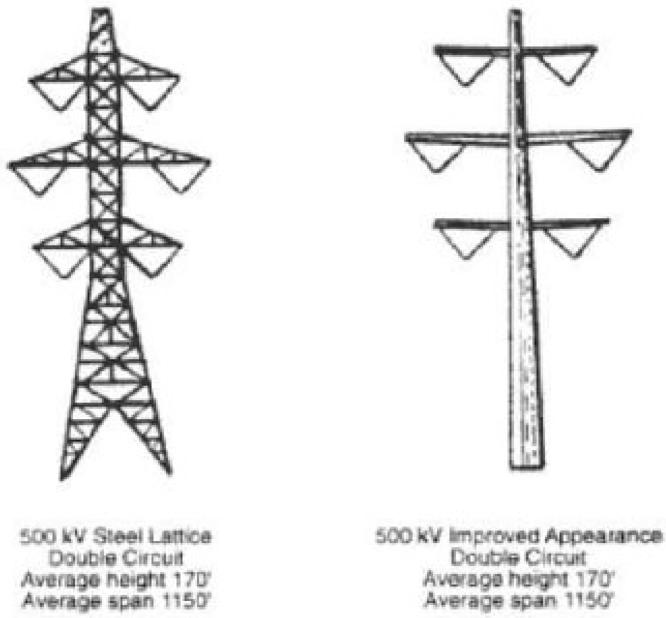

Figure 4: 500 kV double circuit steel lattice tower (left) and pole (right) designs[7]

Figure 5 and Figure 6 show an operational 500 kV double circuit overhead line and Figure 7 shows a four bundled conductor for the overhead lines.

7 https://energypedia.info/wiki/File:Towers.jpg

Figure 5: 500 kV double circuit overhead lines and towers (series on the right)[8]

Figure 6: 500 kV double circuit overhead lines and towers [3]

8 https://themooraboolnews.com.au/?p=3195

Figure 7: Four bundled conductors

3.2 Underground cable design and performance

500 kV underground cable system is technically complex and usually involves custom design for each application. The design of cable route and laying methods are subject to environmental constraints and overall project requirements. Typically, for urban areas, a tunnel may be required whereas in rural areas, direct buried in trenches are common.

For long length of cables, reactive compensation such as shunt reactors are required to be installed at effective locations to reduce the high capacitive charging of the cables. Detailed modelling is required to identify the amount of reactive compensation but shunt reactors would be installed within above ground compounds similar to small substations.

In order to meet the Project capacity requirements, two sets of cables per phase per circuit can deliver approximately 2,850 MVA, therefore, four sets of cables totalling 5,700 MVA are required. Figure 8 shows an illustration of four sets of underground cables laid in trenches. Figure 9 shows cables laid in an underground tunnel.

The underground cable system comprises of below ground infrastructure with insulated cables, trenches/tunnels, joint pits and above ground infrastructure of transition stations at both ends of the cable, which generally considered as lower visual impact from ground level.

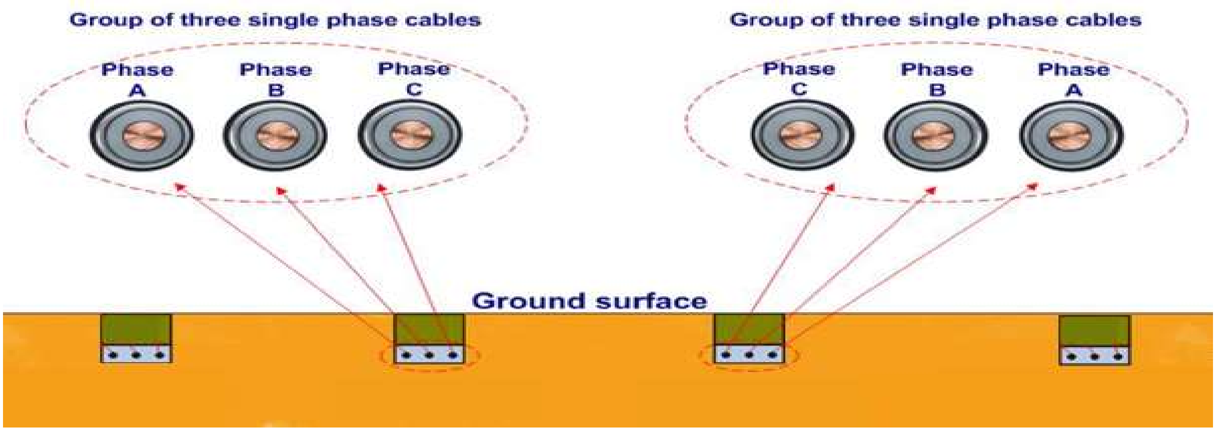

Figure 8: Four sets of 500 kV underground cables in trenches

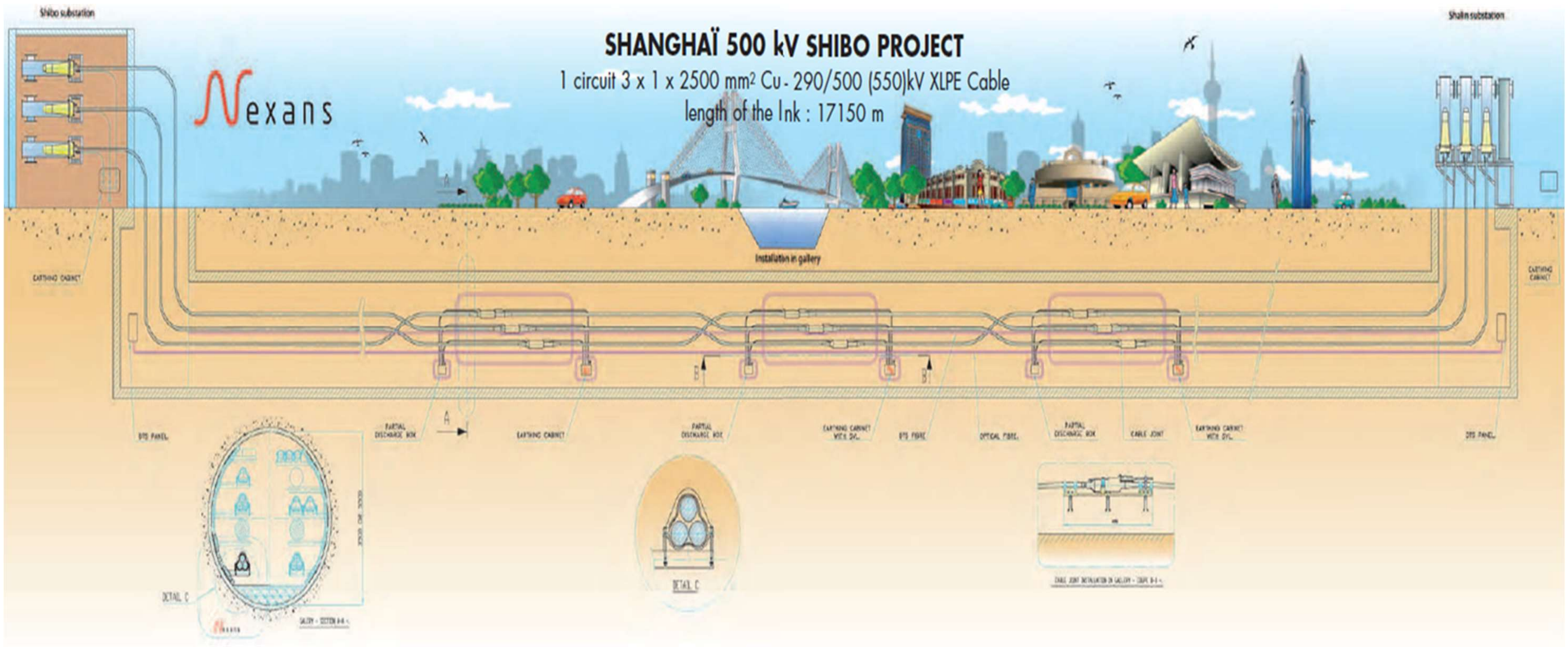

Figure 9: 500 kV underground cable in an underground tunnel [4]

Figure 10 shows a transition station where the underground cable is terminated. Figure 11 shows a cross-section of a 2,500 mm^2 500 kV underground cable.

Figure 10: 400 kV underground cable outdoor termination at a transition station

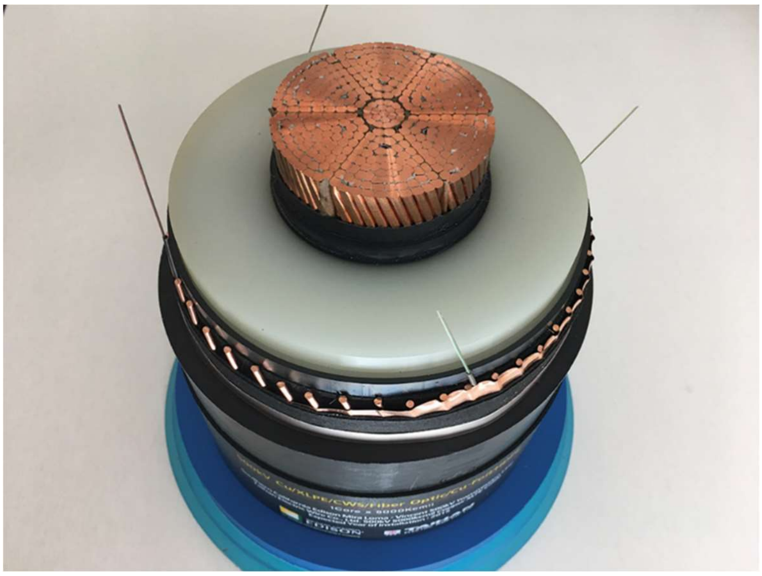

Figure 11: 500 kV 2,500 mm^2 XLPE cable with laminated copper sheath and embedded optical fibre[9]

[9] https://www.tdworld.com/intelligent-undergrounding/article/20969593/engineering-a-500kv-underground-system

4 Technical Details and Challenges

4.1 Overhead line

4.1.1 Reliability

The Victorian electricity system code [5] outlines that the benchmarked performance standard of forced outage rate due to primary or secondary failure and lightning/storms for overhead transmission line is less than 1.0 and 0.5 incident per annum per 100 circuit km, respectively. In the case of this Project, the forced outage rate for the 75 km of double circuit overhead line is calculated as 2.25 incident per annum. This benchmarked performance standard represents a probability of line outage but does not necessarily means the structural failure of overhead line infrastructure.

4.1.2 Transmission tower fallen incidents

There were two recent incidents of structural damage to overhead transmission towers in Victoria and South Australia.

In Victoria, there was an extreme localised storm event on Friday, 31 January 2020 that caused six 500 kV double circuit overhead line towers to fall over and one severely damaged near the town of Cressy in South West Victoria. Winds in excess of 160 km/hr created a strong downdraft known as a downburst that is believed to have flattened six steel transmission towers completely.

The damage to the towers caused trips to both lines and impacted supply to the Alcoa Portland aluminium smelter, and resulted in a disconnection of the Heywood interconnector between Victoria and South Australia, separating South Australia from the National Electricity Market.

Emergency restoration structures were temporarily erected and the first line was re-energised by 17 February 2020 and the second line was back in service by the 3 March 2020. The replacement of the damaged towers is still in progress at the time of writing this report.

Figure 12, Figure 13 and Figure 14 show the fallen 500 kV towers.

Figure 12: Fallen 500 kV double circuit tower (Moorabool to Haunted Gully and Mortlake)[10]

Figure 13: Fallen 500 kV double circuit tower (Moorabool to Haunted Gully and Mortlake) [11]

10 https://www.energynetworks.com.au/news/energy-insider/2020-energy-insider/towers-down-yet-sa-powers-on/

11 https://www.energynetworks.com.au/news/energy-insider/2020-energy-insider/towers-down-yet-sa-powers-on/

Figure 14: Fallen 500 kV double circuit tower (Moorabool to Haunted Gully and Mortlake)[12]

In South Australia, on Wednesday 28 September 2016, tornadoes with wind speeds in the range of 190–260 km/hr occurred in areas of South Australia. Two tornadoes almost simultaneously damaged a 275 kV single circuit transmission line and a 275 kV double circuit transmission line, approximately 170 km apart.

The damage to these three transmission lines caused them to trip, and a sequence of faults in quick succession resulted in clusters of generation (Wind Farms) to trip and Heywood interconnector to disconnect. As the supply-demand became imbalanced, frequency decline resulted in a state wide blackout at 4:18 pm within 2 minutes from the start of the event.

The first customers had power restored by 7:00 pm on 28 September 2016 and about 40% of the load had been restored by 8.30 pm, and 80 to 90 % had been further restored by midnight. It was a swift response from ElectraNet and AEMO to re-electrify the entire state.

Figure 15, Figure 16 and Figure 17 show the fallen 275 kV towers.

[12] https://www.energynetworks.com.au/news/energy-insider/2020-energy-insider/towers-down-yet-sa-powers-on/

Figure 15: Fallen 275 kV tower in South Australia[13]

Figure 16: Fallen 275 kV tower in South Australia[14]

13 https://www.abc.net.au/news/2017-03-28/wind-farm-settings-to-blame-for-sa-blackout-aemo-says/8389920

14 https://reneweconomy.com.au/blackout-reality-check-coal-and-extra-link-may-not-have-changed-anything-24659/

Figure 17: Fallen 275 kV tower in South Australia[15]

4.1.3 Easement requirements

Easements are in place to protect the safety of people living, working or playing near electricity infrastructure by controlling the activities under or near the network. In addition, easements ensure maintenance and inspection access, restricting vegetation growth and preventing close interaction with electricity infrastructure. Network utility personnel have the right to safely access, operate, maintain and upgrade the network as required.

A list of permitted and prohibited uses of transmission line easements can be obtained from the AusNet Services Living with Transmission Line Easements [6].

Examples of permitted uses of transmission line easements within its clearance requirement are agriculture, grazing, market gardens, nurseries, water storage dams, trees, shrubs, sewerage, parking lots, tennis courts, ground level sports such as football, cricket, golf and basketball.

Examples of prohibited uses of transmission line easements are buildings, structures, houses, eaves, awnings, canopies, carports, garden sheds, swimming pools, storage, parking of large trucks and caravans.

15 https://reneweconomy.com.au/aemo-report-into-sa-blackout-raises-questions-answers-none-55986/

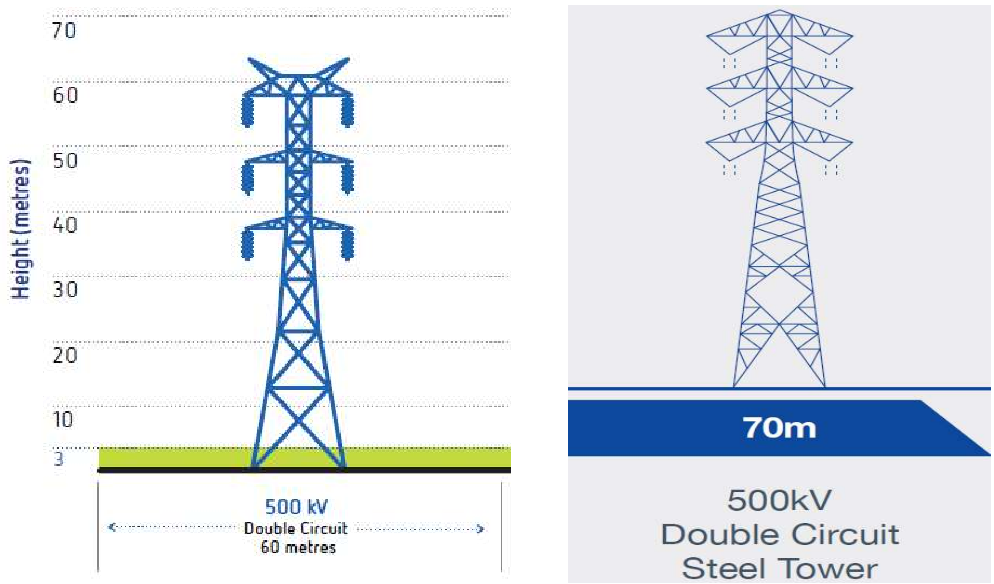

Figure 18: Typical easement widths specified by AusNet Services [6] (left) and TransGrid [3] (right)

500 kV double circuit overhead transmission line has a typical easement width between 60 m and 70 m.

4.1.4 Vegetation management

The network utility must ensure that vegetation maintenance is in place to prevent bush fire hazards and to protect the overhead line infrastructure from being damaged. The vegetation management activities and methods are in consultation with local authorities and interest groups, such as Landcare Australia, the Department of Environment, Land, Water and Planning (DELWP) and local Councils.

According to AusNet Services [6], the maintenance of the area covered by the easement is the responsibility of the landowner or tenant (depending on terms of use). Easements must be maintained subject to the safety restrictions and AusNet Services reserves the right to carry out additional land management functions within the easement where unsuitable vegetation, ground surface level conditions, or other activities that compromise the safe and reliable operation of the transmission lines. The maximum mature height of vegetation on easements is 3 m.

4.1.5 Tower footing (effects on ground disturbance)

A tower footing is the concrete which encases the pole butt or the tower leg. It can be anywhere from 3 to 10 m deep. Due to the large tensions on the structures any excavation within 20 to 30 m of a structure may weaken the structure foundation and cause a collapse. During construction, ground disturbance is subject to the erection of the transmission towers at every 400m to 500 m span along the transmission line route.

Tower footing design should comply with the requirements specified in AS/NZS 7000 (Overhead line design – detailed procedures), AS/NZS 2159 (Piling – design and installation) and relevant utility design guidelines.

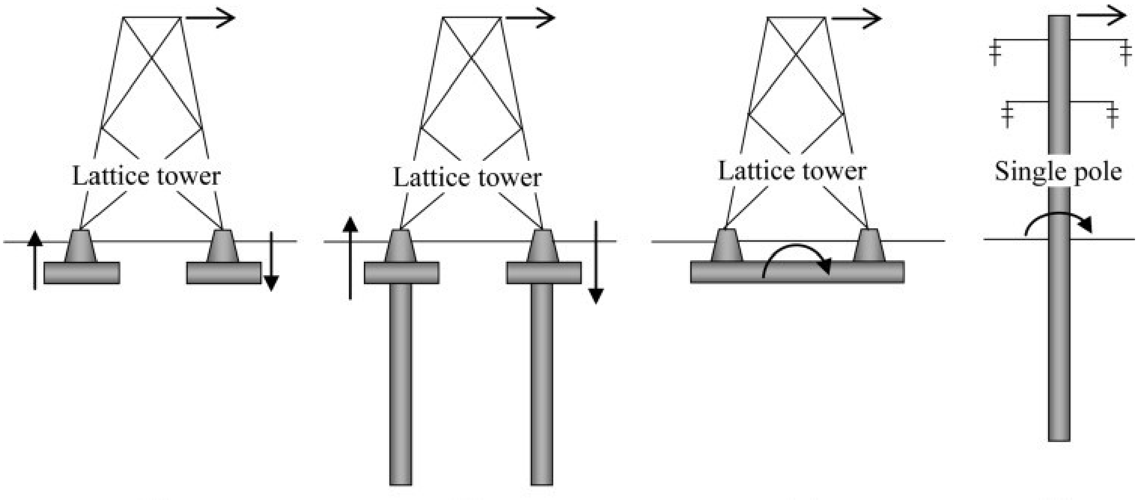

Figure 19: Examples of tower footing designs

4.1.6 Induced voltages

Induced voltages resulting from overhead lines are generally only of concern where long sections of metallic objects run parallel and in close proximity to the overhead lines. Such metallic objects would include railway tracks, pipelines, cables and fencing. Induced voltages result from the currents flowing in the overhead line. The effects fall off rapidly as the distance between the overhead line and objects increases.

There may be a rise in earth potential, along the route of the overhead line during normal operation and fault condition. A rise in earth potential may result in voltages being impressed on nearby metallic objects leading to issues with touch potential.

Voltages on the metallic objects can be controlled by appropriate earthing methods, however this will result in currents flowing in the metallic object which may be undesirable due to heating effects. There will be negligible voltage or current induced where the cables and the metallic objects cross at, or close to, a right angle.

In order to assess the impact of induced voltages on nearby metallic objects, a study that includes modelling is required.

4.1.7 Audible noise

Energy dissipation known as corona loss is common for overhead lines especially at 500 kV. This discharge of energy occurs when the electric field strength on the surface of the conductor is greater than the breakdown of air surrounding the conductor. A visible glow of light near the conductor can be seen and the discharge causes audible noise to emit. The audible noise sounds like crackling and hissing to human ears.

The noise problems which become a concern to the power industry are at higher transmission network voltages. As such, these transmission lines are designed, constructed and maintained so that during dry conditions they should operate below the corona-inception voltage, meaning that the line will generate a minimum of corona-related noise. In poor weather conditions, however, corona discharges can be produced by water droplets, fog and snow.

The audible noise is expressed as sound pressure levels in decibels (dB). In terms of sound pressure levels, audible sound ranges from 0 dB (the threshold of hearing) to approximately 120 dB (the threshold of pain).

In order to put the noise level into perspective, Table 3 shows typical sound levels from various sources measured by Safe Work Australia.

Table 3: Typical Sound Levels Associated with Various Sources[16]

Typical sound level in dB	Sound source
140	Jet engine at 30 m
130	Rivet hammer (pain can be felt at this threshold)
120	Rock drill
110	Chainsaw
100	Sheet metal workshop
90	Lawn mower
85	Front-end loader
80	Kerbside heavy traffic or lathe
70	Loud conversation
60	Normal conversation
40	Quiet radio music
30	Whispering
0	Hearing threshold

According to Safe Work Australia, over an eight-hour shift a worker can’t be exposed to more than 85 dB. Whether this is exceeded depends on the level of noise involved and how long a worker is exposed to it. Ideally, noise levels should be kept below 50 dB if work requires high concentration or effortless conversation.

EirGrid conducted audible noise measurement for 230 kV and 400 kV line, recorded audible noise of low 40 dBs and mid 40 dBs, respectively. Korean Electric Power Corporation (KEPCO) conducted a test at 15 m from the outermost phase of a 765 kV line in fair and rain weather, recorded audible noise of 42.1 dB and 48.8 dB, respectively [7].

It is estimated that an audible noise of up to 45 dB can be heard at 15 m away from the 500 kV overhead lines.

16 https://www.safeworkaustralia.gov.au/noise

4.2 Underground cable

4.2.1 Reliability

There is limited reliability data in the public domain however International Council on Large Electric Systems (CIGRE) has published fault statistics for underground power cables. These statistics suggest that, for a cable system over the full 75 km, it can be expected that there will be, on average, a fault every 9.5 months. Therefore, the forced outage rate is calculated as 0.79 incident per annum. This is mainly due to the large number of joints required. If longer lengths of cable can be installed between joint bays, then the fault rate will improve. The CIGRE document [8] was published in 2009 and it can be expected that the cable system technology has improved in the intervening years therefore a higher reliability may be expected.

4.2.2 Damage to cables

Cable damage after installation is generally due to third party excavation associated with civil construction works, utility installation works or agricultural works. To reduce the risk of damage cables are usually installed at a suitable depth and protected with cable protection tiles. The cable protection tiles sit above the cables and if struck by a third party should encourage them not to dig any further. Route markers are also often, where practicable, used above ground at, for example, field boundaries or a change in route direction. Vibration or subsidence due to construction works, piling works or heavy construction traffic can also have a negative impact on cable systems.

In some areas cable systems can be targeted by vandalism or theft. For transmission cable systems the cable itself is usually too difficult to access but link housings, especially above ground ones, can be a prime target. Above ground link housing may also be susceptible to accidental damage through impact from passing vehicles.

Damage can be caused by flora or fauna. Tree roots can cause problems for underground power cables by removing moisture from the soil and affecting the thermal resistivity. In addition, if tree roots grow around underground cables they may dislodge the cable if the tree topples for any reason or, in extreme case, roots can directly penetrate or constrict the cable. Burrowing animals can destabilise soil around cables allowing unrestrained movement of the cable. Rodents and insects have been known to eat into the surface materials of underground cables, exposing the metallic sheath or screen. Where a thin metallic foil is used as the primary moisture barrier the creatures may penetrate the foil compromising the cable integrity. Over time an exposed sheath may deteriorate again compromising the integrity of the cable. The materials used for the outer layers of the cable can be formulated with additives to discourage the effects of fauna.

Heat introduced into the local environment from district heating schemes, water pipes, drainage systems or other electrical equipment may lead to the cable overheating. Third party activity may also result in changes to the thermal properties of the local environment. Overheating can lead to reduction in the life expectancy of the cable system or, in the extreme, immediate failure.

4.2.3 Easement requirements

Generally speaking, a 500 kV underground cable will be installed at a depth of between 1 m and 2 m to the top of the cable or duct. The width will depend on the number of circuits and the number of cables required per phase.

For this Project, two circuits will comprise of two conductors per phase per circuit, totalling four sets of cables. The indicative laying method for optimising current ratings purposes the cables may be installed flat spaced with a spacing between each phase of around 300 mm to 500 mm; requiring a trench width of up to 2 m depending on backfill arrangements. Alternatively, if the ratings permit, the cables can be installed in trefoil groups with a reduced trench width requirement. Wider separations may be necessary where the installation depth is increased to cross an obstacle, for example a drainage ditch or hedgerow. Each group of three cables will be separated by at least 5 m between trenches to minimise the mutual thermal influence from cable losses. These dimensions are indicative for a typical cable laying method and do not represent the specifics of this Project.

The use of horizontal directional drilling is often used where cable circuits cross rivers, railways or major roads. The separation between cables, or cable groups, will increase significantly due to the tolerance limits on the drilled bores and the effects on the current ratings due to the depth to needed to pass under the obstacle. There will be large drill launch and reception sites at each end of the bore. The width of these sites will depend on the number of bores and their separation.

Figure 20 shows horizontal direct drilling with ducts protruding ready for cable installation; the main cable swathe clearing can be seen in distance.

Figure 20: Horizontal Direct Drilling

It is normal practice to install a temporary haul road for construction of underground cables over long routes. This haul road is often accommodated in between the two circuits by increasing the circuit separation; although a haul road to the side may be preferred as the overall width taken by the installed cables is less. To avoid removing excavated materials from site, additional areas either side of the cables routes are utilised for storage of top soil and sub soil.

During construction, a corridor swathe of up to 100 m is not uncommon. An indicative sketch showing the corridor arrangement and a haul road, for a double circuit with two conductors per phase, during construction an approximate corridor swathe of 72 m is shown below:

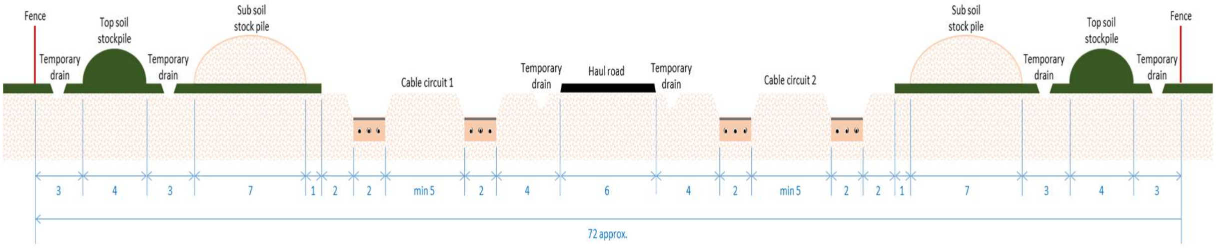

Figure 21: Corridor swathe during construction

When fully commissioned, the minimum estimated easement requirement taking into consideration operations, maintenance and access to assets, with and without a haul road are approximately 42 m and 48 m, respectively.

4.2.4 Ground disturbance

During construction there will be significant ground disturbance as soil will be dug out to build trenches or tunnels. Ground nearby used for materials storage, temporary haul roads and temporary accommodation will also be disturbed.

Ground surface disturbance from installed cables is not usually expected due to the depth of installation and the type of materials used. In rare cases, where cables with large conductors are installed at relatively shallow depths, the thermal expansion during loading can result in bulging and cracking of the soil at the surface due to cable movement. In some environments a degree of settling may occur following installation works.

Heat generated from cable losses can drive moisture out of the soil. Loss of moisture can affect the soil stability of slopes either directly or through its effect on local flora.

Figure 22: Typical ground disturbance during construction

More construction photos on underground cables are shown in Appendix B.

4.2.5 Cable alignment flexibility

The flexibility of the underground cable alignment is driven by the physical characteristics of the cable. The manufacturer will specify a minimum bend radius, maximum pulling tension and maximum side wall pressure for underground power cables. The minimum bend radius is normally around twenty times the outside diameter of the cable, however larger bend radii may be required along the route to avoid exceeding the maximum pulling tension and maximum side wall pressure during cable pulling.

4.2.6 Induced voltages

Induced voltages resulting from underground cables are generally only of concern where long sections of metallic objects run parallel and in close proximity to the cables. Such metallic objects would include railway tracks, pipelines, cables and fencing. Induced voltages result from the currents flowing in the underground cables. The effects fall off rapidly as the distance between the cables and objects increases. Voltages on the metallic objects can be controlled by appropriate earthing system, however this will result in currents flowing in the metallic object which may be undesirable due to heating effects. There will be negligible voltage or current induced where the cables and the metallic objects cross at, or close to, a right angle. Induced voltages will be lower where the underground cables are installed in trefoil formation.

Induced voltages will also be present on the cable system metallic sheath or screen and the associated earth bonding system. Metallic components subject to induced voltages are shielded from inadvertent contact.

There may be a rise in earth potential, along the route of a cable system, in the vicinity of joint bays and associated link housings. This may be due to transfer of earth potential from substations at the end of the cable route or may result from current flows in the cable sheath or screen under certain fault conditions. A rise in earth potential may result in voltages being impressed on nearby metallic objects leading to issues with touch potential.

In order to assess the impact of induced voltages on nearby metallic objects, a study that includes modelling is required.

5 Operation and Maintenance (O&M)

5.1 Overhead line

Overhead transmission line system is designed to operate continuously (24 hr, 365 days) within thermal limits unless there is a threat such as bush-fire approaching the overhead lines. General practice is that, even during big storms, the overhead line will still be operating but the power flows may be reduced in anticipation of possible transmission line trips.

Overhead lines typically have a maximum design temperature of up to 93^{0}C. The continuous current rating of the cable system is determined by the balance between the heat generated and the heat dissipated resulting in the permitted maximum temperature. It is possible to carry larger currents for short periods depending on the installation design and how the overhead line has operated. Wind monitoring devices can be installed to monitor wind speeds, which cools down the conductor temperatures and are applied in real-time rating system.

Table 4 below shows transmission line inspection program developed by AusNet Services.

Table 4: Transmission line inspection program [9]

Inspection Type	Description	Frequency
Line and easement inspection	To identify line and easement defects. Focus on the clearance space around the transmission line, transmission line component faults and easement issues.	Once a year
Vegetation inspection	Conduct using LiDAR (a mix of aerial and ground) Focus on vegetation around the transmission line.	Once a year
Condition assessment inspection	Detailed inspection and condition assessment to identify line, conductor spacing and easement defects and to assess the serviceability of all elements of the line and easements.	Three, six or nine times a year
Non-invasive inspection	Conduct using specialised equipment such as thermovision camera, corona camera, radio frequency interference and etc.	Three times a year
Smart Aerial Image Processing (SAIP)	Image capture using helicopter-mounted high resolution video to capture a continuous stream of digital images which are processed by specialised software to identify defects.	Six times a year

5.2 Underground cable

Underground cable system is designed to operate continuously (24 hr, 365 days) within thermal limits. Cables with cross-linked polyethylene insulation typically have a maximum design temperature of 90°C. The temperature will increase when the cable is transmitting power due to losses. The generated heat dissipates into the surrounding environment. The continuous current rating of the cable system is determined by the balance between the heat generated and the heat dissipated resulting in the permitted maximum temperature. It is possible to carry larger currents for short periods depending on the installation design and how the cable has been operated. The use of a distributed temperature sensor, an optical fibre running the length of the cable either internally or in close proximity, can help determine the operating capacity, especially when combined with a real-time rating system.

Modern extruded cable systems are designed to minimise maintenance requirements. The key maintenance activity required is the periodic testing of the metallic sheath or screen; this requires the cable circuit to be out of service whilst voltages are applied to the metallic sheath or screen via earth bonding system link housings along the cable route. It is likely that the cable terminations are filled with an insulating fluid which would need to be monitored for leaks and repaired where necessary. Depending on local environmental conditions it may be necessary to periodically clean the insulators of the cable terminations; this should only be done with the cable circuit out of service. Regular patrols along the route are recommended so that any third party activity that may affect the cable can be caught before there is a problem. Flora, in particular trees, should be controlled in the vicinity of the cables.

Table 5 below shows underground cable maintenance program developed by Powerlink.

Table 5: Underground Cable Maintenance Program [10]

<table>
<tr><th>Maintenance Type</th><th></th><th>Activity</th><th>Frequency</th></tr>
<tr><td rowspan="7">Preventative Maintenance</td><td rowspan="5">Routine Preventative Maintenance</td><td>Underground cable patrols (ground patrols) – not applicable to cables located within substations</td><td>Monthly</td></tr>
<tr><td>Underground cable Level 1 Maintenance</td><td>6 months</td></tr>
<tr><td>Underground cable Level 2 Maintenance
Cables with extruded insulation located in substations.
Fluid filled cables located in substations.
Fluid filled cables not located in substations.
Cables with extruded insulation not located in substations</td><td>4 times yearly</td></tr>
<tr><td>Dial before you dig</td><td>Continuously as per inquiries</td></tr>
<tr><td>Transition site maintenance</td><td>Annually</td></tr>
<tr><td rowspan="2">Condition Based Maintenance</td><td>Cable termination replacement</td><td>Based on condition and type of cable termination</td></tr>
<tr><td>Distributed temperature measurement</td><td>Based on change of easement conditions</td></tr>
</table>

Maintenance Type		Activity	Frequency
		Cable joint replacement	Triggered by joint damage, low reading of earth sheath resistance or by Partial Discharge (PD) indication
		Partial discharge measurement on cable, cable joints and/or cable terminations.	Based on condition

6 Electro-Magnetic Field (EMF)

In AC theory, the current and voltage are electrical quantities in sinusoidal waveforms running at 50 Hz frequency. When power is transmitted, electric and magnetic fields are generated, and these two components when considered together are known as Electro-Magnetic Field (EMF).

6.1 Electric fields

Electric fields are invisible areas of energy, often referred as radiation that is associated with the use of electrical power. In theory, electric fields are created by differences in voltage, where the higher the voltage, the stronger will be the resultant field. An electric field will still exist even when there is no current flowing but as long as there are differences in voltage.

The electric field strength is measured in Volts per metre (V/m).

The electric field strength decreases with distance from source and emits in a straight-line path, which can be shielded (blocked) by most objects, including trees, buildings, soil and human skin. As such, no electric field modelling is expected to be conducted for this Project.

In the case of electric power transmission, there will be electric field emissions near overhead line but negligible electric field near underground cable.

6.2 Magnetic fields

Magnetic fields are invisible areas of energy, often referred as radiation that is associated with the use of electrical power. In theory, magnetic fields are created when electric current flows, where the greater the current, the stronger the magnetic field.

The magnetic field strength is measured in Ampere per meter (A/m) or in flux density with two type of units: micro-Tesla (µT) or milli-Gauss (mG). The unit of conversion for 1 µT is equivalent to 10 mG.

The magnetic field strength decreases with distance from source and can pass through most materials, and cannot be easily attenuated. Therefore, magnetic field exposure is often analysed to identify safety levels for humans. As such, magnetic field modelling has been conducted for this Project.

In the case of electric power transmission, there will be magnetic field emissions near overhead line and underground cable.

6.3 Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)

ARPANSA is the Australian regulatory body that is responsible for the licencing, compliance, inspection and enforcement in relation to the use of radiation under the Australian Radiation Protection and Nuclear Safety Act 1998 and the Australian Radiation Protection and Nuclear Safety Regulations 1999. One of ARPANSA's roles is to regulate ionising radiation such as X-rays, gamma rays, neutrons, and non-ionising radiation such as power lines, radio and microwave frequencies, lasers and ultra-violet.

ARPANSA takes into account international best practice in relation to radiation protection and nuclear safety. Although the Act does not define the term international best practice, ARPANSA has taken it into account by, among other things, considering the codes, standards, recommendations and guidelines that are produced by the following international organisations:

- UNSCEAR - United Nations Scientific Committee on the Effects of Atomic Radiation
- IAEA - International Atomic Energy Agency
- WHO - World Health Organisation
- ICRP - International Commission on Radiological Protection
- ICNIRP - International Commission on Non-Ionizing Radiation Protection
- NEAOECD - Nuclear Energy Agency of the Organisation for Economic Co-operation and Development

The publications produced by the above organisations reflect an international consensus on what constitutes a high level of safety for the purpose of protecting people and the environment from the harmful effects of radiation.

6.4 Human exposure reference levels

Since the 1970s, there has been significant amount of research conducted to address concerns regarding reference levels for safe exposure from non-ionising radiation from equipment such as overhead lines, transformers and cables.

The ICNIRP published guidelines in 1998 for limiting exposure to time-varying electric and magnetic fields in the frequency range of up to 300 GHz [11]. These guidelines, which are intended to prevent the acute effects of exposure to DC, low frequency, radio frequency and microwave fields on humans, are based on biological considerations from which dos-metric quantities are derived, with sufficient margins of safety introduced. These are known as "basic restrictions". These quantities relating to electromagnetic energy absorption and current flow in the tissues of the body are not directly measurable, but from these, electromagnetic quantities such as electric and magnetic field strengths and the equivalent plane wave power flux density (PFD) are derived, assuming whole body exposure in the far-field. These values are known as the "reference levels" in the ICNIRP guidelines. In December 2010, the ICNIRP published the latest guidelines for limiting exposure to time-varying electric and magnetic fields in the frequency range 1 Hz – 100 kHz [12].

Two sets of reference levels are defined, for general public and for workers. Those for the general public are more stringent than those for workers. For this Project, it is considered that the relevant limit is that for the general public, since anybody may walk underneath the overhead line or above the underground cable.

ARPANSA adopts these reference levels published by ICNIRP. The reference levels at 50 Hz are summarised in Table 6. It can be seen that the levels were relaxed in 2010.

Table 6: ICNIRP reference levels at 50 Hz

ICNIRP Guideline Year	Reference level, general public	Reference levels, occupational
1998	80 A/m, or 100 µT or 1,000 mG	400 A/m, or 500 µT or 5,000 mG
2010	160 A/m, or 200 µT or 2,000 mG	800 A/m, or 1,000 µT or 10,000 mG

6.5 Typical magnetic field levels

ARPANSA has conducted magnetic field measurement near electrical sources at different locations such as in houses, offices, substations and near power lines.

Table 7 shows typical values of magnetic field ranges measured near electrical appliances in houses and offices.

Table 7: Typical magnetic field levels

Appliance	Range of measurements (mG)
Electric stove	2 - 30
Refrigerator	2 - 5
Electric kettle	2 - 10
Toaster	2 - 10
Television	0.2 - 2
Personal computer	2 - 20
Electric blanket	5 - 30
Hair dryer	10 - 70
Pedestal fan	0.2 - 2

Table 8 shows typical values of magnetic field ranges measured at substations and near power lines

Table 8: Typical magnetic field levels measured near power lines and substations

Electrical Equipment	Location of measurement	Range of measurements (mG)
Distribution Overhead Line	directly underneath	2 - 30
	10 m away	0.5 - 10
Transmission Overhead Line	directly underneath	10 - 200
	at edge of easement	2 - 50
Substation	at substation fence	1 - 8

6.6 Magnetic field modelling

Magnetic field modelling of 500 kV AC power transmission was conducted by comparing the field levels of overhead lines with underground cables transmitting the same level of power.

6.6.1 Methodology

The methodology used in this study are as follows:

- The overhead lines and underground cables are modelled using a numerical tool, in 2D. 2D modelling is sufficient since, where a person stands above underground cable or below the overhead line, the length of line or cable can be considered of infinite length.

- Areas where the magnetic field must be calculated are defined in the numerical tool as well. These are planes that can be either vertical or horizontal. In this case, the simulation plane is vertical, from 0 to 5 m in height, and extending 40 m each way from the centre of the line, hence 80 m total width. This width corresponds to the easement of 60 m extended by 10 m on each side.
- The tool simulates the magnetic field, by using the Biot-Savart law, which is appropriate at low frequencies.
- The magnetic field results are compared with the limits defined in Table 6 (ICNIRP reference levels at 50 Hz) for general public.

6.6.2 Model

The modelling tool used in this study is MAGIC® (Magnetic Induction Calculation). This is a software for calculating the magnetic fields generated by electrical sources such as transformers, power line systems, HV/LV substations, joint holes, bus-bars, electrical systems.

The modelling assumptions are:

- The overhead lines are unarmoured / unscreened.
- The underground cables contain screen / metallic sheaths. However, the screen or sheath is made of aluminium / copper / lead, which will provide negligible attenuation to the 50 Hz magnetic field.
- In all cases, no attenuation from screening / armouring is taken into account for this study.
- It is considered that 500 kV transmission lines are ideally balanced (transposed).

Two models were created:

- One for the overhead power lines (Figure 23), the magnetic field decreasing with the distance from the cables, the simulations are performed where the field is likely to be highest, i.e. at the centre between two transmission towers, where the cables are closest to the ground.
- One for the underground cables (Figure 24) with two subsets are presented:
  - One with phase shifting, which is expected to minimise the magnetic field levels.
  - One (alternative model) without phase shifting, which is expected to lead to higher field levels.

  The spacing between the conductors (173 mm) is taken from [3], page 61, for a 3,000 mm² cable. There are 5 configurations for the sheath / screen, leading to various cable diameters. The further apart the conductors are, the higher the resulting magnetic field. Therefore, for a worst case scenario, since the spacing between conductors is equal to the conductor diameter, the largest cable was selected.

The drawings in the Figure 23 and Figure 24 below are not to scale, but all relevant dimensions are shown (in mm).

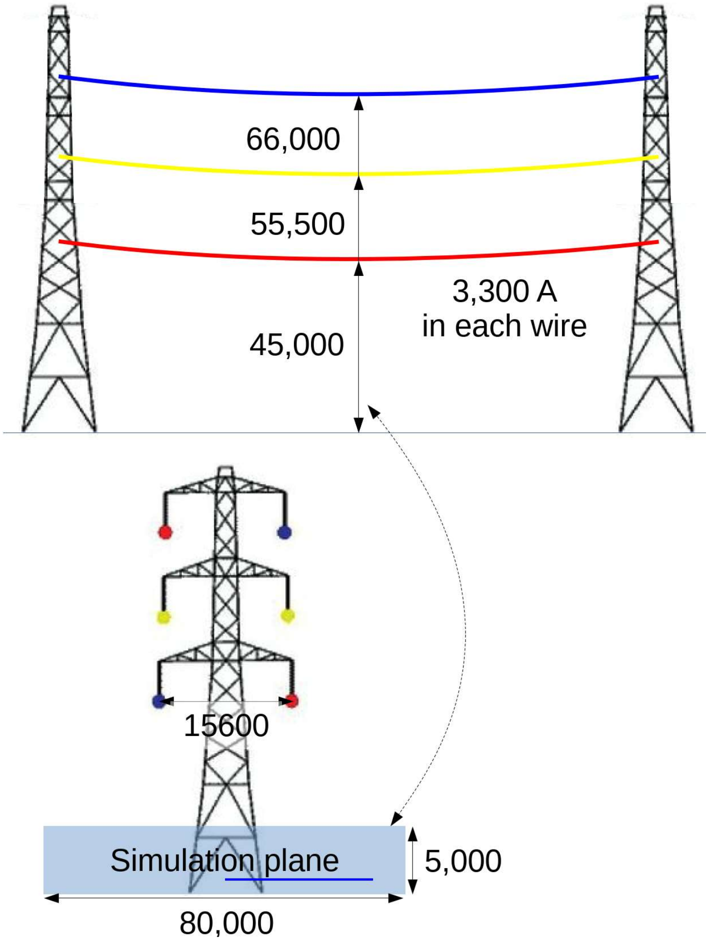

Figure 23: Overhead line model

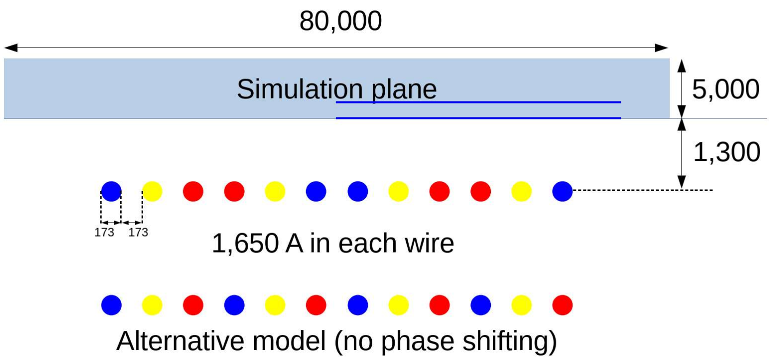

Figure 24: Underground cable model

6.6.3 Modelling results

The results are presented in the following figures:

- Figure 25: Magnetic field level from the overhead line.
- Figure 26: Magnetic field level from the underground line, with phase shifting.

- Figure 27: Magnetic field level from the underground line, with phase shifting. This is a zoom view where the field is the highest in Figure 26, in the pink box.
- Figure 28: Magnetic field level from the underground line, without phase shifting.
- Figure 29: Magnetic field level from the underground line, without phase shifting. This is a zoom view where the field is highest in Figure 28, in the pink box.
- Figure 30 and Figure 31 show the results from 0 to 30 m from the centre line of the cables (corresponding to the dark blue lines in Figure 23 and Figure 24). The results are split between 0 and 5 m on the one hand, and 5 and 30 m on the other hand, so that the scale can be changed for better legibility.

All field levels are presented in µT (coloured scale from blue to red), with scale shown on the right of each figure. The axes represent the distances in metres and correspond to the blue areas shown in Figure 23 and Figure 24.

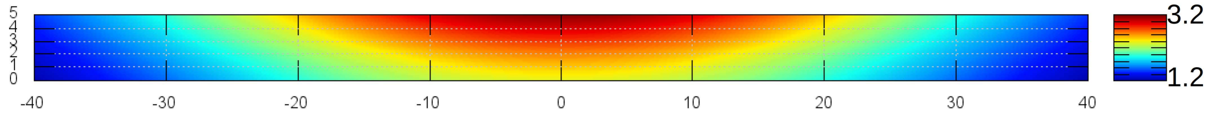

Figure 25: Predicted magnetic field – overhead line

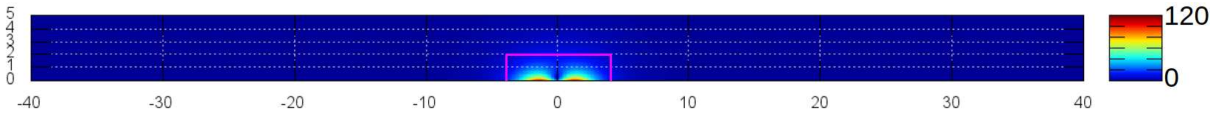

Figure 26: Predicted magnetic field – underground cable with phase shifting

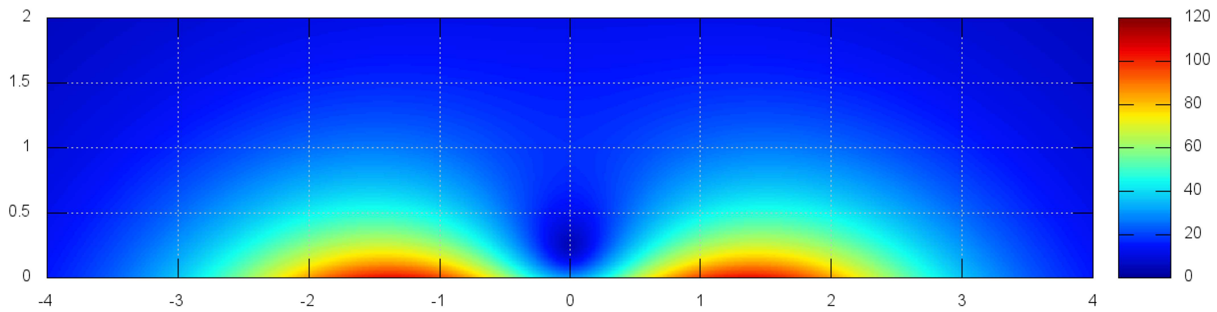

Figure 27: Predicted magnetic field – underground cable with phase shifting (zoom view)

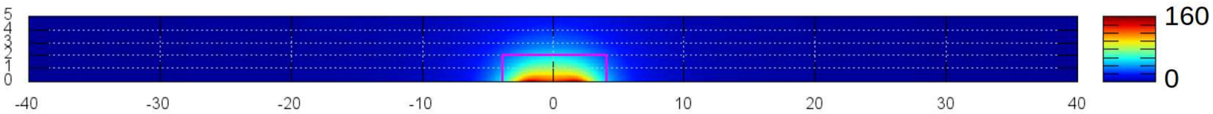

Figure 28: Predicted magnetic field – underground cable without phase shifting

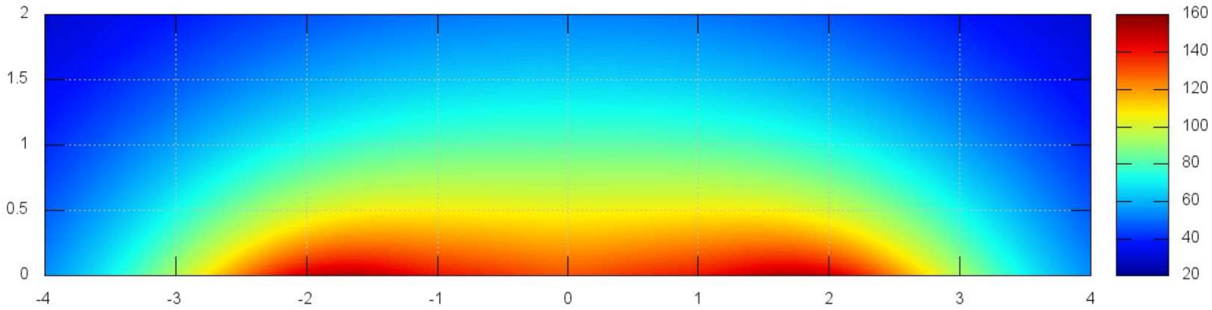

Figure 29: Predicted magnetic field underground cable without phase shifting (zoom view)

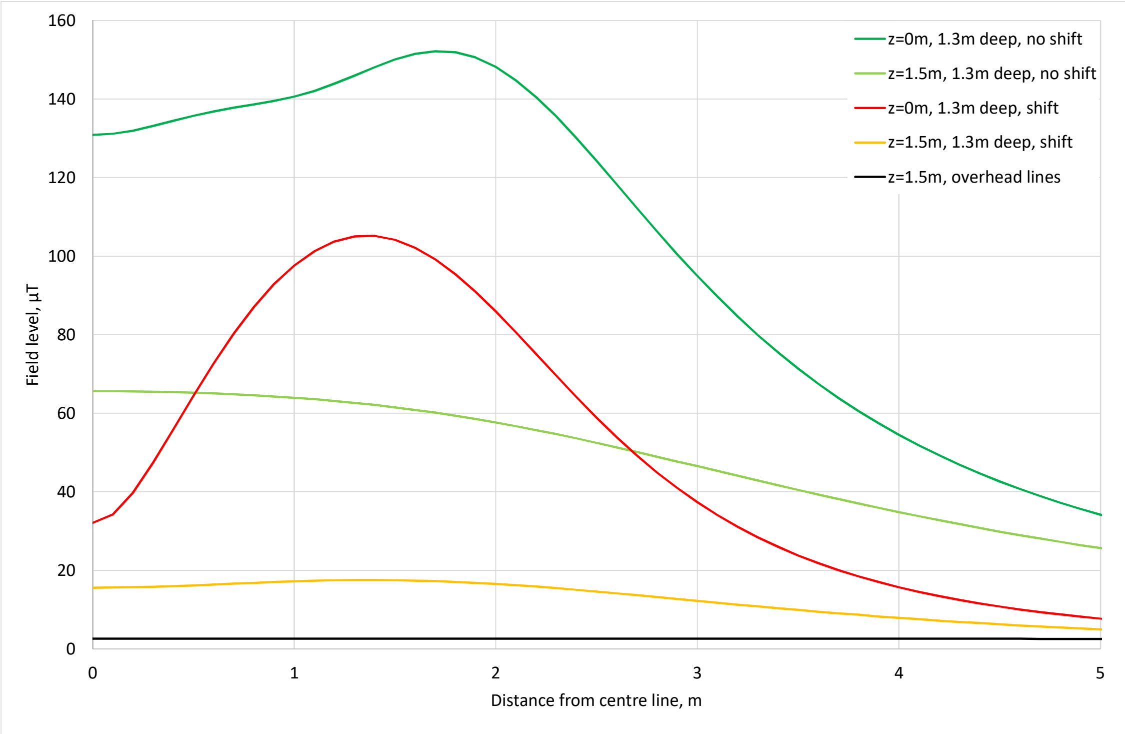

Figure 30: Results from 0 to 5 m from centre line of equipment source

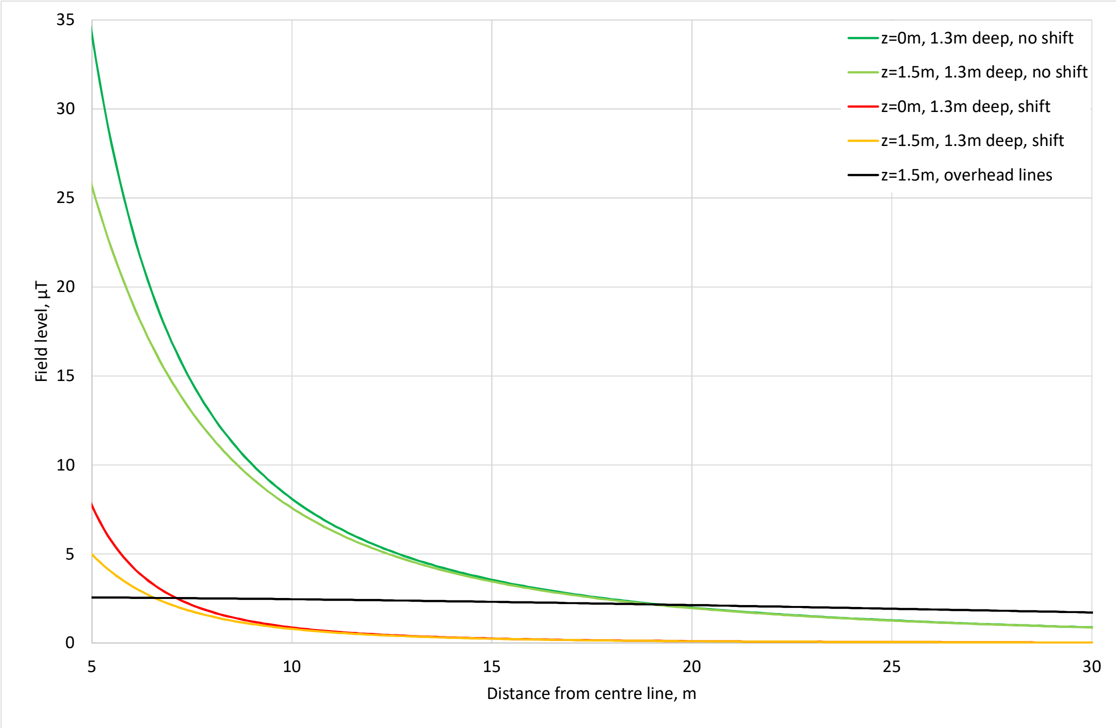

Figure 31: Results from 5 to 30 m from centre line of equipment source

The magnetic field exposure limit for the general public is 200 µT (2000 mG). The results can be summarised as in Table 9.

Table 9: Results of Magnetic Fields against distance from source

Configuration	Height	0m	Peak	5m	10m	15m	20m	30m
Overhead Line	1.5 m	2.6 µT	**2.6 µT**	2.6 µT	2.5 µT	2.3 µT	2.1 µT	1.7 µT
Underground cable with phase shifting	0 m	32 µT	**105 µT**	7.7 µT	0.87 µT	0.25 µT	0.11 µT	0.03 µT
	1.5 m	16 µT	**18 µT**	5.0 µT	0.79 µT	0.24 µT	0.10 µT	0.03 µT
Underground cable without phase shifting	0 m	131 µT	**152 µT**	34 µT	8.1 µT	3.5 µT	2.0 µT	0.89 µT
	1.5 m	66 µT	**66 µT**	26 µT	7.6 µT	3.5 µT	2.0 µT	0.88 µT

The two selected heights, 0 and 1.5 m, respectively represent the feet height and a typical person's chest or head height. The "Peak" column corresponds to the peak level for each configuration, which is not necessarily at the centre line.

6.6.4 Results discussion

These simulations show the following:

- The results from the simulation are lower than the reference level of 200 µT, for the underground cables with and without phase shifting, the resulting magnetic field are **105 µT** and **152 µT,** compared with the reference level of 200 µT.

- Underground cables lead to higher field levels than the equivalent overhead power line. A 1.5 m above ground level (typical chest / head height), the field level is about **2.6 µT** for overhead lines and **18 µT** for underground cables with phase shifting. This is mainly due to the closer distance between the cables and a person walking near the lines.
- Phase shifting has a significant impact on the field levels. Again at 1.5 m above ground level, the field level without phase shifting is about **66 µT**, hence 3.7 times (or 11 dB) above the field level with phase shifting. It is therefore important that the contractor installing the underground line implements this technique.

In order to decrease the field level from the underground cables, the following could be implemented (a risk / cost analysis would need to be performed beforehand):

- Bury the lines deeper. If the cables can be buried at for example 2 m instead of 1.3 m below ground (see results in Figure 32 to Figure 34, with phase shifting), then the field level would not exceed 38 µT at ground level and 11 µT at 1.5 m high.
- Use a trefoil arrangement instead of flat arrangement for the circuits. This would greatly decrease the field levels. It is however understood that cables in trefoil configuration will carry lower current levels, which may in turn require an additional set of cables (5 sets) to carry all the power.
- Add metallic covers above the circuits, e.g. at street level, at least in areas where many people may walk just above the cables. A metallic cover (which must be steel, and not stainless steel) will provide some level of attenuation, depending on its extent and its thickness.

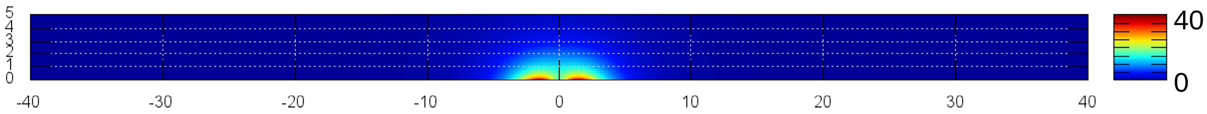

Figure 32: Predicted magnetic field – underground cable with phase shifting buried 2 m deep

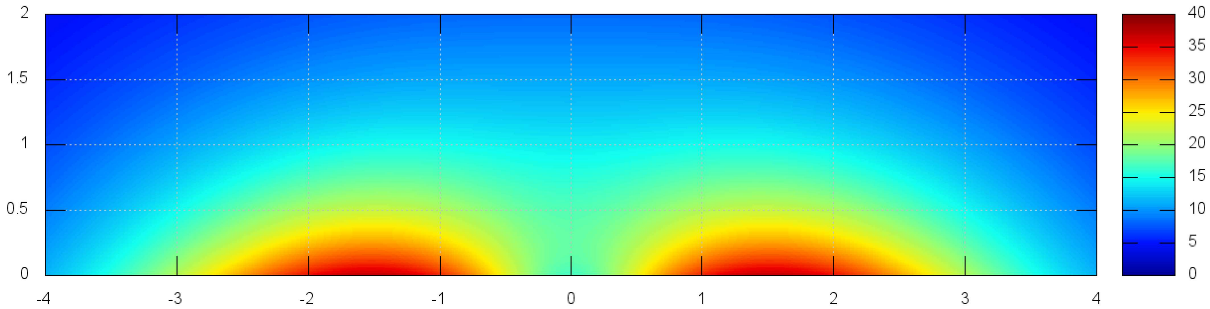

Figure 33: Predicted magnetic field – underground cable with phase shifting 2 m deep – Zoom View

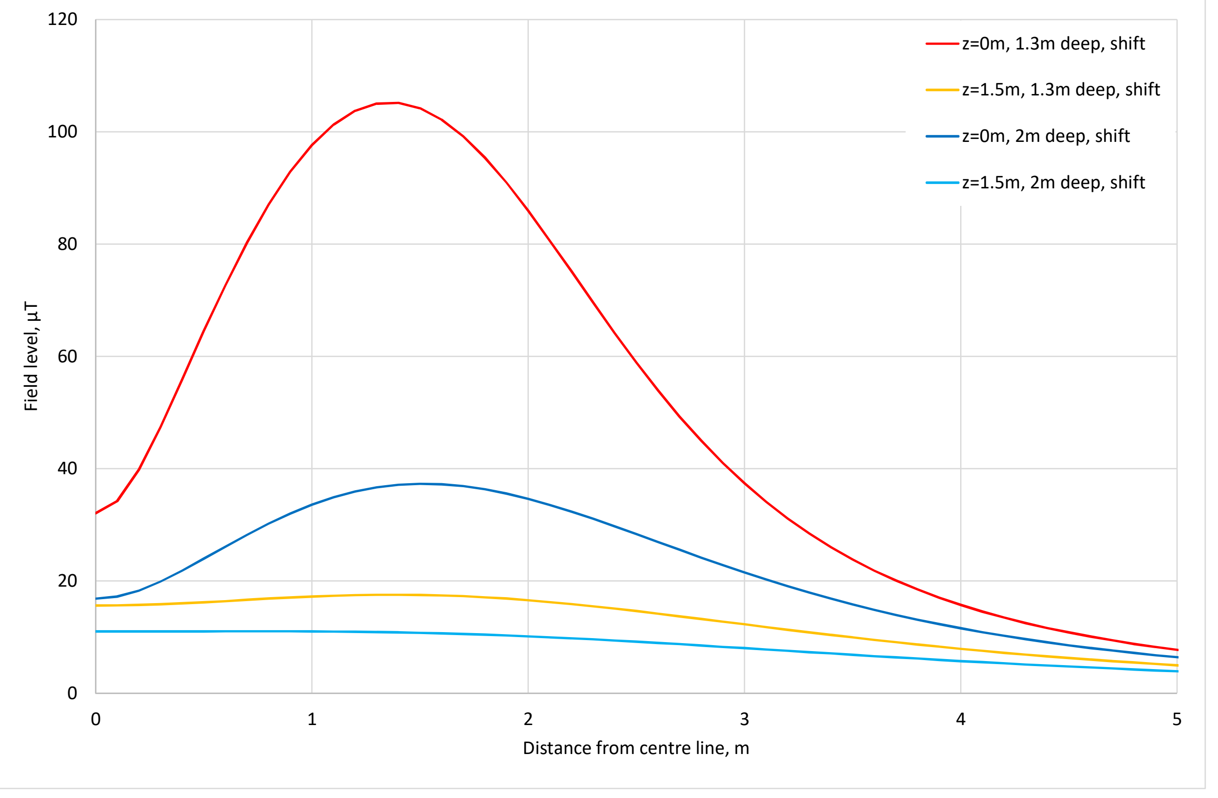

Figure 34: Comparison of field level depending on cable depth

6.7 Prudent avoidance

There is no established evidence that exposure to magnetic fields from power lines, substations, transformers or other electrical sources, regardless of the proximity, causes any health effects. In view of the epidemiological studies, however, the possibility remains that prolonged exposure to higher than typical magnetic fields may increase the risk of leukaemia in children.

Since the late 1980s, many reviews of scientific literature have been published by authoritative bodies. There have also been a number of inquiries such as those by Sir Harry Gibbs in NSW [13] and Professor Hedley Peach in Victoria [14]. These reviews and inquiries have consistently found that:

- adverse health effects have not been established.
- the possibility cannot be ruled out.
- if there is a risk, it is more likely to be associated with the magnetic field than the electric field

Both Sir Harry Gibbs and Professor Peach recommended a policy of prudent avoidance, which Sir Harry Gibbs described in the following terms:

"…. [doing] whatever can be done without undue inconvenience and at modest expense to avert the possible risk …"

The ICNIRP reference levels address short-term, or immediate effect, noticeable exposure, e.g. local tissue heating. They do not address long-term effects based on long-term epidemiological studies of large groups of people. There is a very large body of research covering different aspects of effects on health. Some research papers have claimed a causal link between 50 Hz magnetic fields from overhead power lines and the potential for childhood leukaemia and suggest levels as low as 0.3 µT can represent a risk. These effects are still debated and various research continues in a number of different countries.

The ICNIRP states that:

"WHO's cancer research institute, IARC (International Agency for Research on Cancer), evaluated low frequency magnetic fields in 2002 and classified them in category 2B, which translates to "possibly carcinogenic to humans."

6.8 Consideration

Given the inconclusive nature of the science, it is considered that a prudent avoidance approach continues to be the most appropriate response in the circumstances. Under this approach, subject to modest cost and reasonable convenience, power utilities should design their facilities to reduce the intensity of the fields they generate, and locate them to minimise the fields that people, especially children, encounter over prolonged periods.

7 Health and Safety

7.1 Overhead line

The health and safety risks present during construction and the typical risks are associated with excavation to erect tower footings, assembling the tower structures, materials handling, vehicle movements and stringing conductors from one tower to another. Care needs to be taken to avoid contact with high pressure water pipelines, gas lines or other electricity lines (buried or overhead) during construction works.

The health and safety risks present during operations and maintenance activities and the typical risks are associated with structural failure such as tower collapse due to inclement weather, and fallen conductor on the ground.

A suitable risk assessment study should be completed prior to works and the appropriate mitigation taken.

7.2 Underground cable

The biggest health and safety risks occur during construction and installation of the cable system. Typical construction risks associated with excavation, materials handling, vehicle movements and so on will be present. Care needs to be taken to avoid contact with high pressure water pipelines, gas lines or other electricity lines (buried or overhead) during the works. Damage to the utility may result in injury or death due to a sudden release of energy. It should be noted that cables for 500 kV are bulky and require special care when handling. Cable drum supports and cable pulling equipment must be adequately anchored to prevent inadvertent movement which may cause injury.

Cable jointing works will often include the use of sharp blades and flames; technicians need to be suitably trained. Joint bays may be classed as confined spaces and terminations may require scaffolding and working at height. Some materials used in cable jointing may be harmful if the appropriate precautions are not taken during handling.

During normal operation there should be minimal health and safety risk from an underground cable system. Induced voltages on the cable system metallic sheath or screen and the associated earth bonding system may pose a hazard to personnel working on one circuit whilst the neighbouring circuit is still in service. A suitable risk assessment study should be completed prior to work and the appropriate mitigation taken.

When the cable is in service and where excavation works take place in close proximity to the cable system, any damage caused to the cable may lead to a fault occurring. This is especially likely where mechanical diggers or similar equipment are used. In such circumstances there is significant risk of injury or death resulting from the explosive nature of a high energy electric arc during the fault or from electrocution. Appropriate precautions should be taken prior to any excavation works in the vicinity of underground cables to ensure that no contact is made with the cables.

8 Approvals and Standards Requirements

8.1 Network planning approvals

Regulatory Investment Test for Transmission (RIT-T) is an economic cost-benefit assessment which is used to assess and rank the economic efficiency of a list of proposed network options and finally identify the preferred option. The preferred investment option maximises the present value of net market benefit for the economic life of the project. All Transmission Network Service Provider (TNSP) participating in the National Electricity Market (NEM) must apply for a RIT-T to all proposed transmission augmentations in accordance with clause 5.16.4 of the National Electricity Rules (NER). AEMO is the jurisdictional planning body responsible for planning and directing augmentations to the Victorian Declared Shared Transmission Network (DSTN).

RIT-T process under the NER is outlined below:

- Publication of Project Specification Consultation Report (PSCR)
- Followed by 12 weeks of stakeholder consultations and submissions
- Publication of Project Assessment Draft Report (PADR)
- Followed by 6 weeks of stakeholder consultations and submissions
- Publication of Project Assessment Conclusions Report (PACR)
- Determination of the Project by the Australian Energy Regulator (AER)

For this Project, under the NER requirements, AEMO has completed the RIT-T application and process.

8.2 Environmental planning process

In Victoria, environment assessment of the potential environmental impacts or effects of a proposed development may be required under the Environment Effects Act 1978.

The process under this Act is not an approval process itself, rather it enables statutory decision-makers (Ministers, local government and statutory authorities) to make decisions about whether a project with potentially significant environmental effects should proceed. An Environment Effects Statement of the development may be required subject to the decision of the Minister for Planning.

More information can be found on the Victorian planning environmental assessment “Ministerial Guidelines for Assessment of Environmental Effects”[17].

8.3 Overhead line standards

Approval requirements are usually specified by the electricity network owner or operator. These are generally based on Australian and international standards:

- AS/NZS 7000 – Overhead line design - detailed procedures
- AS/NZS 1170.2 - Structural design actions wind actions

[17] https://www.planning.vic.gov.au/environment-assessment/what-is-the-ees-process-in-victoria

- AS/NZS 3995 - Design of steel lattice towers and masts
- AS/NZS 2159 - Piling - Design and installation
- ASCE (American Society of Civil Engineers) - Guidelines for Electrical Transmission Line Structural Loading

Once installed, the overhead line will need to undergo testing and commissioning activities.

8.4 Underground cable standards

Approval requirements are usually specified by the electricity network owner or operator. These are generally based Australian and international standards:

- AS/NZS 1660 - Test methods for electric cables, cords and conductors Insulation, extruded semi-conductive screens and non-metallic sheaths
- AS/NZS 3808 - Insulating and sheathing materials for electric cables
- IEC 60228 – Conductors of insulated cables
- IEC 60287 – Electric cables – Calculation of the current rating
- IEC 60853 – Calculation of the cyclic and emergency current rating of cables
- IEC 61443 – Short circuit temperature limits of electric cables with rated voltages above 30 kV (Um=36 kV)
- IEC 62067 – Power cables with extruded insulation and their accessories for rated voltages above 150 kV (Um=170 kV) up to 500 kV (Um=550 kV). Test methods and requirements.

In addition, CIGRE documents provide guidance on aspects of cable system design and installation (for example):

- Technical Brochure 194 – Construction, laying and installation techniques for extruded and self-contained fluid filled cable systems
- Technical Brochure 283 – Special bonding of high voltage power cables
- Technical Brochure 347 – Earth potential rises in specially bonded screen systems
- Technical Brochure 640 – A guide for rating calculations of insulated cables

Other documents that may influence the design include:

- Energy Networks Association EREC C55/5 – Insulated sheath power cable systems

IEC 62067 requires that a manufacturer demonstrates their ability to supply a cable system in the required voltage class through pre-qualification testing. In addition, the manufacturer should be able to provide type test evidence for the particular design of cable system being offered. Routine and sample tests are required during manufacture of the cable system components. Once installed the cable system needs to undergo electrical tests for commissioning.

9 Estimated Project Timeline

9.1 Overhead line

The Project timeline for the 500 kV double circuit overhead line of 75 km from AusNet Services for the Western Victoria Transmission Network Project is approximately 5 years. The construction will take approximately 2 years to complete as depicted in Figure 35 below.

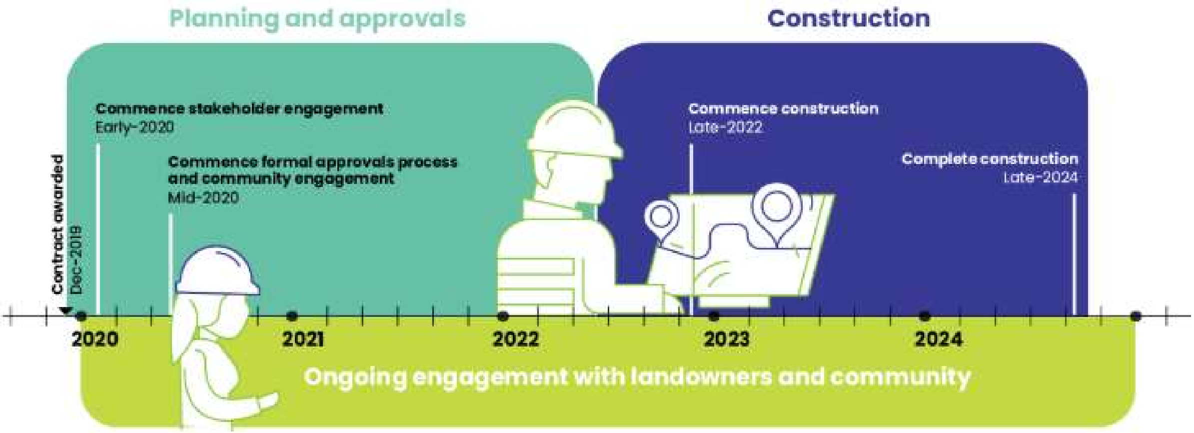

Figure 35: Project timeline for Western Victorian Transmission Network Project[18]

9.2 Underground cable

It is assumed that the planning and approvals will have similar timeline of approximately 3 years as the overhead lines depicted in Figure 35. The construction timeline is on the assumption that the 500 kV double circuit underground cable has two conductors (cables) per phase installed in buried ducts for the full 75 km route, is approximately 6 years. It has been assumed that horizontal directional drills will be required at a number of major crossings along the route and that these will be completed in the early stages of the project. It may be possible to reduce the lead time (potentially by half the estimated time) by increasing resources for working simultaneously at multiple locations

[18] https://www.westvictnp.com.au/project-information

along the underground cable route, which may impact on the construction cost.

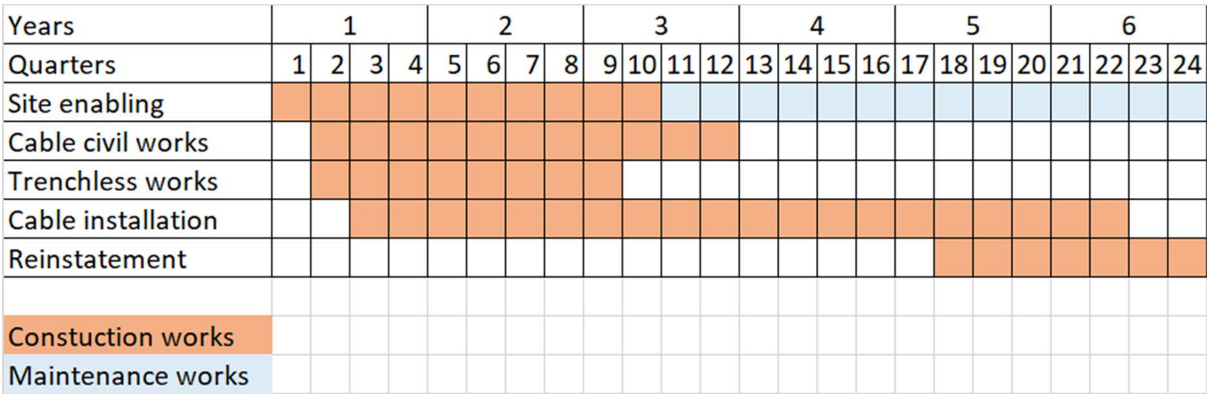

Figure 36: Construction timeline for a 500 kV double circuit underground cable

10 Conclusion

AC overhead transmission line installation is a capital cost effective solution. However, the overall Project should also consider a number of other factors including, the environmental impact, social impact, visual impact, bush fire threat and ease of maintenance and upgrade.

Minor damage to overhead lines will not result in long power outages because they are easy and quick to repair. Major damage to overhead lines may result in longer power outages, for example the 7 damaged towers in South West Victoria in January 2020, required 2.5 weeks to re-energise one overhead line.

AC underground transmission cables have been built in several world capitals or in areas that require special considerations. These cables are very expensive compared with overhead lines and are used in densely populated urban areas where there is limited right-of-way for overhead lines. Transition stations to connect the overhead line and underground cables have to be built at each end of the underground cable segment. The longest underground cable installation is in Tokyo with about 40 km route length and has shunt reactors at its ends for reactive compensation. Underground cables are generally very reliable as they are not affected by wind, storm, bushfire and aerial collision. However, major damage to cables such as inadvertent excavation or premature failure may require a significantly greater amount of time to repair than overhead lines due to their complexity and custom built design.

A feasible alternative to the proposed 500 kV double circuit overhead line would be 500 kV double circuit underground cable. Whilst this would be approximately ten times more expensive than an overhead line, the overall cost impact could be reduced by placing only the most sensitive sections underground. Although using underground cable for a portion of the route is not a simple solution it appears to be technically feasible. Another option is to install some or all of the new overhead line adjacent to the route of the existing overhead line easement (Sydenham-Moorabool-Elaine-Ballarat).

The major differences between a 500 kV double circuit overhead line and a 500 kV double circuit underground cable found in our assessment are as follows:

- Large visual impact for overhead line due to the above ground infrastructure and minimum (or negligible) visual impact on underground cable.
- During construction, major ground disturbance for underground cables as compared with overhead lines.
- Indicative EMF modelling results found that the magnetic field level for a person standing above the underground cables are higher than standing below an overhead line. However, significant reduction of magnetic field level (even lower than overhead lines) when standing 15 m away from the underground cables.

References

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[2] TransGrid Annual Report 2003

[3] TransGrid Fact Sheet – What is the high voltage transmission network?

[4] Nexan 60-500 kV High Voltage Underground Power Cables XLPE insulated cables

[5] Electricity System Code October 2000 – Office of the Regulator-General, Victoria

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[9] AusNet Services Cost pass through application – 500kV Transmission Line Tower Collapse July 20

[10] Powerlink – HV Underground Cable Asset Methodology – Framework - June 2018

[11] ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields up to 300 GHz Health Physics, April 1998, Volume 74, Number 4

[12] ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields (1 Hz – 100 kHz)

[13]Gibbs, Sir Harry (1991). Inquiry into community needs and high voltage transmission line development. Report to the NSW Minister for Minerals and Energy. Sydney, NSW: Department of Minerals and Energy, February 1991

[14] Peach H.G., Bonwick W.J. and Wyse T. (1992). Report of the Panel on Electromagnetic Fields and Health to the Victorian Government (Peach Panel Report). Melbourne, Victoria: September, 1992. 2 volumes: Report; Appendices

[15] Parsons Brinkerhoff Electricity Transmission Costing Study – January 2012

Appendices

A. Terminal Station

This section is to provide supplementary information of the Project in relation to a terminal station.

A typical terminal station consists of incoming and outgoing transmission lines, gantries of steel lattice structures, lightning masts, transformers, circuit breakers, current and voltage transformers, capacitor and reactor banks, bus-bars, control building, internal roadways and carparks.

The proposed terminal station is an outdoor switchyard with 500 kV and 220 kV primary equipment. The approximate layout of the proposed Terminal Station is similar to the existing Moorabool Terminal Station (located in City of Greater Geelong Local Government Area (LGA)) with 4 x 500 kV overhead transmission lines, 2 x 500/220 kV transformers, 6 x 220 kV overhead transmission lines. Moorabool Terminal Station has a land size of approximately 15 hectares.

Figure 37 below shows the layout of Moorabool Terminal Station.

Figure 37: Moorabool terminal station layout

B. Photos of 500 kV Underground Cable Construction

Figure 38: Cable being pulled from a drum that is mounted on a motorised stand

Figure 39: Cable construction site[19]

[19] https://www.tdworld.com/intelligent-undergrounding/article/20969593/engineering-a-500kv-underground-system

Figure 40: Cable construction corridor[20]

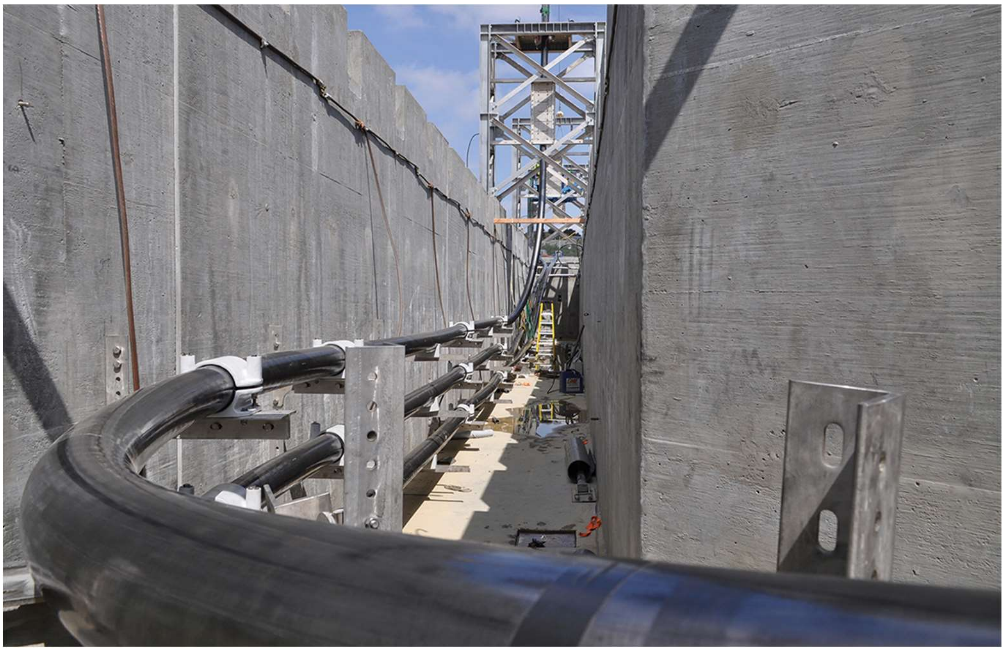

Figure 41: Views from inside the Western Transition Station cable trench[20]

20 https://www.tdworld.com/intelligent-undergrounding/article/20969593/engineering-a-500kv-underground-system

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