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Summary Report

Comparing high voltage overhead and underground transmission infrastructure (up to 500 kV)

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Foreword

This report summarises the findings of an independent systematic literature review of high voltage overhead and underground transmission infrastructure, which was undertaken by The University of Queensland and Curtin University.

This is the summary report for the study which is complemented by more detailed reports provided separately in Chapters 1 to 8 which cover the themes and cases studies in more detail.

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Abbreviations and Acronyms

Abbreviation	Description
AC	Alternating Current
ACSR	Aluminium conductor steel-reinforced cable (or conductor)
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AVP	AEMO Victorian Planning
CBA	Cost Benefit Analysis
CIGRE	International Council on Large Energy Systems
DC	Direct Current
EHV	Extra High Voltage—consensus for AC Transmission lines is 345kV and above
EIS	Environmental Impact Assessment
EIR	Environmental Impact Review
EIS	Environmental Impact Statement
ELF	Extremely low frequency
EMF	Electromagnetic Fields
ENA	Electricity Networks Australia
EPR	Ethylene propylene cable
EPRI	Electrical Power Research Institute
GIL	Gas Insulated Line
GC	Gas cable
HDD	Horizontal Directional Drilling
HPOF	High-pressure oil-filled cable

Abbreviation	Description
HTLS	High Temperature Low Sag Conductors
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ISP	AEMO's Integrated System Plan
NEM	National Electricity Market
OH	Overhead
OHTL	Overhead transmission line
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
REZ	Renewable Energy Zone
RIT-T	Regulatory Investment Test—Transmission
ROW	Right of Way (e.g. easement)
SCOF	Self-contained oil-filled cable
SLO	Social Licence to Operate
UG	Underground
UGC	Underground cable
UGTL	Underground transmission line
XLPE	Cross-linked polyethylene

Executive Summary

Background

Decarbonisation of Australia's energy system through electrification via renewable energy sources is a key pillar of the transition to a climate-friendly economy. Without grid expansion, either with new or upgraded transmission lines, decarbonisation and a successful transition is at risk. However, the challenges of grid expansion are not limited to the techno-economic ones. Experience from around the world shows that transmission lines tend to be less accepted than most other energy infrastructures, with public opposition leading to significant project delays. This is also being experienced here in Australia. Successful navigation of such challenges requires a systemic approach to the problem. Recognising there is a complex interplay between the economic, environment, and technical constraints that impact society's response and ultimate acceptance. This in turn requires strong leadership to move the agenda forward with significant attention to the procedural and distributive justice considerations of such projects. Informed by a systematic literature review we summarise the main trade-offs between overhead and underground transmission line infrastructure by considering the technical, economic, environmental and social and cultural factors.

This research project to assemble the literature and case studies was undertaken between February and July, 2023. However, there is additional and ongoing engagement with a range of different groups to understand the various publics' responses to the information, including First Nations People and farmers. The considerable developments in relation to social licence, community engagement and opposition that have occurred in more recent months are not detailed in this report. For example, the findings from the NSW Parliamentary Inquiry, and the draft determination and rule change for enhancing community engagement in transmission building, proposed by the Australian Energy Market Commission (AEMC) are not detailed in this review. We also note that a further Inquiry by a Select Committee in NSW was announced in September. Finally, the Australian Energy Infrastructure Commissioner is also undertaking a review to "enhance community support and ensure that electricity transmission and renewable energy developments deliver for communities, landholders and Traditional Owners".

Technical Considerations

For years, HVAC overhead transmission lines have been the most common form of transmission line infrastructure, providing the lowest cost system for connecting multiple generators and ensuring bulk supply of electricity to customer load centres. They are designed to meet high-performance standards for safety and reliability with proven technologies for structures, conductors, and insulators that with good maintenance practices have a long service life of between 60 to 80 years.

Alternatively, when traversing high-density urban areas where there is already congestion of overhead lines, or in areas of environmental sensitivity or natural beauty, HVAC underground transmission cables have been used. However their application is limited to much shorter route lengths, for example around 50km for 500kV. This is due to the significant charging currents associated with the highly capacitive characteristics required for longer HVAC underground cables. To counteract the resulting energy losses caused by this phenomenon, expensive reactive power compensation plant (e.g. shunt reactors) are required. Usually made from polyethylene (XLPE), the cables are expected to have a service life of around 40 to 50 years.

High Voltage Direct Current (HVDC) (overhead or underground) transmission is an alternative to the HVAC system. Its main advantages are that it provides for:

(a) High power transfer power over very long distances with lower line losses compared to HVAC.
(b) Interconnection of asynchronous AC grids, for example between two regions or countries.
(c) More compact line infrastructure "foot-print" requiring narrower land corridors due to fewer conductors or cables compared to the equivalent rated HVAC overhead or underground line.
(d) Long offshore or on-shore cable connections where the route length exceeds the feasible or critical route length for a HVAC transmission cable of equivalent power transfer capability

The main disadvantages of HVDC is the requirement for large and expensive AC/DC converter stations at terminal connection points to the main HVAC transmission grid. For example the converter stations for the Suedlink project will occupy around 7 hectares [1]. Noise levels from the equipment at converter stations can also be a significant environmental issue [2]. The requirement for large and expensive converter stations tends to limit application of HVDC to point to point connections.

Until now, HVDC has been used extensively for inter-regional transmission connectors and offshore and onshore renewable zone interconnections in more highly populated regions (i.e. Europe, America, and Asia). In Australia, there are only three examples - Basslink submarine cable; Directlink (Northern NSW); and Murraylink (Vic to SA) - constituting a small component of Australia's transmission grid.

Economic Considerations

Multiple studies by government bodies, Transmission Network Service Providers (TNSPs), industry organisations, and other stakeholders compare the cost of overhead versus underground cable transmission. Based on published literature, including the Parsons Brinkerhoff UK report [3] (often referred to by the industry for its methodology for evaluating lifetime costs) and the Australian Energy Market Operator (AEMO) [4], the comparative ratios are generally in the range of 3 to 20 depending upon type of construction, route length and other project specific factors. However, Parsons Brinkerhoff note the complexities of undertaking economic analysis stating *"Cost ratios are volatile, ... Use of financial cost comparisons, rather than cost ratios, are thus recommended when making investment decisions."*

A detailed review of HVDC transmission costing and economic factors was not within the scope of this study. However, based on data from Acaroğlu et al [5], ABB [6], Amplitude Consultants [7], and the AEMO Transmission Cost Database, the break-even cost point for HVDC overhead transmission is at a route length of around 600km to 700km when compared to an equivalent of a 500kV HVAC line. The cost ratio of HVDC underground to HVAC overhead was reported as 3.3 for a 1500MW, 1000km case study [5].

However, the economic feasibility of HVDC compared to HVAC, ultimately depends on project-specific factors such as route length and constraints. Regulatory investment test requirements also need to be satisfied and these highlighted costs only relate to the technical costs and do not encompass access to land and costs of gaining a social licence, for example.

Environmental Considerations

While the overall environmental impacts of transmission lines are likely to be negative, the extent to which their impact is felt is context dependent. Principally, habitat loss, fragmentation, and the alteration of environmentally sensitive areas are key negative outcomes of the construction of transmission infrastructure on the natural environment. The clearing of vegetation for easements is likely to have a significant impact on wildlife habitats as well as cause changes in the microclimate by restricting the growth of plants and trees, with secondary impacts on some species including insects, birds, and other mammals. Transmission lines constructed in highly sensitive natural environments including watercourses, wetlands, and national parks, would see these impacts amplified.

Overhead lines are likely to create a barrier effect, where biodiversity is negatively impacted by changes in bird migration patterns because of collision and avoidance of the transmission lines, whereas the use of underground transmission can somewhat mitigate this impact. In contrast, underground transmission may cause soil degradation and hydrological alterations throughout the lifetime of underground lines, whereas initial data indicates that these impacts are less significant in overhead lines being restricted largely to the construction phase and mitigated through carefully designed construction and restoration methods. Bushfires have in a few instances (2 out of 32 noted in the NSW 2019 Inquiry) been started by transmission lines, and also cause damage to both overhead and underground lines.

The generation of electromagnetic fields and noise from transmission lines, particularly overhead lines, has the potential to disrupt not only local nearby communities but also the behaviour and health of some species including bats and other pollinators. Knowledge of the extent of these impacts is less developed but is an important factor to consider given the significant role these species play in an area's overall biodiversity and environmental stability.

Beyond the direct effect of transmission lines on the natural environment, projects must also consider how their construction is likely to impact the archaeological and cultural heritage of the surrounding area. More work in this area will provide a valuable perspective and understanding of other dimensions of environmental impacts.

To minimise the environmental impacts from any transmission project there are strict legislative requirements in place at both Federal and State levels. The Federal Environment Protection and Biodiversity Conservation Act 1999[1] and the Queensland Environmental Protection Act 1994[2] are the main legislative requirements that govern transmission project developments. These require detailed assessment and surveys and a typical time frame to complete such processes is around two years.

Social and Cultural Considerations

The literature review identified a range of factors that influence acceptance – a necessary part of acquiring a social licence. Factors such as aesthetics, human health

1 Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)(www.dcceew.gov.au/environment/epbc)

2 Environmental Protection Act 1994 - Queensland Legislation - Queensland Government (www.legislation.qld.gov.au/view/html/inforce/current/act-1994-062)

and some safety considerations generally see underground performing better than overhead for public acceptance. Augmented with environmental and economic concerns, along with trust in the developer and concerns around procedural and distributive justice reflect the systemic and complex nature of the decision space.

The distribution of benefit and burden is at the heart of distributive justice considerations. Local host individuals and communities bear the major burdens and risks of projects, while benefits are often realised far away in cities or even globally when it comes to emissions reduction. To overcome the likely negative reaction to projects, compensation has played an important factor in positively influencing local host acceptance, along with an expectation that neighbours are included in discussions of compensation to ensure fairness in how the process is perceived.

However, experience has shown the public's response is never solely about the financial incentives. If the process of engagement is not seen as respectful and fair, then it is unlikely any amount of compensation will guarantee the project will progress. Individuals' values also strongly influence attitudes towards a project and ultimately its acceptance. These attitudes might relate to strength of their attachment to the place in which they live, place and social identity along with the timeliness of the process that was used to engage, and availability of information.

Open, regular, and transparent project processes that involve two-way dialogue, significantly help to build trust in project developers. This was evidenced in the current Australian transmission projects where *the speed of delivery and the need to build a lot* has caused concerns for many stakeholders. Multiple developments (e.g. renewables plus transmission) occurring at the same time can lead to cumulative impacts and create additional burdens on communities. Transparent and fair processes need to include all stakeholders, ensuring any power imbalances are addressed. This should also include appropriate place-based engagement and collaboration with Traditional Custodians.

Findings Case Studies – Australia and beyond

Many of the considerations arising from the systematic literature review are vividly illustrated in the current Australian 500kV projects and international cases. Understanding both the historical and current context of project locations, along with engaging early and reflexively, and allowing communities time to engage to understand the trade-offs between options – all help to build fair processes. Impacts on land use, archaeological sites, farming practices, property values, tourism and increased traffic on local roads were all common issues emerging from the case studies.

The need for adequate compensation beyond the host community and the undergrounding of some sections, in response to stakeholder concerns, also helped to build greater acceptance for projects internationally. In the case of the UK and Denmark, the use of aesthetic overhead transmission line structures - more compact with a lower height compared to traditional steel lattice towers for the same system voltage – led to successful project outcomes. However, the downside of these structures is the greater width of the structures resulting in larger easement requirements and land-use restrictions.

Conclusion

While the urgent need to decarbonise our energy system is a global issue, unless directly impacted by a project, the Australian public's understanding of the need for new transmission infrastructure remains low. This is despite the fact, that such investment will ultimately be reflected in state capital borrowings and individual electricity bills. Therefore, to ensure fairness and understanding in the investment and trade-offs required for such a transition, there is a need for increased, easy to understand information and engagement on the topic.

Key considerations include, why there is a need to build more transmission infrastructure, and how it differs to distribution networks. What the differences are between HVAC and HVDC and the trade-offs that emerge when considering either overhead and underground infrastructure. This must include the combination of factors that arise, beyond the techno-economic considerations, to highlight the complex decision space that is required when choosing a final route.

While there is no one size fits all for final route selection, transparent, collaborative constraint mapping, undertaken between projects developers and communities can help to build trust in the process and more successfully lead to the identification of a preferred route option. However, this is only if distributive and procedural fairness considerations have been central to the process. Given the delays that have occurred both in Australia and beyond, there is a need for strong leadership that, where necessary, can make the tough decisions, if necessary, for the resumption of land and to clearly articulate the trade-offs that led to the final decision.

1.

Introduction

1.1 Background

The Australian federal government has committed to reducing its greenhouse gas emissions by 43% below 2005 levels by 2030. This target is set under the Paris Agreement, a global effort to combat climate change. As one of the measures supporting this commitment an additional target has been set to reach 82% renewable energy generation by 2030. This includes a range of initiatives to promote the deployment of renewable energy sources including solar, wind, and hydroelectric power.

State Governments accordingly have established plans and strategies to support and, in many cases, exceed the national targets. For example, the *Queensland Energy and Jobs Plan (2022)* set a target of 70% renewable energy generation by 2032. An essential component of this plan is to establish a "SuperGrid" to provide a new backbone transmission network that will connect more renewable energy and storage sites across the state. The other states and territories, which operate in Australia's National Electricity Market (NEM): New South Wales, Victoria, South Australia, ACT and Tasmania, have similar plans for expanding the transmission networks to connect projects in renewable energy zones (REZs).

Transmission line infrastructure in Australia and overseas is predominantly overhead construction. Based on 2015 data collected by Geoscience Australia [8], only about 0.9% of the transmission line circuit route of 220kV or greater is underground in Australia. This is generally consistent with data reported internationally by CIGRE [9] of about 0.5% for lines in the 315 to 500kV range being underground. This has mainly been attributed to technical limitations and the significant cost of undergrounding compared to the construction of overhead transmission lines. The capital cost of underground compared to overhead transmission infrastructure is generally reported by many TNSP's[3] to be in the order of 5 to 10 or even higher, depending on project specific factors.

The proposed large scale renewable generation facilities, mainly solar and wind farms require greater land areas and are largely being located in greenfield areas with little or no existing transmission network infrastructure. These new developments are naturally creating community concerns around a range of potential impacts, including but not limited to: visual amenity; environmental impacts; cultural heritage considerations; Traditional Owner rights; agricultural land use; and social licence to operate.

While national and state regulatory frameworks seek to ensure these concerns are addressed in the planning phase of new infrastructure projects, there has been a marked increase in public opposition to proposed transmission projects in Australia. This has not only resulted in significant delays to projects, along with increasing project costs as a result of the delays, it has also caused significant negative impacts on landholders' and other local communities' overall wellbeing. Different groups have invested much time and effort in opposition to transmission projects proposed for their local communities, seeking answers around the trade-offs between overhead and underground transmission infrastructure. With the urgent need to decarbonise and increasing timeframes for the processes and approvals the situation is becoming critical.

1.2 About this Review

This review aims to investigate the benefits and trade-offs between overhead and underground transmission line infrastructure, specifically focusing on issues associated with under-grounding new transmission infrastructure. It seeks to establish a clear and consistent approach to the evaluation of overhead lines and underground cable transmission, including the consideration of community concerns around the need for new transmission infrastructure to connect large renewable energy generation projects. It does this through systematic reviews of the literature as well as incorporating experiences of Transmission Network Service Providers (TNSPs) in Australia and overseas.

[3] Underground-construction-summary-November-2021.pdf (www.westernrenewableslink.com.au)
HumeLink: Connecting Wagga Wagga, Bannaby and Maragle | Transgrid (www.transgrid.com.au/projects-innovation/humelink#Resources)
Electricity Transmission Costing Study (www.theiet.org)

The study has a particular focus on 500kV infrastructure which is expected to be the system voltage for high-capacity transmission lines in Australia going forward.

To ensure a comprehensive and independent analysis, the research project began with a three hour collaborative, co-design workshop with key agricultural, resources, community, and customer representatives from Powerlink's Customer Panel to help to set the guidelines for this review to accurately identify the knowledge gaps. In total there were seven participants from the Customer Panel, two representatives from Powerlink and four of the technical experts from the research team. Chief Investigators, Ashworth and Ackermann, guided the workshop process. Participants were asked to identify what they saw as *"The top 3 issues and opportunities relating to either overhead (O) or underground (U) cables"?* Eight different themes emerged from the workshop and to prioritise these, participants were asked to rate each theme on a scale from 0 (lowest priority) to 10 (highest priority). Reflected in Table 1, the first column shows the number of supporting statements that emerged in each theme, while the following columns, provide the mean and standard deviation of combined scores, illustrating the priority and degree of consensus across each of the themes.

Social licence and impacts on landholders and communities received the highest average score and the highest degree of consensus. *Ensuring new transmission has minimal environmental impact* was the next highest priority followed by *Community consultation and engagement*. Both of the latter are key constructs and considerations for achieving a social licence to operate. This reinforces the importance of the social and cultural aspects in achieving new transmission upgrades regardless of whether they are overhead or underground.

Table 1. Key themes emerging from the workshop with relative priority ranking

Theme	No. of Supporting Statements	Mean	SD (Degree of consensus)
Social licence and impacts on landholders and communities	33	8.9	1.1
Minimising environmental impact	34	7.6	2.2
Community consultation and engagement	35	7.5	1.4
First Nations engagement and benefits, FPIC	12	7.2	2.5
Corridor selection and securing land access	11	7.2	1.6
Whole of life cost	10	6.7	2.9
Speed of delivery and need to build a lot	13	6.5	1.7
Building a smarter more resilient grid	6	6.0	3.5

Subject matter experts were engaged to undertake a peer review of the research. This inclusive approach aimed to address a broad range of issues and instil confidence in the report conclusions. The study first used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to document the latest peer reviewed literature on the technical, economic, environmental, and societal considerations for the use of overhead and underground transmission infrastructure. This PRISMA review was supplemented by purposeful study of the latest CIGRE and EPRI reference books and reports, along with other grey literature and case study material, to ensure the findings were comprehensive. It was considered essential to adopt a life-cycle approach (from planning phase to end of life) to compare the trade-offs between overhead and underground transmission infrastructure. The findings are currently being shared with different representatives from the general public and their responses documented in the separate report (Focus Group Findings). Additional engagement with First Nations People, farmers and other stakeholders is ongoing and will be documented and shared subsequent to this report.

It is worth noting, the literature review and case studies for this research project were undertaken between February and July, 2023. The considerable developments in relation to social licence considerations, community engagement and opposition that have occurred in more recent months are not detailed in this report. For example, the findings from the NSW Parliamentary Inquiry, and the draft determination and rule change for enhancing community engagement in transmission building, proposed by the Australian Energy Market Commission (AEMC) are not detailed in this review. Although we note that a further Inquiry by a Select Committee in NSW was announced in September. Finally, we note that the Australian Energy Infrastructure Commissioner is also undertaking a review to “enhance community support and ensure that electricity transmission and renewable energy developments deliver for communities, landholders and Traditional Owners”. The findings from this scientific review are complementary, in highlighting the trade-offs across the technical, economic, social, cultural and environmental for transmission infrastructure.

2.

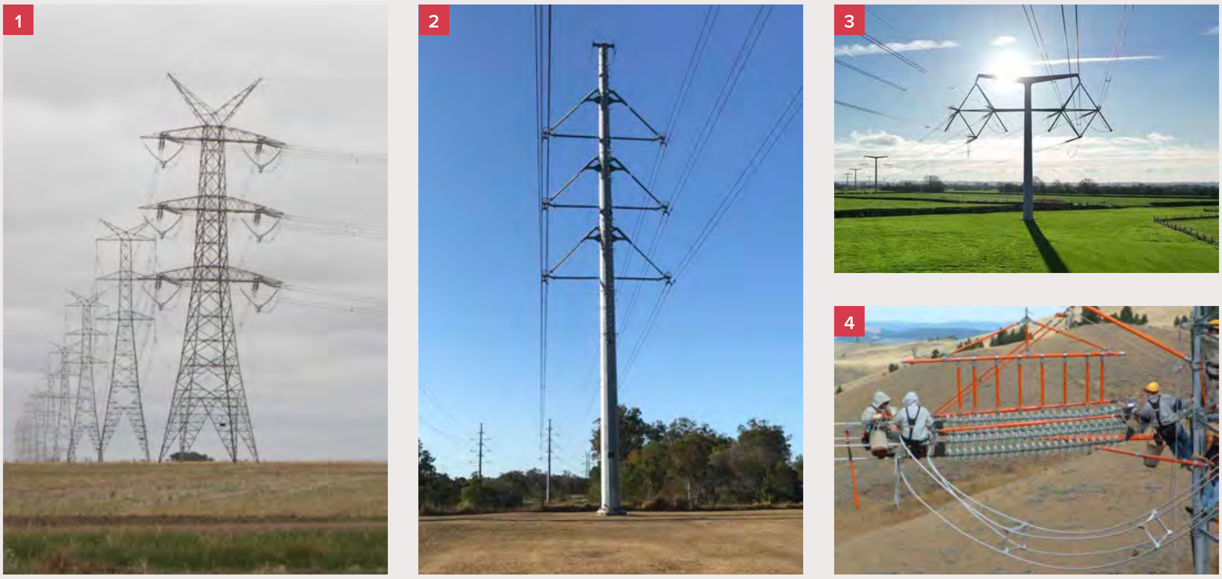
Technical Aspects

2.1 HVAC Overhead Transmission Lines

High voltage alternating current (HVAC) overhead line technology has been the dominant form of transmission infrastructure worldwide since the early twentieth century. This is because it has provided the most cost-effective and technically feasible system for constructing, operating, and maintaining a grid that meets high standards of safety and reliability. Overhead transmission lines have a service life of around 60 to 80 years with appropriate maintenance.

Examples of HVAC overhead transmission infrastructure are shown in *Figure 1*. The design and main components of a HVAC transmission line are described as follows:

- Transmission lines can be constructed as either a **single** or **double circuit lines**. Each circuit will comprise of a 3-phase set of insulators and conductors.
- The most common and cost-effective **tower structure** is the steel lattice construction type. The structures are constructed using prefabricated galvanised steel components which are assembled on-site and mounted on concrete **foundations** or footings.
- **Structure heights** vary from around 30m for 132kV lines up to around 70m for 500kV lines.
- There are two main types of tower constructions by function: (1) **Suspension towers** –with vertical insulator strings supporting conductors with no change in direction of the line, and (2) **Tension towers** – with horizontal insulator strings in both directions of the line from the tower. Tension towers are placed at the ends of long sections of conductors or at change in directions of the line. Tension towers need to have higher strength steel construction and concrete foundations to support the higher tensile loads.
- **Cross arms** are the sections that extend outward from the main structure and support the insulator strings for each circuit.
- **Insulators** support the conductors from the cross arms and ensure that the conductors are electrically isolated from earth including the steel work. Insulators are manufactured as either individual porcelain or glass discs which can be assembled into a string or alternatively a single composite material string. The length of the insulator string increases with system voltage.
- **Conductors** – are normally aluminium alloy or Aluminium conductor steel-reinforced cable (ACSR) which are lightweight and strong and can be strung at high tensions to minimise conductor sags. To increase the power transfer rating of a line **bundled conductors** held together with **spacers** are used. For example, 275kV lines are often designed with 2 conductors per phase. Quad bundled conductor is common for 500kV lines.
- Conductor **span lengths** between structures varies in the range of 200m to 600m depending on environmental, topography and line design requirements.
- **Earth wires** at the top of the structure shield and protect the line against lightning and voltage surges. Fibre optic cables can be integrated into special types of earth wires – Optical Ground Wire (**OPGW**) to provide a telecommunication channel.
- **Vibration dampers** can be attached to the conductors to reduce the effects of vibration fatigue caused by wind.
- **Corona rings** at the ends of insulator strings help provide a smooth surface to mitigate against an electrical phenomenon called corona discharge which can cause noise and electrical losses.



1. 500kV double circuit tension tower and suspension towers (Marcus Wong)
2. 275kV double circuit compact steel pole
3. 400kV T-Pylon structures (National Grid UK)
4. Live insulator change-out (North-Western Energy UK)

Figure 1. Examples of Overhead Transmission Infrastructure

Long overhead transmission lines require reactive compensation plant in the form of shunt reactors or Static Var Compensators (SVCs). The purpose of this equipment is to improve efficiency of power transfer and limit temporary overvoltage that occurs when a line is energised or switched out of service. The reactive compensation plant is usually installed at the line's terminal substations. Underground transmission cables also require reactive compensation, but the requirement can be much greater compared to overhead lines (refer section *2.2 HVAC Underground Transmission Cable*)

The design of a transmission line is a specialised engineering activity which provides an optimal solution for a route to meet functional requirements of power transfer, voltage, rating, and reliability performance based on many input parameters including technical and safety standards and environmental conditions such as ambient temperature, solar radiation, maximum wind loadings, lightning flash density, and ground conditions.

One of the fundamental requirements for overhead transmission lines is a land corridor which is normally secured by an **easement**. The easement width varies depending on the system voltage and other design requirements. An easement provides for construction and maintenance access, and vegetation clearing. Easements will have restrictions on certain activities or objects within an easement (mainly for safety reasons) but may allow some activities subject to conditions including grazing, agriculture, and certain types or size of vegetation. **Typical easement widths** vary from about 30m for 132kV lines to around 70m for a double circuit 500kV line.

Overhead transmission lines can be designed with more **aesthetic or compact structure**s. These include compact steel pole structures (see 275kv pole in *Figure 1*) or painted structures to better blend in with the local environment. Architecturally designed structures (e.g. T-pylons in *Figure 1*) can also be used. However, there are trade-offs in terms of additional cost, maintenance requirements and wider easements (where the structures are lower height with wider cross-arms).

Third party assets such as telecommunication facilities including antennas and repeaters can be co-located on transmission towers. Other non-metallic utility services including fibre optic telecommunication cables can also be installed on the transmission structures. These third party facilities are seen as providing additional potential benefits to communities.

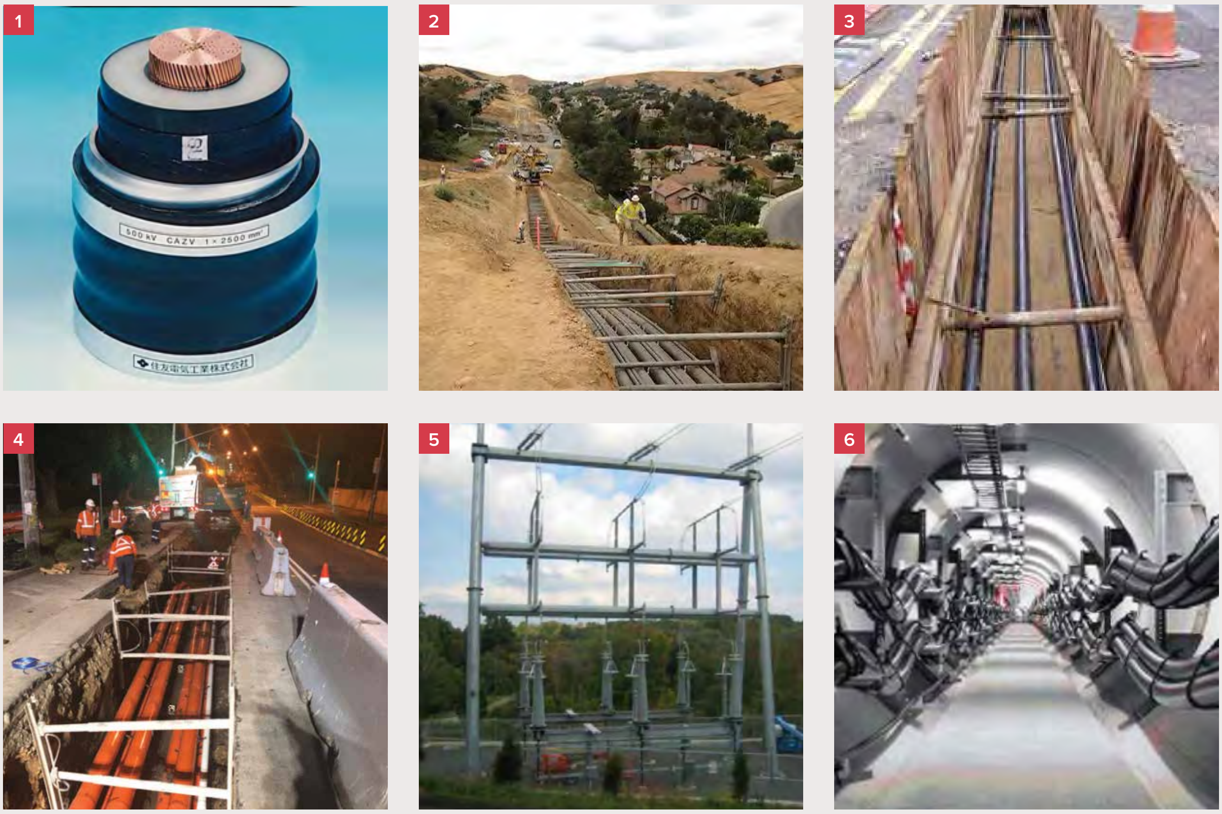
Metallic services or structures running parallel to a transmission line may be subject to induced voltages and currents which are a safety hazard and can also cause corrosion. In these situations, the design needs to be assessed for compliance with technical and safety standards.

2.2 HVAC Underground Cable Transmission

HVAC underground cable transmission infrastructure has primarily been used for short route sections where transmission lines need to traverse high density urban areas, areas where there is already a congestion of overhead lines or areas with environmental sensitivity or natural beauty. Typical underground cable transmission infrastructure is shown in *Figure 2*.

Cross linked polyethylene (XLPE) insulated cables is now the most common type of cable used in HV transmission, and was first widely used in the early 1980's (*Figure 2*). Each cable is one of a 3 phase set, and multiple 3 phase sets may be required to form a circuit depending on the power transfer requirement. The **conductors** used on underground transmission cables are predominantly copper because of the higher conductivity of copper compared to aluminium and its small cross-section required for the equivalent rating. For 500kV transmission cables, copper cross sectional areas of up to 2500mm^2 are common. These larger conductors result in less line losses compared to overhead lines. The cables can be designed to have integrated fibre optics which can be used for real time temperature sensing, with the benefit of increased power transfer capability.

A **technical limitation** with HVAC transmission cables is that feasible route lengths are relatively short compared to overhead lines, for example, of around 50km for 500kV. This is due to the significant charging currents and voltages associated with the highly capacitive HVAC cables. To counteract the resulting energy losses caused by this phenomenon, expensive reactive power compensation plant (e.g. shunt reactors) is required. XLPE cables are expected to have a service life of around 40 to 50 years.



1. 500kV XLPE cable (Sumitomo Electric)
2. 500kV cable installation (Southern Californian Edison)
3. 400kV direct buried cable (National Grid UK)
4. 330kV cable duct installation (Transgrid)
5. Overhead to underground transition station (Public Service Commission of Winconsin)
6. Cable tunnel installation (CIGRE 2017)

Figure 2. Examples of Underground Transmission Cable Infrastructure

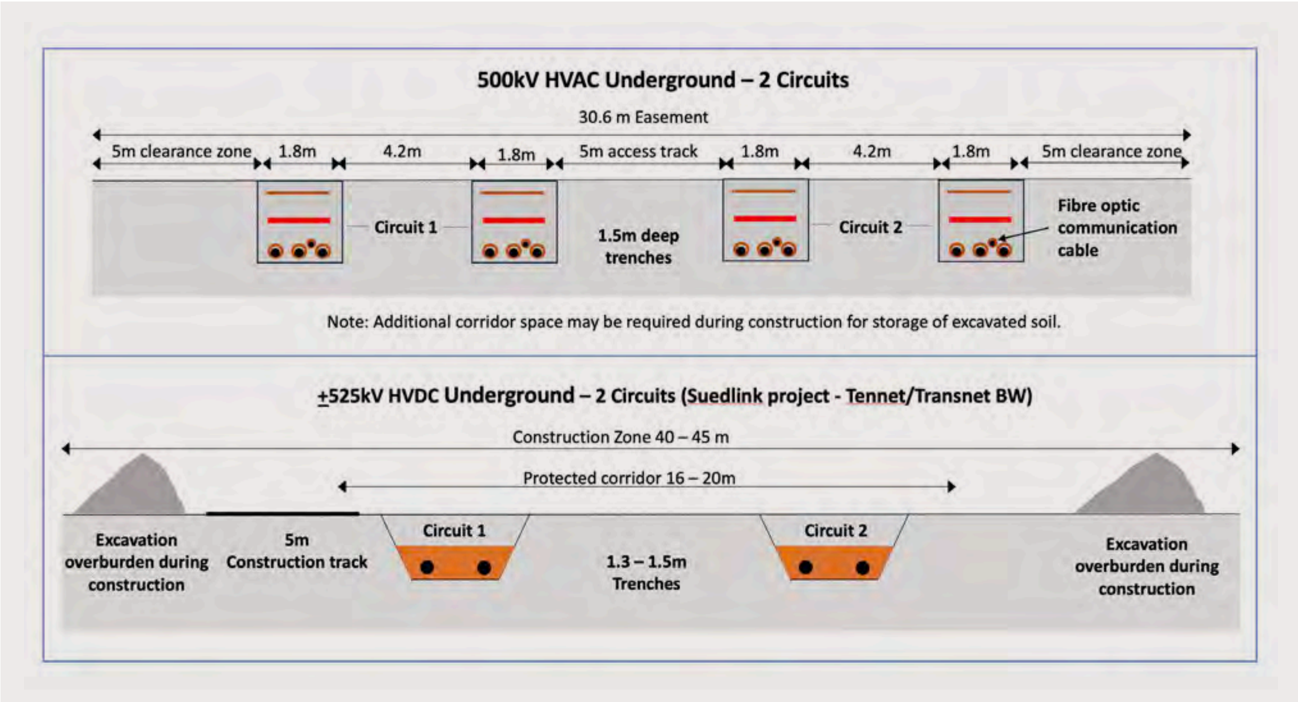


Figure 3. Examples of 2x2500MW 500kV HVAC and 2x2000MW +/-525kV HVDC underground cable installations

Cable Installation methods are also shown in *Figure 2*. Transmission cables are normally installed in **buried conduits or ducts** in trenches around 1.2m to 1.5m deep. Duct installation provides more flexibility during construction as it minimises the duration of when trenches are left open which can be a safety issue and cause inconvenience to local communities. Cables are pulled into the ducts in lengths that vary between around 500m up to 1000m depending on the route constraints. Each section of cable must be jointed to the next section using specially designed joints and installed by highly trained specialist tradespersons. A lower cost method of installation is the **direct buried** method. Cables are laid directly in an open trench which is back-filled upon completion. Cable trenches, whether with duct or direct buried cable, need to be backfilled with special stabilised material which has low thermal resistivity compared to normal soil to optimise power transfer ratings.

Typical trench layout and configuration for a 500kV HVAC double circuit underground transmission line is shown in *Figure 3*.

It is common for telecommunication cables including fibre optic cables to be installed in a transmission cable trench. The fibre optic cable can provide distributed temperature sensing of the cable and provide telecommunication services, such as operational protection and control systems associated with the transmission line. Similar to overhead transmission, in some cases, there may be opportunity for **third party assets** - telecommunication cables to also be installed, thereby providing additional community benefits. “However there are often trade-off’s for co-located third party assets due to safety and operational limitations in safely accessing the assets for maintenance.”

A section of underground cable which forms part of a hybrid transmission line requires a **transition station** at either end of the underground section. Cable terminations are connected to the overhead line at these stations. A typical overhead to underground transmission transition station is also shown in *Figure 2*.

In high density city centres or areas with other constraints limiting excavation, specially designed cable tunnel installations may be required [10] (see example in *Figure 2*).

2.3 HVDC Transmission

High voltage direct current (HVDC) transmission is an alternative technology to HVAC overhead and underground systems for high power transfer over very long distances. HVDC transmission can be either overhead or underground cable. The main advantages of HVDC are that it provides for:

(a) High transfer power capability over long distances with lower line losses compared to HVAC.
(b) Interconnections between asynchronous AC grids or grids operating at different frequencies, for example between two regions or countries;
(c) Long offshore or onshore cable connections where the route length exceeds the feasible or critical route length for a HVAC transmission cable of equivalent power transfer capability; and
(d) More compact infrastructure “foot-print” requiring narrower land corridors – this is due to less conductors or cables compared to the equivalent rated HVAC overhead or underground line.

An example of HVDC underground installation configuration compared an equivalent HVAC underground line is shown in *Figure 3*.

The main disadvantages of HVDC transmission are:

(a) Requirements for large and expensive AC/DC converter stations at terminal connection points to the main HVAC grid. For example the converter stations for the Suedlink project will occupy around 7 hectares [1];
(b) Additional system losses from converter stations;
(c) Limited capability for intermediate connections along a transmission route. Although multi-terminal HVDC transmission schemes are an option, the requirement for any additional converter stations along a transmission route, tends to limit the economic feasibility of intermediate connections;
(d) Noise levels from the equipment at converter stations can be an environmental issue [2]; and
(e) Additional measures to mitigate increased corrosion risk with DC systems.

There are two main types of converter technologies used for HVDC-transmission:

- Line-commutated converters (LCC) based on thyristors; and
- Voltage source converters (VSC) based on transistors.

VSC-based converters have become the most used technology in recent years, particularly for applications such as offshore wind farm connections and grid interconnections. LCC technology is mainly used for very high power transmission with ultra-high DC voltages (800 kV and above) and overhead DC lines [11].

In Australia, only a relatively small component of the transmission grid is HVDC. This includes: (1) Basslink submarine cable connecting the Tasmanian and mainland grids; (2) Directlink (Northern NSW); and (3) Murraylink (Vic to SA). In other parts of the world, such as Europe, America, and Asia, HVDC has been used extensively for inter-regional transmission connectors, and offshore / onshore renewable zone interconnections. The transmission grid serving the Australian eastern states and territories is characterised as one of the longest in the world with generation and bulk supply to customers dispersed along the grid. As a result, the drivers for long point to point inter-regional connectors which become more economic for HVDC have been minimal. This is in contrast to countries with much higher population, energy generation load densities.

2.4 Electromagnetic Fields (EMF)

Electromagnetic fields (EMF) is the term used to describe the combination of electric and magnetic fields that are generated by electrically energised or charged objects, including power lines, cables, appliances, and electronic devices. These fields are present everywhere in our environment, including the Earth’s natural magnetic field. There is much information available on EMF from many sources. Scientific research on the health effects of EMF from powerlines has occurred since the 1970s when concerns were first raised.

The electricity transmission and distribution industry in Australia has continued to monitor the scientific research, advice and guidelines from national and international organisations including Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), International Commission on Non-Ionizing Radiation Protection (ICNIRP), and the World Health

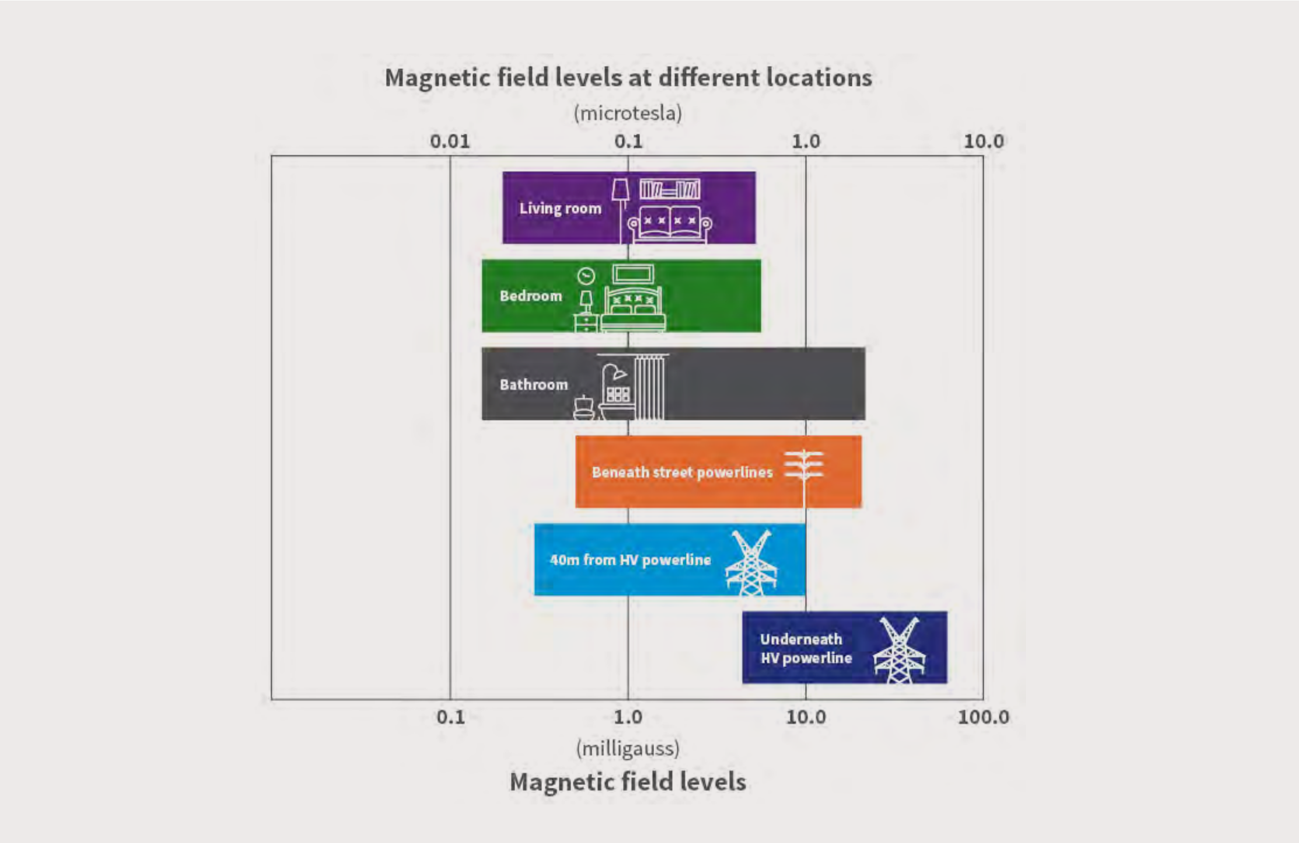


Figure 4. Comparison of Magnetic Fields from Household Appliances and Power Lines (ARPANSA4)

Organisation (WHO).

ARPANSA provides advice on its website[5] that:

"The scientific evidence does not establish that exposure to extremely low frequency (ELF) EMF found around the home, the office or near powerlines and other electrical sources is a hazard to human health".

ARPANSA provides a comparison of magnetic fields from typical household appliances and transmission and distribution lines in *Figure 4*.

Australian TNSPs broadly adopt the approaches recommended by Electricity Networks Australia (ENA) as outlined in their handbook [12]. This includes adopting the prudent avoidance approach, also known as the precautionary principle, which is a guiding principle used in the management and mitigation of EMF near power lines. It emphasises taking proactive measures to reduce exposure to EMF, even in the absence of conclusive scientific evidence of harm.

There are various measures that can be incorporated in the design of transmission lines to mitigate or reduce EMF field levels. Most measures involve some trade-offs, but the cost of doing so is not usually significant. Such measures include (a) increasing the height of overhead conductors, (b) reducing conductor/cable spacing, and (c) transposition arrangement of phase conductor/ cables in a double circuit line to have a cancelling effect.

[4] https://www.arpansa.gov.au/understanding-radiation/radiation-sources/more-radiation-sources/electricity
[5] Source: ARPANSA Electricity and Health, ARPANSA Extremely Low Frequency Electric and Magnetic Fields (www.arpansa.gov.au)

2.5 Comparison of Technical Performance of Overhead and Underground Transmission

A comparison of the key technical and performance factors for overhead and underground transmission is provided in *Table 2*.

Table 2. Comparison of Technical Performance Factors of Overhead and Underground Transmission

Factor	HVAC Overhead Transmission	HVAC Underground Cable	HVDC Transmission
Feasible maximum line route lengths	Overhead transmission lines can traverse long routes up to around 1000km.	500kV – 40 to 50km	Route lengths greater than 1000km are possible.
Auxiliary plant requirements	Overhead lines require less reactive compensation plant (per km) compared to underground cables	Reactive compensation plant such as shunt at termination points are required for underground transmission to counteract the more significant capacitive effects of cables compared to an overhead line	Reactive plant not applicable. HVDC converter stations are required at terminal points of the line.
Power Transfer Capacity	500kV - 2000 MW to 3000 MW per circuit	500kV – Up to 2500MW per circuit is feasible using multiple 2500mm^2 copper conductor XLPE cables	Typically, less than equivalent rated HVAC overhead or underground lines.
Corridor and easements	500kV double circuit - 70m	500kV double circuit - 30m to 35m Additional land requirements for overhead to underground transition stations must also be considered.	Typically, less than equivalent rated HVAC overhead or underground lines.
EMF (Electro Magnetic Fields	Magnetic field levels are maximum under the centreline of the transmission line and decrease less gradually with distance from the line compared to an underground line. Transmission lines are designed to meet industry compliance limits within the corridor. Electric fields are emitted from overhead lines, but lines are designed to be within compliance limits.	Magnetic field levels are above the centreline of the underground transmission line and decrease more rapidly with distance from the line compared to an overhead line. Electric field are contained within a cable with outer earth bonded metallic sheath.	DC magnetic fields are static and subject to higher reference limits (i.e., less onerous) compared to AC. **Overhead** - DC electric fields are static and subject to higher reference limits (i.e., less onerous) compared to AC. **Underground** - Electric field are contained within a cable with outer earth bonded metallic sheath. Design measures to ensure compliance with standard limits are applied.

Factor	HVAC Overhead Transmission	HVAC Underground Cable	HVDC Transmission
Reliability performance	Reliability of performance (typical forced outage rate of 0.5 to 1.0 per 100 km/ year) Structural failures (for Australia, failure rate is around 1 in 150,000 per annum - CIGRE 2010 [13]) Overhead lines are exposed to severe weather including lightning strikes. Repair time for faults is much shorter duration compared to underground.	For XLPE cables outage rates are typically less than 1 outage /100km/year and lower than equivalent overhead lines. Repair time for underground cable faults are longer duration than overhead lines due to excavation, cable jointing and electrical testing work required e.g., up to 4 weeks. [14]	Not Assessed in this study but would tend to be similar to HVAC overhead and underground given similar hardware and constructions.
Audible noise	Audible noise can sometimes be emitted from overhead transmission lines due to wind effects and (2) a corona discharge. However, these issues are addressed through appropriate design and maintenance.	No audible noise.	**Overhead** – similar to HVAC is dependent on voltage and size of conductors. Design measures are applied to ensure noise levels are within compliance limits. **Underground** – No Audible noise **HVDC converter stations** – noise will occur. This needs to be considered in the design and location of converter stations in order to minimise impact.
Construction timeframes	500kV double circuit, 100km 2 years	500kV double circuit, 50km 3-4 years	Similar to HVAC Overhead and Underground
Expected service life	60 to 80 years	40 – 50 years for XLPE cables	Similar to HVAC Overhead and Underground

3.

Economic Aspects

There have been many studies by government bodies, TNSP's, industry organisations and stakeholders comparing the cost of overhead and underground cable transmission infrastructure either generally or for a specific project. The UK Parson Brinkerhoff transmission costing study [3] is often referred to in the industry for its methodology when evaluating lifetime costs. This study concluded *"Cost ratios are volatile, and no single cost ratio comparing overhead line costs with those of another technology adequately conveys the costs of the different technologies on a given project. Use of financial cost comparisons, rather than cost ratios, are thus recommended when making investment decisions.*

HVAC Transmission - the cost ratio of HVAC underground to overhead transmission based on published literature including Parsons Brinkerhoff [3] and AEMO [4], are generally in the range of 3 to 20 depending upon many specific factors in a project. It is difficult to get accurate cost estimates for 500kV HVAC transmission infrastructure in Australia due to the lack of recent projects at this voltage, as well as current global and local economic factors influencing the cost and availability of resources. A lower cost ratio of 3 to 5, for example would tend to apply for the lowest cost option of direct buried underground, or long cable routes (with better economies of scale). A ratio of 5 to 10 would correspond to higher cost options of cable in ducts or for shorter lengths of underground cable. A higher ratio of 10 to 20 would tend to apply to more expensive cable tunnel installations.

HVDC Transmission generally becomes more economic for longer route interconnector transmission lines. HVDC overhead and underground lines are generally lower cost per km to construct compared to equivalent rated HVAC, but the significant costs of AC/DC converter terminal stations must be included in the total project cost. There is a "break even distance" for the cost of HVDC versus HVAC transmission. This is illustrated in the diagram by Stan et al., in Figure 5 [15]. The "break even distance" will depend on project specific parameters such as power transfer capacity, number of circuits, system voltage, converter technology, installation conditions and environmental factors. As an indication, based on data from Acaroğlu

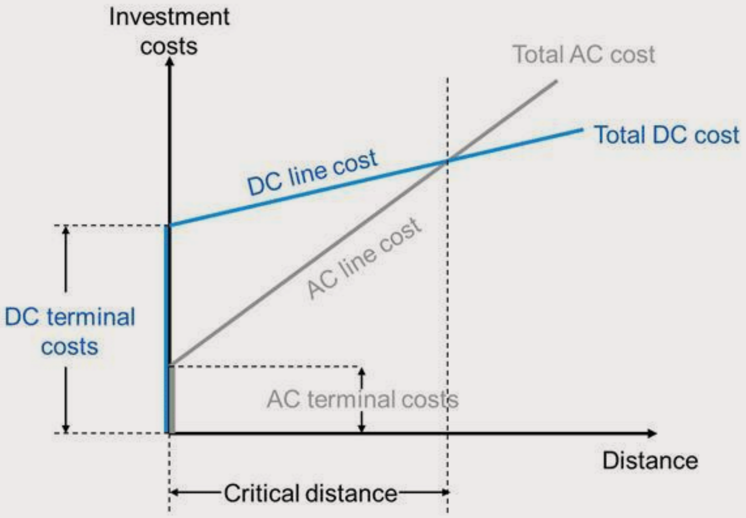


Figure 5. HVDC Transmission Line Economics (Stan et al [15])

et al [5], ABB [6], Amplitude Consultants [7], and the AEMO Transmission Cost Database, the break-even distance for HVDC overhead transmission is around 600 to 700 km when compared to a 500kV HVAC line. The cost ratio of HVDC underground to HVDC overhead is around 5, and the cost ratio of HVDC underground to HVAC overhead was 3.3 for a 1500MW, 1000km case study [5]. The Suedlink 2 x 2000MW 700km underground HVDC project in Germany is currently estimated to cost €11B EUR (2022) ($18.3B AUD) which is approximately $26.2M AUD per km.

The economic feasibility for application of HVDC compared to HVAC, ultimately depends on project specific requirements, factors and constraints which determine whether HVDC should be considered. Regulatory investment test requirements also need to be satisfied.

Current Challenges - There is no doubt that transmission infrastructure projects are facing several challenges as a result of global, national and local factors. For example, internationally, many countries have similar large scale grid expansion programs linked to renewable energy targets and will be competing for many of the same material and labour resources required in Australia.

Reports published by Infrastructure Australia [16] and AEMO [17] highlight additional challenges including:

- Demand driven risks having increased over the last 12 months
- Supply side risks have surged in 2021-22 and continue (COVID-19, Ukraine War, labour shortages)
- Increasing project costs and complexities
- The market is arguably at capacity, so project slippage is now expected
- Availability of skilled labour resources in the energy industry
- Delays in gaining approvals due to social licence issues and other factors which tend to exacerbate the cost challenges.

These issues have also been recognised in the recent recommendations from the UK's Electricity Networks Commissioner, *Nick Winser*[5]. In response to similar challenges the Commissioner made a number of recommendations to speed up the deployment of transmission infrastructure. Notable was to reduce the time for commissioning from twelve to fourteen years by half to reduce the burden of costs for society.

[5] Accelerating electricity transmission network deployment: Electricity Networks Commissioner's recommendations - GOV.UK (www.gov.uk)

4.

Environmental Aspects

The body of knowledge regarding overhead transmission line impacts on biodiversity has clearly grown over the years. However, while context dependent, it mainly points to overall negative impacts. Despite this, the quantification of the size, pathways and details of such impacts are still not well known. This shortcoming is reflected throughout the literature, with existing research largely failing to address cumulative impacts of transmission projects (combined with renewable energy projects), or pre- and post-installation impacts.

4.1 Potential Impacts and Mitigation

It is well documented that transmission lines can act as a physical barrier hindering movement across and along them for some animals. This is usually as a result of vegetation clearance for the required easements (overhead and underground) along with the physical presence (size, shape etc.) of transmission lines and towers. Such an effect can start as early as the construction phase and last throughout operation and decommissioning [18]. Mitigation measures proposed in the literature for overhead lines include the use of coloured line markers, different tower designs, and sounds to scare the birds away. [19]. On the flipside, one of the most recognised benefits of transmission lines for biodiversity is the use of the infrastructure itself, as a resource. Transmission towers provide a tall, permanent structure, mostly free of human interaction which makes them suitable for birds to perch, rest, hunt and nest.

Habitat loss and fragmentation are other key negative outcomes of the construction of transmission lines on the natural environment. The degree of fragmentation will depend upon the transmission voltage, the associated easement width, the type of tower for overhead transmission (lattice, tubular….), and the transmission infrastructure within the landscape, and their location within the landscape. [20]. Impacts can occur with mammals, birds, and amphibians due to altered movement patterns, isolation, and changes in population.

The clearing of vegetation for easements needed for the construction of both overhead and underground lines is likely to have a significant impact on wildlife habitats as well as cause changes in the microclimate by restricting the growth of plants and trees. Associated species including insects, birds and other mammals will thus experience secondary impacts as a result of these changes. However, the review reported mostly positive impacts being established within easements for overhead transmission, mainly because the sites under towers are often undisturbed for extended periods of time facilitating seed dispersal and plant development, being below bird perching sites, increasing biodiversity abundance. Where transmission lines are constructed in highly sensitive natural environments including watercourses, wetlands and national parks, special attention is required as any biodiversity effects would likely be heightened.

The generation of electromagnetic fields and noise from transmission lines, particularly overhead lines, has the potential to disrupt not only local communities when constructed near populated areas, but also the behaviour and health of some species including bats and pollinators. Knowledge on the extent of these impacts is less developed than other areas. However, it is an important factor to consider, given the significant role these species can play in an area's overall biodiversity and environmental stability.

Both underground and overhead options share some similar environmental costs although they each bear unique opportunities for positive outcomes when utilised in suitable areas. For example, while overhead lines are likely to create a barrier effect, causing changes in bird migration patterns as a result of collision and avoidance of the transmission lines, the selection of underground transmission cables in some areas would be able to somewhat mitigate this cost. In contrast, despite the high likelihood of soil degradation and hydrological alterations throughout the lifetime of underground HVAC lines, these impacts tend to only occur during the construction of overhead lines and so are much less significant for overhead transmission lines.

In this light, conducting due diligence into what is the most effective approach for each environment as part of the formal *Environmental Impact Assessment* can help to mitigate the overall negative impacts of a project. This includes understanding the geographical context to provide insights into the surrounding ecosystem and how exactly local flora and fauna will likely respond to the new transmission infrastructure. One example of this approach being beneficial comes from habitat conversion whereby a close understanding of the area being cleared has the opportunity to provide new significant ecosystems for a variety of species. However, to be successful, management practices that are tailored to the local context are required. A context dependent approach opens the opportunity for a more holistic attitude towards the environmental impact of a project. In this light, stakeholders understand not just how different aspects of the environment are affected, but how these aspects interact with one another to see the overall impact of a project.

Beyond the direct effect of transmission lines on the natural environment, projects must also consider how their construction is likely to impact archaeological and cultural heritage of the surrounding area. Given the potential impacts and the lack of literature predicting these effects, minimising and understanding the effects of a transmission line project must be a key priority in any new transmission line project's planning stage. The lack of studies considering the environmental impacts through an Indigenous lens and utilising traditional knowledge is a gap in the literature and more work in this area will provide a valuable perspective and understanding of other dimensions of environmental impacts.

4.2 Environment Impact Processes

Hand in hand with environmental impacts is the need for an Environmental Impact Assessment (EIA) - an essential and critical stakeholder engagement activity forming part of the approval process for a transmission project. The purpose of an environmental impact assessment is to systematically evaluate and understand the potential environmental, social, cultural and economic impacts associated with the construction and on-going operation of a project. The triggers, requirements and process for EIA's are stipulated in legislation which is generally similar in principle around the world.

The **Federal Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)**[6] and regulations are Australia's main environmental law. It provides a regulatory framework to protect and manage matters of national environmental significance including unique plants, animals, habitats and places. These include heritage sites, marine areas and some wetlands. The Act also protects listed threatened and migratory species [21]. It requires detailed assessments and surveys with a typical timeframe to complete the process being approximately two years.

The Queensland **Environmental Protection Act 1994**[7] is the key legislation in Queensland to manage and regulate environmental protection and conservation. Its primary purpose is to safeguard Queensland's natural environment, including land, air, water, and biodiversity. Environmental Impact Statements (EIS) is a key element of the Environmental Protection Act and is applied to evaluate and assess the potential environmental impacts of proposed activities, developments, or projects.

To streamline the process and avoid duplication between Federal and State regulatory processes, the Australian government and state governments, including Queensland, can enter into **bilateral agreements**. These agreements aim to harmonise and integrate the environmental assessment and approval processes between the Commonwealth (EPBC Act) and the state (Queensland's environmental legislation). In Queensland, the bilateral agreement applies to proposals that are 'controlled actions' requiring assessment under Part 8 of the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). Controlled actions are defined in Section 75 of the EPBC Act. They include actions that are likely to have a significant impact on a matter of national environmental significance, or that involve a change in the population, distribution, or migration of a listed migratory species.

An EIA for a transmission project covers a range of factors and impacts that may arise during the design, construction, operation, or maintenance of the infrastructure including:

- project need, justification and feasibility, and any alternatives that have been considered
- a review of the planning laws and approvals which are relevant to the proposed infrastructure
- environmental considerations including the existing environment and any potential impact on factors such as biodiversity, flora, fauna, air quality, noise, waterways, vegetation, and soils
- matters of environmental significance in the area
- transport and traffic
- bushfire risk
- health and safety
- land use
- social considerations
- economic considerations including benefits such as local jobs
- current and future land use

[6] Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) - DCCEEW (www.dcceew.gov.au/environment/epbc)
[7] Environmental Protection Act 1994 - Queensland Legislation - Queensland Government (www.legislation.qld.gov.au/view/html/inforce/current/act-1994-062)

- visual amenity
- electric and magnetic fields
- cultural heritage – indigenous and non-indigenous
- the community and stakeholder engagement and consultation process
- the location of other infrastructure and industry
- the actions the proponent will take to manage and minimise environmental and social impacts that may result from the design, construction, operation, or maintenance of the new infrastructure.

For a transmission line project, the process starts with early engagement of key stakeholders to develop alternative solutions including route corridor options to inform the draft Terms of Reference for the environmental impact assessment. The regulatory requirements for environmental impact assessment process typically include the following formal stages[8]

1. Submission of a draft Terms of Reference (ToR)
2. Publication notification of a draft (ToR)
3. Final ToR issue – EIS in preparation
4. Public notification of EIS
5. Proponent responds to submissions
6. EIS Assessment report

[8] Types of EIS | Environment, land and water | Queensland Government (www.qld.gov.au)

5.

Social and Cultural Aspects

There is a large body of research that identifies frameworks that describe the key factors influencing a social licence and acceptance of transmission projects. All these factors are currently being observed in local community opposition to the proposed transmission projects in NSW and Victoria, resulting in significant project delays along with increased angst for the individuals involved. The weight of public concerns cluster around issues of **procedural justice** (is the process fair and transparent) and **distributive justice** (are the project benefits distributed fairly), as well as **trust** in the project developer. This clearly demonstrates that the public's response to transmission projects extends well beyond the physical features of the technology.

The literature also highlights that whether an individual feels positively or negatively towards a project and how they evaluate the balance of costs, risks and benefits will also affect their willingness to accept or tolerate it. Additionally, research by Devine-Wright, [22], [23], [24] suggests that rather than a "Not in my Back Yard" (NIMBY) response to a project, it is an individual's strength of **place attachment** (length of time in the place) and **place identity**, that if threatened by impending changes in their area, will influence their response to a project.

Regardless, public opinion is not static and the public's attitudes and responses will continue to be influenced by project related events throughout its life, but once formed can be difficult to change. This is particularly important in the context of the Australian cases, where opposition will likely travel across states, based on the shared identities of local land holders and communities, rather than solely on the techno-economic project properties.

5.1 Factors Influencing Social Licence and Acceptance

Given that each site has its own unique characteristics, the **context** in which a project occurs is very relevant to the social and cultural considerations of a project. Context considerations include not only on what has happened to that community in the past (either positive or negative) but also what is happening in the present along with the reputation and performance of the project developer. How the distribution of benefit and burden is perceived, is at the heart of distributive justice considerations. That is, it is often local host individuals and communities in **close proximity** to transmission infrastructure who bear the major burdens (**visual impacts, potential loss of livelihoods**, impacts on **property values**; **loss of tourism** etc.) and risks of projects (**human health** including concerns about EMF and noise impacts) while benefits are often realised far away in cities, or even globally when it comes to emissions reduction. To overcome the likely negative reaction to projects, **compensation** has been an important factor in positively influencing local host acceptance. This includes the expectation that neighbours are also included in considerations of compensation to ensure fairness in the process. Balancing individual and collective compensation will also influence acceptance of projects.

However, it is never solely about the financial incentives. Individual values strongly influence attitudes towards a project and ultimately its acceptance - the more open, transparent and just project processes are - will significantly help to build trust in the project developer. The literature was clear, trust in all entities and individuals, involved formally or informally in the process, effect overall acceptance. Other requirements included the need for adequate **information and knowledge sharing**, and the presence of good **governance** mechanisms to minimise any potential risks arising from projects and ensure adequate **engagement** and consultation.

Similarly, if the process of engagement has not been seen to be respectful, fair, and transparent then it is unlikely any amount of compensation will guarantee project progress. This was evidenced in the current Australian transmission projects where the *speed of delivery and the need to build a lot* has caused concerns for many stakeholders. For example, with the Humelink project, landholders complained about a lack of transparency around the proposed routes, with only those landholders who fell directly into the proposed route being first engaged. This meant there was limited information about what the project was about for the wider community. It resulted in complaints about the limited time to subsequently learn and engage with the project once it became more widely known and alternative routes were proposed. There was also a feeling that with the route selection already decided, it was a fait accompli and there was limited opportunity to provide any meaningful input into the selection despite their local knowledge.

Constraint mapping is an essential tool for transmission experts when route planning. Common constraint considerations include cultural heritage, endangered species, areas of environmental significance, population density, existing land use and so forth and are well documented in the CIGRE Report 147 [25]. A mix of qualitative and quantitative assessment is then undertaken to identify the most preferred routes. The list of constraints are usually shared with communities to build transparency in the siting process but also to identify if there are any additional local constraints that may have been overlooked by the proponent and need to be included in the constraint mapping exercise. To help build support for the final outcome, undertaking a weighting exercise, that brings together community and proponent preferences will help reach agreement on the preferred priorities for siting. While such processes can be exacerbated by individual preferences and values, such rigor goes some way in helping to gain broad community support for the final route selection 147 [25] p.26.

5.2 First Peoples' Impacts

The implementation of transmission line projects in Australia will also bring proponents and government, and in some locations, other stakeholders, into contact with First Peoples. First Peoples are fundamental rights-holders in many locations in Australia with approximately 60% of mainland Australia expected to soon be managed or jointly-managed by First Peoples. While transmission projects may impact First Peoples in ways similar to other groups of rights-holders and stakeholders, very little time and effort have been invested in understanding the impacts upon First Peoples. This is a substantial knowledge gap, given the typically marginalised status of First Peoples, and the situation-specific character of their connections to the world around them.

First Peoples may be impacted by transmission line projects in ways that differ to other rights-holders and stakeholder groups, as a result of fundamental differences in the perspectives, attitudes, responsibilities and behaviours of First Peoples individuals, groups and Communities to the wider Australian community. These may include:

- *Loss of species of cultural significance and important for subsistence,*
- *Compromising intangible sites* of cultural significance,
- *Degradation or destruction of tangible sites* of cultural significance,
- *Visual disruption* of the night sky,
- *Ecological impacts* associated with these losses rendering First Peoples unable to meet their cultural, social and personal responsibilities,
- *Social and personal health and wellbeing impacts and costs* associated with individual and collective losses that leave First Peoples unable to meet the social and personal cultural responsibilities
- *The weaving of transmission lines into contemporary stories and Songlines*
- *Declining opportunities for self-determination*, which exacerbate existing marginalisation of First Peoples as individuals and Communities.

Unlike planning to avoid health impacts where in most cases the application of prudent avoidance can be implemented without the need for a specific assessment, cases where First Peoples are potentially impacted will require comprehensive assessment of the tangible and intangible aspects of Country.

5.3 Principles for Collaboration and Engagement

Illustrating the importance of gaining social licence and acceptance, there are a multitude of guidelines that exist in Australia for engaging with communities on transmission and energy projects, with many more emerging. For example, the Queensland Farmers' Federation recently released their Renewable Energy Toolkit; The Energy Charter, The Landholder and Community Better Practice Engagement Guide which underpins their Better Practice Social Licence Guideline; and the Energy Grid Alliance, and Acquiring Social Licence for Electricity Transmission: A Best Practice Approach to Electricity Transmission Infrastructure Development. Internationally, the Renewables Grid Initiative provides a wealth of resources (videos, fact sheets etc.) and publications, that explain impacts and trade-offs for transmission infrastructure projects.

The First Nations Clean Energy Network *Best Practice Principles for Clean Energy Projects*[9] provides useful guidance for transmission line project proponents. They are not dissimilar to the social licence and acceptance

[9] Accessed from: https://www.firstnationscleanenergy.org.au/

factors for engagement and are intended to help ensure projects provide economic and social benefits and ensure Free, Prior and Informed Consent (FPIC) is secured for First Peoples as rights-holders, for the activities conducted. The 10 Principles are: “Engage respectfully; Prioritise clear, accessible and accurate information; Ensure cultural heritage is preserved and protected; Protect Country and environment; Be a good neighbour; Ensure economic benefits are shared; Provide social benefits for Community; Embed land stewardship; Ensure cultural competency; and Implement, monitor and report back.”

Already reflecting some of these principles, *Table 3* summarises the key recommendations for stakeholder engagement from CIGRE, 2017 [26] and enhances these with additional contributions from the PRISMA review.

[9] Accessed from: https://www.firstnationscleanenergy.org.au/

Table 3. Merging CIGRE, 2017 [26] Engagement Principles and Systematic Review Findings

Principles as per (CIGRE, 2017)	(CIGRE, 2017) - Recommendation	Enhanced Principles	Additional contribution from the PRISMA literature review
Approach to stakeholder relationships	Stakeholder engagement processes should be consistent and aim to build trust.	Approach to developing relationships	Highlights that consistency in collaborative protocols and processes across industry and economic sectors, combined with coordinated and efficient processes, can help to reduce engagement fatigue and frustration. Thus, improving the quality of the process for host communities, rights-holders, and the broader public.
Project scoping (Proportional approach)	The scope of stakeholder engagement for each project stage, must be defined including its objectives, constraints and limitations.	Project scoping (Proportional approach)	To minimise the contestation of the need for new OHTL and avoid compromising First Peoples' and other stakeholders' rights, early collaboration and engagement at the electricity system planning level is required.
Stakeholder identification	The stakeholder mapping and selection process needs to be consistent. Local stakeholders including those with specific community interests and those difficult to reach need to be specifically targeted. The engagement also needs to reflect an understanding of stakeholders' requirements and preferences.	Rights-holder and stakeholder identification	Culturally appropriate dialogue and clear communication of stakeholder and rights-holder mapping and selection processes is an integral part of the relationship building and engagement processes.
Start engagement early	Early engagement, i.e. during the formative stage, is valuable for knowledge creation including for subsequent engagement and for establishing the integration of stakeholders' input into routing and design.	Start collaboration and engagement early	The literature goes further and advocates for rights-holder and stakeholder collaboration at electricity system level planning and potentially even earlier when planning the transition to a low carbon economy. However, this is outside the scope of transmission company remits. Collaboration should ideally begin prior to the conceptualisation of a project.
Targeted mix of consultation/ engagement methods	Engagement methods need to be tailored to their targets and allow for regular engagement. A dedicated community liaison representative is suggested.	Targeted mix of methods for building relationships and engagement	Amongst other challenges, collaboration and engagement processes need to account for individual and community willingness and capacity to engage with the complexity of the electricity system and its governance, as well as the process more broadly. The literature emphasises the value of a single point of contact for stakeholders and rights-holders which can contribute to a more fair and just process.

Principles as per (CIGRE, 2017)	(CIGRE, 2017) - Recommendation	Enhanced Principles	Additional contribution from the PRISMA literature review
Create an open and transparent process	The scope of the engagement is transparent at each stage of the project and broadly communicated.	Create an open and transparent process	Transparency of the collaborative process and quality information provision contributes to procedural fairness and building trust.
Provide feedback to stakeholders (Monitor and evaluate)	A clear and transparent process is established to demonstrate and communicate how stakeholders' input was integrated into the project and provide rationale for inclusion and exclusion.	Provide feedback to rights-holders and stakeholders (Monitor and evaluate)	The literature shows that this step is amongst the most important, if not the most important, for building trust and fostering subsequent constructive engagement and participation.
Engagement should be proactive and meaningful	For engagement to be meaningful, it needs to have influence on the project outcomes. As such the scope of influence need to be clear and clearly communicated. Engagement should be proactive, accessible and inclusive.	Collaboration and engagement should be proactive and meaningful	Meaningful relationship building is paramount. Acknowledging that full consensus is unlikely to be reached even with best practice public engagement. Having a clear picture of "good enough" consensus and communicating it upfront improves transparency and perceptions of fairness.

6.

Case Studies

6.1 Current Australian NEM Project Stakeholder Engagements

The related factors necessary for achieving social licence and acceptance are highlighted and reinforced in the current Australian 500kV projects: Humelink (NSW), VNI West (Vic) and Western Renewables Link (Vic). A key finding from all three is the importance of recognising the context, both historical and current, in which the project is occurring.

Noting that project proposals and announcements, technology type, levels of communication and engagement, host individual and communities' knowledge and awareness of the technology, will influence the context and how the project is perceived. There were multiple findings from across the three projects. Key findings and observations include:

- The need to have clear justification for route selection, why the decision was made and to provide enough time for community members to understand the implications of the proposal.
- A sentiment by host communities in all three projects was that project coordinators were quite dismissive of the topic of undergrounding, including their sentiment regarding the long-term advantages of underground transmission. Many in host communities argued that the initial cost and time investment of undergrounding would be far outweighed by the significant benefits it offers.
- Community Consultant Groups were established to improve the dialogue between project proponents and local stakeholders.
- A lack of leadership at the local level, in some instances, meant that decisions were delayed and without clear communication, led to misinformation being introduced into the community.
- Indigenous groups raised concerns around construction ground disturbance directly disturbing and destroying archaeological artifacts and structures, along with vegetation clearance removing the protective cover and concealment of archaeological sites that could impede the ability to effectively protect the site during a fire.
- The proponents, sought expressions of interest for cultural heritage surveys which have now been conducted in collaboration with Registered Aboriginal Parties, providing valuable insights for assessing impacts and implementing appropriate mitigation measures.
- Impacts on health and safety included concerns about increased mental health and wellbeing - coupled to this were examples of engagement fatigue where people were being asked to engage in multiple processes, not only for transmission line projects but also renewable energy projects.
- The potential for increased bushfire risks was also raised as both a health and safety and environmental concern, in particular transmission lines hindering effective bushfire responses therefore increasing their risk of exposure in the case of a fire.
- There were significant concerns raised around the impacts on land use and property values including increased traffic on local roads, decreased tourism in some areas, impacts on farming operations and access.
- Alternative transmission technologies such as HVDC or hybrid HVAC and HVDC networks are being promoted by some stakeholder and advocacy organisations.
- A NSW parliamentary inquiry on undergrounding released its report in late August 2023, recommending that Humelink should proceed as an overhead transmission project. While Powerlink Queensland is progressing the Borumba Pumped Hydro Connection and Copperstring 2032, given the infancy of these projects when the review was undertaken, they were not included as case studies.
- September 13, a further Inquiry by a Select Committee in NSW was announced and their findings are expected in March 2024.

6.2 International Case Studies

The six case studies are projects that have been completed or are currently in construction and include five overseas projects and one Australian project. The projects involve 400 and 500 kV HVAC overhead and underground, 330kV HVAC underground and one HVDC transmission project. Key findings include the importance of extensive community and stakeholder consultation, with on-going engagement undertaken to gain approval and minimise the risk of project delays and opposition. For example, the National Grid UK's document - the Preliminary Environmental Impact Assessment (PEIA) set out the preferred route, explained their methodology and identified the likely impact of the proposals on the environment from the beginning. This transparent approach was deemed by the proponent to help minimise opposition to the project.

Other factors that were considered to influence project success included the use of aesthetic overhead transmission line structures combined in some cases with the need for underground sections to be installed. The Hinkley Point Connection Project (UK) involved the replacement of an existing 132 kV lattice steel tower line with new aesthetic 400kV T-Pylon structures. The community had become used to the existing transmission line and the new structures were designed to be more aesthetically pleasing. In the case of the UK T-Pylons and in the Danish case, Thor-gi tubular steel structures were used; which are more compact with a lower height compared to traditional steel lattice towers for the same system voltage. The downside of these structures, however, is the greater width of the structures and larger easement requirements and land-use restrictions. Additionally, the proponents were prepared to underground 8.5 km of the route in an area, because it was recognised as an area of natural beauty. Case studies from Denmark (400kV) and California (500kV) also demonstrated the need for underground sections; ranging from 5.6km to 26km respectively. The rationale for underground sections were in response to community concerns, or political / regulatory interventions.

Appropriate compensation was also deemed a critical facilitator, particularly to farmers and landholders. For example, in Denmark the company, Energinet, established an agreement with the farmers' organisation on how to compensate farmers and landowners if overhead lines or underground cables are located on their property. Landowners adjacent to line were also eligible for compensation based on a proximity distance criteria scale.

The Powering Sydney's Future project is a 20km long 330kV underground cable transmission line, linking major substations in a heavily populated urban environment. The case study provides perspectives on managing a project that has significant impacts during the construction phase, affecting many diverse communities, major roads and local businesses.

The case study of the Baleh-Mapai 500kV transmission line in Sarawak involves a double circuit overhead line traversing 177km of mainly rural and remnant forest areas. The case study provides an overview of the project's detailed Environmental and Social Impact Assessment and stakeholder engagements with affected communities.

7.

Conclusions

1.

There is no doubt that transmission infrastructure projects are facing several challenges because of global and national factors. Reports published by Infrastructure Australia [16] and AEMO [17] highlight challenges such as:

- Demand driven risks have increased over the last 12 months.
- Supply side risks have surged in 2021-22 (COVID-19, Ukraine War, labour shortages)
- Increasing project costs and complexities
- The market is arguably at capacity, so project slippage is now expected.
- Availability of skilled labour resources in the energy industry
- Internationally, many countries have similar large scale grid expansion programs linked to renewable energy targets and requiring the same material and labour resources.
- Delays in gaining approvals due to social licence issues and other factors tend to exacerbate the cost challenges.

2.

HVAC underground cable transmission is feasible only for relatively short route lengths e.g. around 50km for 500kV. This is due to the high electrical capacitance of transmission cables which requires expensive reactive power compensation plant (e.g. shunt reactors) to counteract the resulting transmission impacts from this phenomenon.

3.

Case studies involving 400 to 500kV HVAC transmission lines in UK, Europe and USA demonstrated that to gain public acceptance and obtain regulatory approvals, undergrounding some short sections ranging from 5 to 20km was necessary in certain locations e.g. urban areas, areas with a congestion of existing overhead infrastructure, and areas of environmental significance or natural beauty. Visual impact was the main influencing factor. However, the picture is far more complex, as overhead and underground impacts and trade-offs require high levels of contextualised understanding and consultation with all stakeholders in order to potentially lead to social acceptance.

4.

It is difficult to get accurate cost estimates for 500kV HVAC transmission infrastructure in Australia due to the lack of recent projects at this voltage, as well as current global and local economic factors influencing the cost and availability of resources. The comparative cost ratio of underground to overhead construction is reported to vary from 3 to 20 depending on the type of construction, route length and other project specific factors [3], [4]. A lower cost ratio of 3 to 5, for example would tend to apply for the lowest cost option of direct buried underground, or long cable routes (with better economies of scale). A ratio of 5 to 10 would correspond to higher cost options of cable in ducts or for shorter lengths of underground cable. A higher ratio of 10 to 20 would tend to apply to more expensive cable tunnel installations.

5.

HVDC can be a feasible alternative to HVAC transmission for specific applications requiring high power transfer capacity over very long route lengths (i.e. several hundred kms depending on power transfer) that are point to point without intermediate connections. The economic feasibility for application of HVDC compared to HVAC, ultimately depends on project specific requirements including construction and environmental factors which determine whether HVDC should be considered. Regulatory investment test requirements also need to be satisfied.

6.

While TNSP's use constraint mapping internally to inform their route selection which includes checking in with the community that they have not overlooked local constraints, there is an opportunity to improve overall buy in for the final route selection by involving the community in weighting the importance of each of the constraints at the early planning stages and creating agreement for prioritising the various constraints. This can build community ownership of the final decision and ultimately minimise overall opposition to the project.

7.

There is a need for more consistent public education and information which explains in plain language: (1) Why we need to build more transmission infrastructure; (2) What HVAC and HVDC transmission infrastructure is; and (3) How transmission costs will be reflected in state capital borrowings and electricity bills – more transparent conversations around this at both the federal and state level should help increase the public's understanding of the trade-offs required.

8.

Context specific considerations also includes First Nations People and ensuring adequate engagement and collaboration with Traditional Custodians is in place from the start – the First Nations Clean Energy Network have published principles for engagement which provide an excellent basis for informing these processes.

9.

While there is an urgency to have projects built, stakeholders are requesting more time to understand the implications of the project. This suggests proponents need to build some flexibility into the project timeline and see it as an investment in the final outcome – the more open this process is the more likely it will lead to improved outcomes.

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1.

Comparison Table

Comparing high voltage overhead and underground transmission infrastructure (up to 500 kV)

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Contents

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Abbreviations and Acronyms

Abbreviation	Description
AC	Alternating Current
ACSR	Aluminium conductor steel-reinforced cable (or conductor)
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AVP	AEMO Victorian Planning
CBA	Cost Benefit Analysis
CIGRE	International Council on Large Energy Systems
DC	Direct Current
EHV	Extra High Voltage—consensus for AC Transmission lines is 345kV and above
EIS	Environmental Impact Assessment
EIR	Environmental Impact Review
EIS	Environmental Impact Statement
ELF	Extremely low frequency
EMF	Electromagnetic Fields
ENA	Electricity Networks Australia
EPR	Ethylene propylene cable
EPRI	Electrical Power Research Institute
GIL	Gas Insulated Line
GC	Gas cable
HDD	Horizontal Directional Drilling
HPOF	High-pressure oil-filled cable

Abbreviation	Description
HTLS	High Temperature Low Sag Conductors
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ISP	AEMO’s Integrated System Plan
NEM	National Electricity Market
OH	Overhead
OHTL	Overhead transmission line
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
REZ	Renewable Energy Zone
RIT-T	Regulatory Investment Test—Transmission
ROW	Right of Way (e.g. easement)
SCOF	Self-contained oil-filled cable
SLO	Social Licence to Operate
UG	Underground
UGC	Underground cable
UGTL	Underground transmission line
XLPE	Cross-linked polyethylene

Glossary

Term	Description
Impedance	The impedance in an AC electrical circuit or transmission line are a combination of characteristics which oppose current flow and result in voltage drop or rise and losses in the line. Impedance comprises of two components a) resistive, and b) reactive. The reactive component is a combination of inductance and capacitance.
micro-Teslas (µT)	A measurement unit for magnetic field strength (1µT = 10mG)
milli Gauss (mG)	A measurement unit for magnetic field strength (1µT = 10mG)
Right of Way	The general term used for a corridor secured for a transmission line. An easement provided a legal right of way on a property which may be privately or publicly owned. Transmission lines may also be installed on wider public road corridors.
Trefoil	Trefoil refers to a method of laying and arranging 3 single core cables in a triangular formation to form a 3-phase circuit.

1.

Introduction

This study aims to investigate the benefits and trade-offs between overhead and underground transmission line infrastructure, specifically focusing on issues associated with undergrounding new transmission infrastructure. It seeks to establish a clear and consistent approach to the evaluation of overhead lines and underground cable transmission, including the consideration of community concerns around the need for new transmission infrastructure to connect large renewable energy generation projects. It does this through systematic reviews of the literature as well as incorporating experiences of Transmission Network Service Providers (TNSPs) in Australia and overseas.

The study has a particular focus on 500kV infrastructure which is expected to be the system voltage for high-capacity transmission lines in Australia going forward. A detailed review of HVDC transmission is not within the scope of this study, however an overview of key aspects has been provided.

Historically, transmission networks in Australia developed from the need to transfer large amounts of power from large coal fired power stations, typically co-located near coal reserves, over long distances to major cities and industrial load centres. In contrast, the proposed large scale renewable generation facilities, mainly solar and wind farms, require greater land areas and are largely being located in greenfield areas with little or no existing transmission network infrastructure. These new developments are naturally creating community interest and concerns around a range of potential impacts, including but not limited to: visual amenity; environment; Traditional Owner lands; agricultural land use; and social licence to operate concerns. This has led to questions surrounding when it is appropriate to underground transmission infrastructure and the likely implications of doing so.

Here we provide an overall summary of the findings of the study presented in a table format comparing overhead and underground infrastructure against technical, economic, environmental and social factors.

2.

Comparison Table – HV overhead and underground cable transmission lines

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
			Technical Factors - System Design, Installation and Performance		
1	**Power transfer capacity (typical):**	500kV: AC Single Circuit Quad Bundle ~3000 MW. 330kV: AC Single Circuit ~ 1000 MW. 275kV: AC Single Circuit Twin bundle – 800 to 1000 MW. 132kV: AC Single Circuit Single bundle ~ 200 MW.	500kV AC: 2000MW 330kV AC: 800MW 275kV AC: 800MW 132kV AC: 150MW	+/- 525kV: 2000MW +/1 320kV: 750MW	+/- 525kV: 2000MW +/1 320kV: 750MW
2	**Feasible maximum line route lengths**	Overhead transmission lines can traverse long routes up to 1000km. Overhead lines require less reactive compensation plant (per km) compared to underground cables.	40 to 60km based on critical length (length where cable capacitance equals the rating on cable, typically around 85km for 330 kV and 76km for 500 kV; practical lengths will be around half of these values). Reactive compensation plant such as shunt reactors or static var compensators at termination points are required for underground transmission to counteract the more significant capacitive effects of cables compared to an overhead line.	Feasible route length for comparable power transfers to HVAC lines is currently **up to around 750 to 1000km**. Route lengths greater than 1000km are feasible.	
3	**Conductors, Insulators and Cables**	Typically, aluminium and aluminium with steel core, with 2 conductor bundles at 275/330kV and quad bundles at 500kV. Insulator strings can be glass, porcelain or composite.	XLPE insulated cable is the most common technology. The first installation at 500kV was in 1988, so the technology is now mature.	Conductors similar to HVAC. Longer insulator strings generally required due to higher voltage across insulators compared to 3 phase AC.	XLPE cables similar to HVAC. However cable design provides for insulation subject to greater electrical stresses compared to HVAC.
4	**Reactive compensation equipment requirement**	Reactive compensation is required for longer line routes but is much less than the requirements for an equivalent rated UGTL.	Significant reactive compensation is required for circuit lengths at 50% to 100% of the critical length (around 50km to 70 km for EHV cables).	Not applicable.	Not applicable.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
	Technical Factors - System Design, Installation and Performance				
5	**Power conversion equipment requirement**	Not Applicable.	Not Applicable.	AC/DC power conversion equipment required at each end of the transmission line. This is a major cost factor for HVDC systems.	
6	**Above ground impacts and construction requirements**	Typical lattice tower height and conductor span lengths for double circuit: 500kV : 60 to 80m high, spans 300 to 500 m 330kV : 50 to 60m high, spans 300 to 400 m 275kV : 40 to 50m high, spans 300 to 400 m 132kV : 30 to 40m high, spans 200 to 300 m Alternative pole or aesthetic designs may have lower heights. Aesthetic structures such as steel poles, T-pylons (UK) and lower height structures can be used in specific applications. However, there may be significant trade-offs such as cost, access and maintenance, additional structures and increased easement width.	Transition structures and fenced ground terminations required for connection to OHTL or at terminal substation.	Structure heights depend on DC voltage but will typically be less than the equivalent rated HVAC OHTL Structures will be more compact as less conductors will be needed. HVAC lines can be converted to HVDC application.	Transition structures required for connection to OHTL or at terminal substation.
7	**Below ground impacts and construction requirements**	Tower foundations and earthing conductors.	Depending upon design, voltage and power transfer rating: Cable trenching to lay conduits or cables - typically 1 to 2 m deep. Trench widths varying depending on number of cables and power transfer rating e.g. 500kV : 4 to 5m wide per circuit 330kV : 1.5 to 2m wide per circuit 275kV : 1.5 to 2m wide per circuit 132kV: 1 to 1.5m wide per circuit Horizontal direction drilling or micro-tunnelling required at some locations e.g., under waterway, rail corridors or busy roads. Cable tunnels will generally be required in high density urban areas for EHV cables.	Tower foundations and earthing conductors. Special earthing design required for ground electrodes.	Similar to HVAC UGTL, however trench widths will be less as a lesser number of cables will generally be required for same power transfer capacity.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
8	**Induced voltages**	OHTL's can induce voltages in nearby metallic objects such as fences, rail tracks and pipelines. Earthing and mitigation measures, such as phase conductor arrangements need to be considered in the design of an OHTL to ensure that the hazard is mitigated, and the design complies with standards.	UGTL's can induce voltages in nearby metallic objects such as fences, rail tracks and pipelines, however the earthed metallic screen significantly mitigates the induced voltages. Earthing arrangements of UGTL's that have metallic outer sheaths must also be considered as the induced voltages can cause current flows in the sheath that result in heat losses. Arrangements such as cross-bonding cancel the induced voltages in a 3-phase cable installation.	Induced voltages from HVDC lines into nearby metallic objects are static and tend to be lower than HVAC lines. Both steady state and fault currents in the HVDC line must be considered. Ground potential rise due to discharge currents via earth electrodes in HVDC systems must be considered in the design.	
9	**Vehicle access tracks**	Access tracks required for construction (heavy vehicle) and on-going maintenance (light vehicle). Primary requirement is access to structure location for construction lay down areas and where there is an ongoing requirement for vegetation management along the route.	Apart from where installation is under a formed public road, access tracks along the cable route are normally required for construction and on-going routine inspection and maintenance. The impact will vary depending upon the route, terrain, and installation methods.	Access tracks required for construction (heavy vehicle) and on-going maintenance (light vehicle). Primary requirement is access to structure location for construction lay down areas and where there is an ongoing requirement for vegetation management along the route.	Apart from where installation is under a formed public road, access tracks along the cable route are normally required for construction and on-going routine inspection and maintenance. The impact will vary depending upon the route, terrain, and installation methods.
10	**Future connection capability**	HVAC OHTL's provide the most economic and flexible capability for future connections to the line.	HVAC UGTL's provide economic and flexible capability for future connections to the line. Cost will be greater than OHTL's however with more expensive underground works to extend, joint and terminate cables.	HVDC lines provide the least economic and flexible capability for future connections due to the requirement for additional converter stations. HVDC is more suited to applications for direct power transfer between two distant locations.	
11	**Reliability**	Reliability of performance (typical forced outage rate of 0.5 to 1.0 per 100 km/year). Structural failures (for Australia, failure rate is around 1 in 150,000 per annum). Overhead lines are exposed to severe weather including lightning strikes. Repair time for faults is much shorter duration compared to underground.	For XLPE cables outage rates are typically less than 1 outage/100km/year and lower than equivalent overhead lines. Repair time for underground cable faults is a much longer duration than overhead lines due to excavation, cable jointing and electrical testing work required e.g., up to 4 weeks.	Limited data is available; however, outage rates are expected to be like HVAC OHTLs. The lesser number of conductors in a HVDC line would result is less exposure to faults compared to HVAC.	Limited data is available; however, outage rates are expected to be like HVAC UGTLs. The lesser number of conductors, joints and terminations in a HVDC line would result is less exposure to faults compared to HVAC.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
12	**IElectro Magnetic Fields (EMF)**	Magnetic field levels are maximum under the centreline of the transmission line and decrease less gradually with distance from the line compared to an underground line. Transmission lines are designed to meet industry compliance limits within the corridor. Electric fields are emitted from overhead lines, but lines are designed to be within compliance limits. Magnetic field levels at 40m from overhead transmission line are similar to levels from typical appliances found within a home. The electric fields from transmission lines rated at 330 kV and below will generally produce electric fields less than the reference levels or industry guidelines. Design measures need to address electric fields from 500 kV transmission lines.	Magnetic field levels are above the centreline of the underground transmission line and decrease more rapidly with distance from the line compared to an overhead line. Electric field are contained within a cable with outer earth bonded metallic sheath. EMF levels at 4m from underground transmission line are similar to levels from typical appliances found within a home.	DC magnetic fields are static and subject to higher reference limits (i.e., less onerous) compared to AC. DC electric fields are static and subject to higher reference limits (i.e., less onerous) compared to AC. Design measures to ensure compliance with standard limits are applied.	DC magnetic fields are static and subject to higher reference limits (i.e., less onerous) compared to AC. Design measures to ensure compliance with standard limits are applied. Electric fields are contained within the cable system.
13	**Audible Noise**	Audible noise can occur due to: • corona discharge on the transmission line conductors • dirt or pollution build-up on insulators • wind effects on structure and fittings These effects need to be considered in the design and maintenance measures employed to ensure noise is within compliance limits.	No audible noise from underground cables.	Audible noise – similar to HVAC OHTLs, but is dependent on voltage and size of conductors. Design measures are applied to ensure noise levels are within compliance limits. Audible noise from HVDC converter stations will occur. This needs to be considered in the design and location of converter stations in order to minimise impact.	No audible noise from underground cables. Audible noise from HVDC converter stations will occur. This needs to be considered in the design and location of converter stations in order to minimise impact.
14	**Corridor and easement requirements:**	For double circuit: 500kV AC – 70m wide 330kV AC – 60m wide 275kV AC – 60m wide 132kV AC – 20 to 40m wide Adjoining public roads may form part of a corridor.	For double circuit, rural: 500kV AC – 30 to 40m 330kV AC – 10m to 20m 275kV AC – 10m to 20m 132kV AC – 5m to 10m Urban installation corridor width depends on availability of suitable public road corridors or there is a requirement for a tunnel. Land is also required for underground to overhead transitions.	Corridor widths for HVDC OHTLs of equivalent power transfer ratings are similar to HVAC OHTLs. Buffer zones required for EMF reduction or prudent avoidance would be less.	Corridor widths for HVDC UGTLs of equivalent power transfer rating will be generally less than HVAC UGTLs. This is due to a lesser number of cables and reduced width trench widths required for an installation. Road corridors may be more readily used for cable routes. Land is also required for underground to overhead transitions.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
15	**Lifespan (Typical)**	60 to 80 years.	Greater than 40 years.	60 to 80 years (OHTL) Converters to be considered also.	Greater than 40 years (UGTL cable) Converters to be considered also.
16	**Project timeframes**	e.g. for a 500kV double circuit for 100km route length: Planning and approvals: 3-5 years. Construction: 2 years.	e.g. for a 500kV double circuit for 50km route length: Planning and approvals: 3 years. Construction: 4-6 years.	Construction: 2 years.	Construction: 4 – 6 years.
			Risk Management Aspects		
17	**WH&S – construction**	General construction industry risks. Working at heights risks for erection of towers and conductor stringing. May involve helicopter work. Electrical safety risks – HV switching, testing, live line works.	General construction industry risks. Excavation machinery risks Electrical safety risks – HV switching, testing. Overall risks considered lower for UGTLs compared to OHTLs.	General construction industry risks. Working at heights risks for erection of towers and conductor stringing. May involve helicopter work. Electrical safety risks – HV switching, testing, live line works also at converter stations.	General construction industry risks. Excavation machinery risks. Electrical safety risks – HV switching, testing including converter stations. Overall risks considered lower for UGTLs compared to OHTLs.
18	**Severe weather**	OHTL are exposed to severe weather damage from high winds, flooding, and lightning strikes.	UGTL have limited exposure risk to severe weather. Lightning strikes to the overhead network can cause damage to UGTL.	OHTL are exposed to severe weather damage from high winds, flooding and lightning strikes.	UGTL have limited exposure risk to severe weather. Lightning strikes to the overhead network can cause damage to UGTL lines.
19	**Bushfire risk and exposure**	OHTL can cause bushfires (releasing molten particles from conductor clashing or conductor contact with vegetation or ground). OHTL's may be exposed to bushfire damage risk (high bushfire risk areas).	UGTLs have limited exposure to bushfire damage risks. Above ground equipment including cable terminations at overhead to underground transitions would be exposed.	OHTLs can cause bushfires (releasing molten particles from conductor clashing or conductor contact with vegetation or ground). OHTL's may be exposed to bushfire damage risk (high bushfire risk areas).	UGTLs have limited exposure to bushfire damage risks. Above ground equipment including cable terminations at overhead to underground transitions would be exposed.
20	**Climate change**	Long term climate change effects could increase risks associated with severe weather, wind loads and bushfires on OHTL's. OHTL's line designs will need to consider these impacts which may result in increased project costs.	UGTL's will be less exposed to long term climate change risks. There is exposure to damage in flooding events where erosion of ground can expose cables.	Long term climate change effects could increase risk associated with severe weather, wind loads and bushfires on OHTL's. OHTL's line designs will need consider these impacts which may result in increased project costs.	UGTL's will be less exposed to long term climate change risks. There is exposure to damage in flooding events where erosion of ground can expose cables.
21	**Damage by other parties**	OHTL's may be exposed to malicious and accidental damage. Accidental damage can be by vehicles, construction machinery or aircraft.	UGTL's may be exposed to risk of third-party damage by other excavation machinery including drilling.	OHTL's may be exposed to malicious and accidental damage. Accidental damage can be by vehicles, construction machinery or aircraft.	UGTL's may be exposed to risk of third-party damage by other excavation machinery including drilling.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
22	**Earthquake**	Earthquakes have potential to cause damage to overhead infrastructure. However, repair times will be less than for underground cables.	Earthquakes have potential to cause damage to underground cables, joints, and terminations. Repair time in such situations would be considerably longer than for overhead infrastructure.	Earthquakes have potential to cause damage to overhead infrastructure. However, repair times will be less than for underground cables.	Earthquakes have potential to cause damage to underground cables, joints, and terminations. Repair time in such situations would be considerably longer than for overhead infrastructure.
			Economic Factors		
23	**Capital Investment Costs:** •Planning •Social licence - consultation and engagement. •Design and survey •Approvals •Environmental offsets •Property – easements, right of way, landholder payments •Procurement of plant and materials •Construction (civil, structural, electrical) •Commissioning Indirect costs (overheads)	**Indicative costs** for double circuit OHTL, route 50-100km, including project construction (materials, labour and plant) and excluding property and environmental offsets: 275 kV: \$2M to \$3M per km 500 kV: \$5M to \$6M per km	**Indicative costs** for double circuit UGTL typical 40 km length including project construction (materials, labour and plant) and excluding property and environmental offsets: 275 kV: \$10 M to \$15M per km 500 kV: \$25M to \$30M per km	Project costs were not in the scope of this study. "Break even" distance for HVDC overhead comparted to HVAC overhead is around 600 to 650km for EHV.	
24	**Operating and Maintenance:** •Planned maintenance. •Corrective maintenance •Unplanned maintenance	**Indicative costs:** 0.5 to 1% of capital cost per km per annum for up to 20 years. 1 to 2% of capital cost per km per annum during mid life.	**Indicative costs:** Expenditure per km per annum is typically around 40% of comparative overhead line but can be similar if the patrol specification and frequency of patrols is frequent.	HVDC Transmission lines – Maintenance requirements for overhead and underground line components are expected to be similar to HVAC overhead and underground. However, the additional maintenance requirements associated with AC/DC converter stations would be significant resulting in overall higher lifetime maintenance requirements.	
25	**Operating - Energy Losses**	Cost of losses depend on conductor size selection. Typically, overhead lines losses can be 1.5 to 2.5 times greater than an equivalent underground line.	Cost of losses depend on conductor size selection. Typically, underground cable losses will be less than an equivalent overhead line. Reactive compensation losses need to be considered for longer route lengths (e.g., > 10km).	Losses for HVDC systems can be up to twice that of the equivalent HVAC overhead or underground system due to the additional losses from the AC/DC converter.	

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
26	**Lifetime Cost:** Net Present Value (NPV) of: •Capital Investment cost. •Operating and Maintenance costs over life •Cost of energy losses with annual load growth factor applied over life. •End of life cost (not significant) Key assumptions included in the NPV calculation are: •Expected asset life span e.g., OHTLs – 60 years, UGTLs – 40 years. Financial discount rate or internal rate of return e.g., 5 to 6%.	275 kV OHTL PV costs at 40 years indicates the following: $3.76 M (Initial cost of $2 M + $1.76 M for maintenance and operating costs (losses and unreliability). It should be noted that 40 years is typically only half the life of an overhead line.	275 kV UGTL PV costs at 40 years indicates the following: $11.1 M (Initial cost of $10 M + $1.0M of maintenance. It should be noted that 40 years is typically only 70% life of underground transmission line. The UGTL to OHTL lifetime cost ratio at 40 years is around 2.9. Lifetime costs have been performed for 275 kV transmission (because parameters for OHTL and UGTL were known). It is expected that the UGTL to OHTL lifetime cost ratio for a 500 kV line at 40 years would be similar to 275 kV transmission.	Not in scope of this study.	
			Environmental Factors		
27	**Overall environmental impacts**	Overall negative impacts on the local biodiversity. The geographical context as well as the local ecosystem influence overall impacts. Transmission line add to the cumulative impacts from all infrastructures and developments in a region.	Likely overall negative impacts on the local biodiversity.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.
28	**Barrier effect**	Barrier effect impacts biodiversity negatively. Bird collision and avoidance are the most cited impacts. Flow-on impacts are multiple, including change in migration path and extinction. Potential mitigation measures are through line routing and line markers.	Undergrounding is an effective mitigation measure for the barrier effect.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
29	**Line as resource**	Line as resource is considered positive though with potential negative impacts, particularly on birds. Positive impacts include increased population size and home range. Negative impacts include increased collision, electrocution, predation and invasive species colonisation.	Underground lines cannot act as a resource.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.
30	**Habitat loss**	Habitat loss arises mostly from vegetation clearance, particularly in forested area. The most cited impacts are area abandonment and population decline.	Underground line would result in habitat loss from vegetation clearance.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.
31	**Habitat fragmentation**	Habitat fragmentation arises mostly from vegetation clearance and the barrier effect. Negative impact such as altered movement for mammals and amphibians, and reduced bird crossings with increasing voltage.	Underground line would result in habitat fragmentation from vegetation clearance.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.
32	**Edge effect**	Edge effect arises from vegetation clearance and can have positive, neutral or negative impacts on biodiversity. Most intense impacts are in forested areas. Impact on vegetation from change in microclimate and associated species in those communities such as insects, birds, bats and mammals.	Underground line would result in edge effect from vegetation clearance.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.
33	**Habitat conversion**	Habitat conversion arises from vegetation clearance and can overall be positive, particularly in forestry and intense agricultural land. Maintenance in semi-natural grassland can provide significant ecosystems for a variety of species, notably pollinators and open habitat bird species. To be positive, it requires management practices designed for the local context.	Underground line would result in habitat conversion from vegetation clearance.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
34	**Corridor effect**	Corridor effect arises from the easement providing a connection between areas and can have positive, neutral, and negative impacts. Increased home range for native, non-native, and invasive species. Large carnivores and birds expand their home range, most notably the crow or raven. Limited home range expansion for pollinators. To be positive, it requires management practices designed for the local context.	Underground line would result in habitat conversion from vegetation clearance.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.
35	**EMF**	Potential behavioural, reproductive effects. Some bat species powerline avoidance behaviour is attributed to EMF. EMF affects bees and may pose threat to pollination and colonies survival.	EMF impacts are likely to occur for underground.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.
36	**Fire**	Overhead lines can be a source of fire ignition (1.2% of fires in Spain). Bird electrocution can induce fire – mainly distribution lines (2.4% of the 1.2% in Spain).	Undergrounding would mitigate power line induced fires.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.
37	**Noise**	Noise arises from construction and maintenance, corona discharge and cable vibration from wind. Noise may alter animal behaviours and interfere with animal communication.	Undergrounding would mitigate corona discharge and wind induced noise.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.
38	**Soil degradation, hydrological alterations, air pollution**	Those impacts are mostly associated with the construction and removal phase. Limited data on their impacts in the peer-reviewed literature.	Those impacts would be markedly different and likely more significant for underground cables for the life cycle of the infrastructure.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC underground.
39	**Environmental Assessment Processes**	The Federal Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) and the State's Queensland Environmental Protection Act 1994 are the key legislative requirements for all projects. Detailed Environmental Impact Assessments (EIAs) and surveys are required to ensure protection of environmental significance including unique plants, animals, habitats and places. Environmental Impact Assessments (EIA) are an essential and critical stakeholder engagement activity forming part of the approval process for all transmission projects.			
	Social Acceptance Factors				
40	**Overall social licence and acceptance**	Context dependent and dynamic. Potentially reduced in host communities because of the perceived burden of the project. Influenced by the factors described in this table.	Context dependent and dynamic. Potentially improved in hosting communities. Influenced by the factors described in this table.	Only one study. Similar to overhead AC.	

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
41	**Aesthetic and visual**	Visual impacts negatively influence acceptance. Expected flow on impacts include diminished: recreational activities, tourism, local commerce, and health stress. Tower design, paint, and landscaping of the corridor may positively influence acceptance.	Undergrounding can positively influence visual impacts, but clearing is required (which is a negative impact).	No data.	
42	**Human health**	EMF concerns' influence on acceptance is neutral to negative. Information provision from independent, trusted sources, and transparency in decision-making process can contribute to mitigating concerns.	Limited data in the literature. An awareness gap was identified for underground EMF effects.	Only one study. No influence on acceptance compared to overhead AC.	
43	**Proximity**	Proximity influence is neutral to negative on acceptance. Concerns relate mostly to EMF and effects on property value. Acceptance does not follow a linear rule with distance from the transmission line.	Similar to OHTL, however acceptable distance appears to be reduced compared to OHTL.	No data	
44	**Familiarity**	Familiarity is linked to proximity of an existing OHTL and may positive influence acceptance.	No data.	No data.	
45	**Property valuation impacts**	Expectation of value loss negatively influences land and home owners' acceptance. Actual property value impact may range from +10% to-30%. Property value loss disappears after 5 to 14 years. Value increase was noticed for landscaped corridors.	Losses are expected to be less that for OHTL though not neutral.	No data.	
46	**Financial compensation**	Geographic boundaries, calculation, and administration of compensation are the subject of contestation mitigated with engagement and participation. Individual compensation for land and Homeowners is expected. Beyond property value loss, it needs to account for attachment to place and community (in the case of resumption) and land use. Community benefits positively influence acceptance. For indigenous communities compensation needs to account for cultural value and reparation of historical wrongs.	No data.	No data.	

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
47	**Environmental impacts**	Environmental impacts negatively influence acceptance. Concerns are focussed on vegetation clearance, habitat and wildlife loss, soil degradation, water and groundwater quality and flow, noise, fire, weed dispersal, waste, national park and conservation areas and impacts on agriculture.	Often seen as a mitigation measure of impact on significant landscape and biospheres, however lack of awareness of UGTL environmental impacts was highlighted.	No data.	
48	**Distributive justice: equity**	If the distribution of benefit and burden is unequal it negatively influences acceptance. This may be mitigated with community benefits and sound environmental measures in place. Capacity to negotiate better outcomes is often unequal between communities. This may be mitigated with capacity building and use of independent experts. Accelerated processes negatively influence acceptance.	Undergrounding might be seen as a mitigation of unequal distribution of burdens.	No data.	
49	**Procedural justice:** **Governance**	Fair and transparent governance influence acceptance positively. Coordination and efficiency in the planning processes between jurisdictions and economic sectors alleviate engagement frustration and fatigue compared to multiple, confusing and, at times, contradictory processes. Participation in national transition planning through to regional transmission line planning may influence positive acceptance. Clear goals and outcomes for all processes, including participation, may contribute to alleviating lack of trust issues.			
50	**Procedural justice: Information**	Quality, contextualised, timely and transparent information about available technologies, risks, trade-offs, and governance positive influences acceptance. Trusted sources and easy access also positively influence acceptance.	Similar to overhead AC An awareness and knowledge gap was identified about EMF and environmental impacts from undergrounding.	Only one study. An awareness and knowledge gap was identified about HVDC. Information provision can be helpful towards improving acceptance.	
51	**Procedural justice:** **Engagement & Participation**	There is a need to have a clear and transparent stakeholder identification process. Engagement is the sum of all interactions between all stakeholders of TLs and can influence acceptance. Participation is an essential component of engagement and requires clear goals and expected outcomes. A goal to solely increasing acceptance tends to negatively influence acceptance. Contextualised knowledge creation and relationship building based on shared understanding, transparently incorporated into project design and construction positively influences acceptance. Participation processes that are inclusive and ensure adequate local representation, provide agency and and account for power imbalances positively influence acceptance. Accountability in the process is key.			
52	**Procedural justice:** **Trust**	High levels of trust in the process and the institution positively influences acceptance. Lack of trust hinders participatory processes and ultimately acceptance. The elements highlighted in this summary are critical to building trust in the proponent and their associated activities.			

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
53	**First Nations' Engagement Principles**	"Engage respectfully; Prioritise clear, accessible and accurate information; Ensure cultural heritage is preserved and protected; Protect Country and environment; Be a good neighbour; Ensure economic benefits are shared; Provide social benefits for Community; Embed land stewardship; Ensure cultural competency; Implement, monitor and report back" Source: https://www.firstnationscleanenergy.org.au/network_guides			

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2.

Co-design Workshop Findings

Comparing high voltage overhead and underground transmission infrastructure (up to 500 kV)

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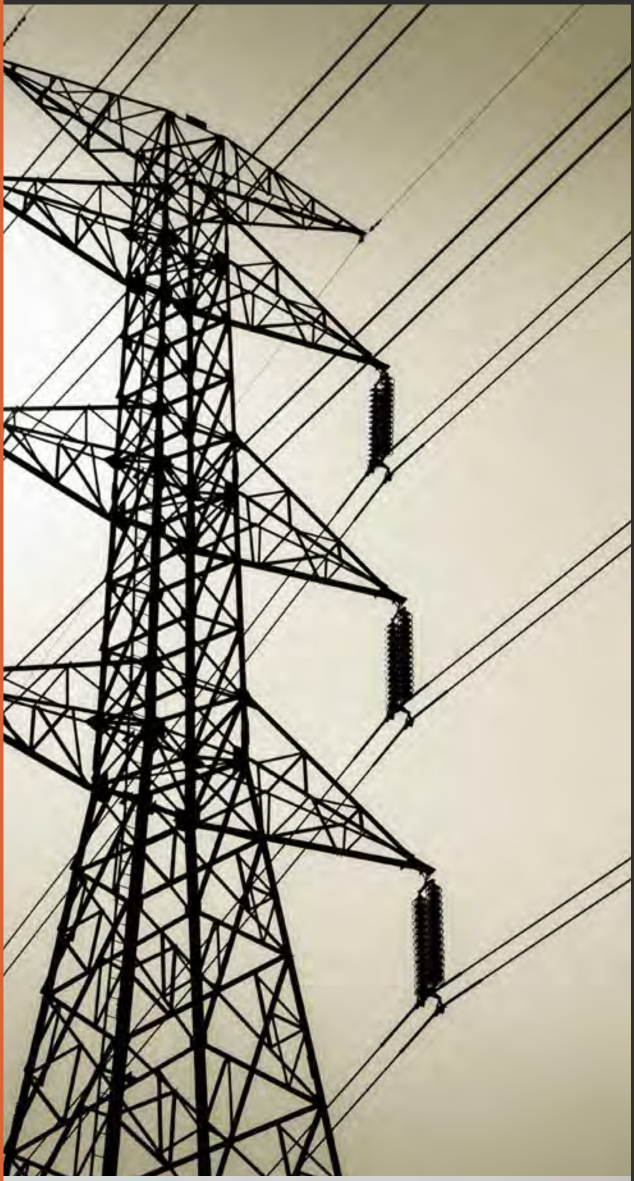
The University of Queensland Australia

Curtin University



Contents

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Who guided us through the research design elements of the project

Report Reviewers

Who generously gave up their time to provide much needed feedback on the report and chapters

1.

Introduction

A three-hour co-design workshop was convened with key stakeholders from Powerlink's Consumer Group to help advise the research team. The aim was to assist the research team in ensuring potential knowledge gaps and subsequent priority research questions were accurately identified. This was seen as an important step to inform the systematic literature reviews across the target areas (technical, economic, environmental, social and community).

In total there were seven participants from the consumer panel, two representatives from Powerlink and four of the technical experts from the research team participated. Chief Investigators, Ashworth and Ackermann, guided the workshop process.

2.

Workshop Design

The workshop commenced with a brief introduction to the project and the purpose of the workshop along with short introductions by each participant. The workshop then moved on to the substantive part comprising the following steps:

Step 1

Participants were asked to identify what they saw as *"The top 3 issues and opportunities relating to either overhead lines (O) or underground (U) cables"? using Strategyfinder software*[1]. Participants were asked to tag their contributions with either an O or U depending on whether they related to overhead or underground. In many instances, the issue/opportunity related to both and therefore was not tagged. During the process of generation, the facilitator clustered the material into rough themes.

Step 2

To review, augment and elaborate on the captured themes, the facilitator openly reviewed each of the clusters, ensuring participants became familiar with all the contributions and either confirmed or suggested changes for the location of contributions in the theme they were situated within. Following this, each of the themes and associated clusters were explored in detail, with participants suggesting further issues and opportunities, identifying causal links, and elaborating statements so that they were clear to all.

Step 3

To help prioritise the themes in an effort to identify which were the most important, each of the theme headings was individually rated on a scale of 0-10. Participants were asked to position one theme at 10 (highest priority) and another at 0 (lowest priority) reflecting relative positioning. They could then rate the remaining themes according to these two anchor points. Participants were then able to view the results along with the degree of consensus about the rating.

The workshop concluded with the facilitators thanking the participants and outlining the next steps.

[1] Strategyfinder is a server-based software program that allows all participants to contribute from their own location anonymously and simultaneously. In addition, through an embedded modelling technique, causal mapping, participants can see how different contributions impact each other building chains of argument and ultimately a network of linked statements. As such, participants are able to explore the thinking of others, delve deeper into their own views, and have a structured conversation. The network is analysable allowing for the management of content and the detection of emergent insights. Prioritisation tools are also available.

3.

Outcomes

From the initial gathering of information, 8 different themes emerged. These are reflected in Table 1 below. The first column shows the number of supporting statements that emerged in each theme, while the following columns, provide the mean and standard deviation of combined scores. This illustrates the priority and degree of consensus across each of the themes.

Social licence and impacts on landholders and communities received the highest average score and the highest degree of consensus. *Ensuring new transmission has minimal environmental impact* was the next highest priority followed by *Community consultation and engagement*. Both of the latter two are key constructs and considerations for achieving a social licence to operate. This reinforces the importance of the people and social aspects in achieving new transmission upgrades regardless of whether they are overhead or underground. It must also be noted that there were a very small number of participants within the workshop so priorities must be read with caution.

Each of the themes are expanded upon below with the series of causal maps arising from the study included at the end of this chapter.

Social licence and impact on landholders and communities was the most highly prioritised theme. The statements surrounding social licence focused around a number of key issues, which reflect much of what has been written in the literature on gaining and maintain a social licence. For example, balancing the global benefits that renewable energy projects bring along with the potential negative challenges for local host communities. This issue arose in several variations and of key concern was the observation that there is a growing scepticism around renewable energy projects, with some suggesting they were losing broader support because of the associated negative impacts, such as visual amenity, impacts on biodiversity, and disruption to day-to-day operations. It was suggested that this was also exacerbated by the short time frames and urgency surrounding the need to deploy renewable energy

Table 1 Key themes emerging from the workshop and their relative priority ranking

Theme	No. of Supporting Statements	Mean	SD (Degree of consensus)
Social licence and impacts on landholders and communities	33	8.9	1.1
Minimising environmental impact	34	7.6	2.2
Community consultation and engagement	35	7.5	1.4
First Nations engagement and benefits, FPIC	12	7.2	2.5
Corridor selection and securing land access	11	7.2	1.6
Whole of life cost	10	6.7	2.9
Speed of delivery and need to build a lot	13	6.5	1.7
Building a smarter more resilient grid	6	6.0	3.5

projects. This led to a suggestions that processes for engagement were emerging that potentially lacked elements of procedural fairness, distribution of benefits and ultimately failed to build trust in the process. The fragile nature of social licence is best reflected in the statement below:

> *Social licence is like an accumulated savings of goodwill (or ill-will). You can gradually build (sp) it up and also burn it very quickly.*

Community consultation and engagement highlighted the need for effective communication between project proponents and impacted communities. It was suggested that this line of engagement should promptly and clearly engage with community concerns and points of misunderstanding to minimise the risk of consultation fatigue amongst locals. The formation of community networks or representative groups as key points of contact for proponents and community were seen as being key. Not only was this raised as being a way to ensure continued local engagement with projects, but it was also seen as a method of building capacity within the local community. This was also considered important to address misinformation which is a key issue for the Victorian projects. An overarching emphasis on making participation in consultation palatable for local populations emerged, with statements calling for engagement that goes beyond just gathering views and attempts to reconcile project ambitions and decision making with a level of local opinion.

Ensuring new transmission has minimal environmental impact recognised there are multiple trade-offs that will influence the choice of overhead or underground transmission lines. Not least whether it involves the upgrade of a pre-existing transmission line or building new lines. This in turn leads to considerations of existing land use or a need for additional land for more or wider corridors. Therefore, raising concerns around competing land-use issues. Other considerations for minimising environmental impacts included considerations of bird life, water, the need to dig trenches, bushfire potential, and others. Similarly, there were statements around the physical differences between overhead and underground lines and the associated visual amenity of these. There was a question whether distributed energy might provide better solutions in some areas and also the importance of education for the short and longer term as new projects come online. EMF was a concern that was raised in the discussion not only for environment but also around health and safety considerations.

First Nations engagement and the benefits of Free, Prior and Informed Consent highlighted the opportunity to improve on existing engagement frameworks with First Nations, pushing for more effective strategies that allow for greater levels of empowerment amongst communities affected by projects. This should take the form of incorporating the priorities of First Nations into the design of transmission infrastructure. As well as through training and capacity building of these populations in regard to how they can participate in projects. It was stressed that the unique and varied First Nations' perspectives need to be understood both in regard to how individual communities engage with projects and the potential benefits they might accrue from being involved, as well as considerations of site specific environmental and cultural significance. It was felt that consulting with Elders may help engagement frameworks better reflect different First Nations' priorities. The discussion also highlighted potential points of issue, particularly in regard to how consultation with First Nations communities in different areas may slow decision making and how this could be minimised by learning from and improving upon past failings and successes of the resources and main roads industries.

Corridor selection and securing land access called for an examination of the differences in reliability and operational impacts of overhead versus underground lines and an investigation into whether implementing new infrastructure or replacing old would be the most effective way forward. This theme emphasised trying to find the balance between the necessary impacts associated with the construction of infrastructure with outcomes that will be satisfactory for those hosting lines and their neighbours. In line with this, a few points were raised including skirting property boundaries to minimise impact across farm land, taking into consideration hosting farmers' biosecurity concerns and requirements for the parties that are going to be using their access tracks, as well as how to manage levels of compensation beyond just host individuals. To secure land access, enhanced landholder payments that have been implemented in Victoria and New South Wales serve as a model to help encourage farmers to become involved in projects. In terms of selecting corridors, recognising the context of locations in terms of their reliability, their vulnerability to extreme weather, and their ability to be repaired and maintained were raised as points that should guide decision making around where projects are built.

Whole of life cost looked to explore ways that the costs of underground and overhead line projects could be minimised both in the short and the long-term. Immediate concerns like the cost of building and operation between the two types of lines were raised with consideration of sunk costs that may emerge if either was constructed at the wrong scale or in the wrong location. In addition, environmental impacts, supply chain issues, and the cost of payments to host communities were also highlighted as needing to be considered in regard to how their situations might change in the future as these projects are carried out. The continued management of costs through good project management that takes advantage of new technology and construction methods was seen as being a key tool in ensuring this. Another idea that emerged in this discussion was the opportunity to coordinate between electricity markets and their subsequent budgets as a way to potentially minimise costs for all involved.

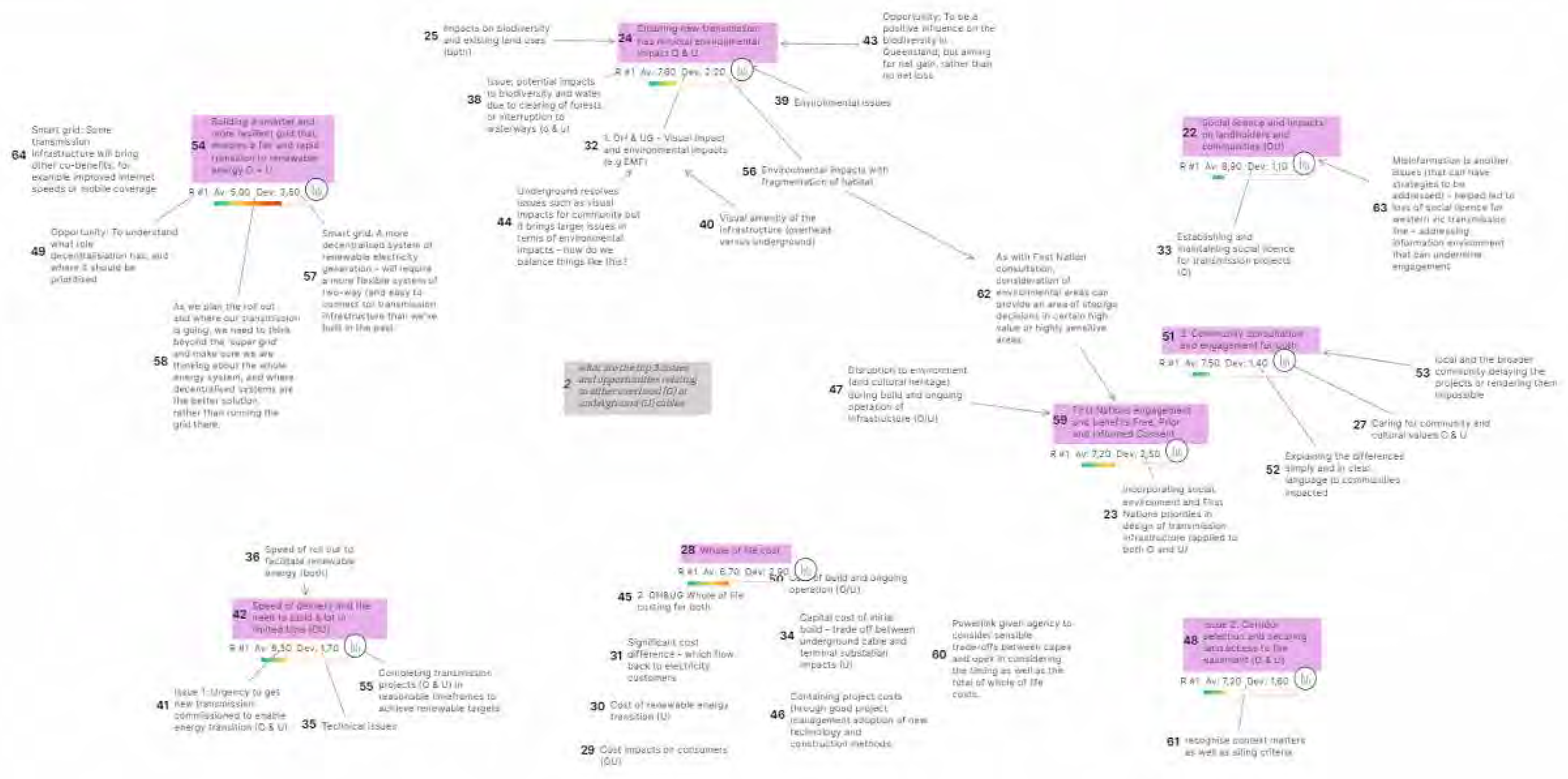
Speed of delivery discussion focused on understanding and weighing the trade-offs between underground and overhead lines and their process of implementation. Recommendations on how this comparison should be carried out took the form of examining differences in financial and temporal costs, the different necessary approval processes, required associated training and development, resource constraints, and the speed of roll out required. Case studies, including that of Germany, the EU and Western Victoria may provide further insights into this. A consideration of labour shortages and competition for workers with the required skills, both domestically and internationally, was also seen as a further important aspect impacting the overall process of implementation of projects. An overarching emphasis emerged highlighting the importance of fact-based analysis that clearly and transparently balances potential costs with the ongoing considerations of each project, so as to allow the most effective roll-out of projects.

Building a smarter and more resilient grid to enable fair and rapid transition highlighted the necessity to look at the transmission roll out within the energy system as a whole. In this light, thinking should go beyond just the “super grid” and recognise where opportunities for alternative decentralised infrastructure might be a more viable option than transmission. Such a decentralised system would require more flexible infrastructure than has been previously used which has the opportunity to introduce other co-benefits such as improved internet speeds and mobile coverage to these communities. The Renewables Grid Initiative in Europe addresses decentralisation in regard to underground lines and may provide insights into this different option. The decentralised alternative needs to be looked at in early consultation stages of a project to understand its viability in different conditions, how it changes regulatory requirements, and whether it fits into the scope of what is being carried out. In some cases it may be outside of a specific project’s control given that it should be explored before the point of choosing to build large transmission lines.

4.

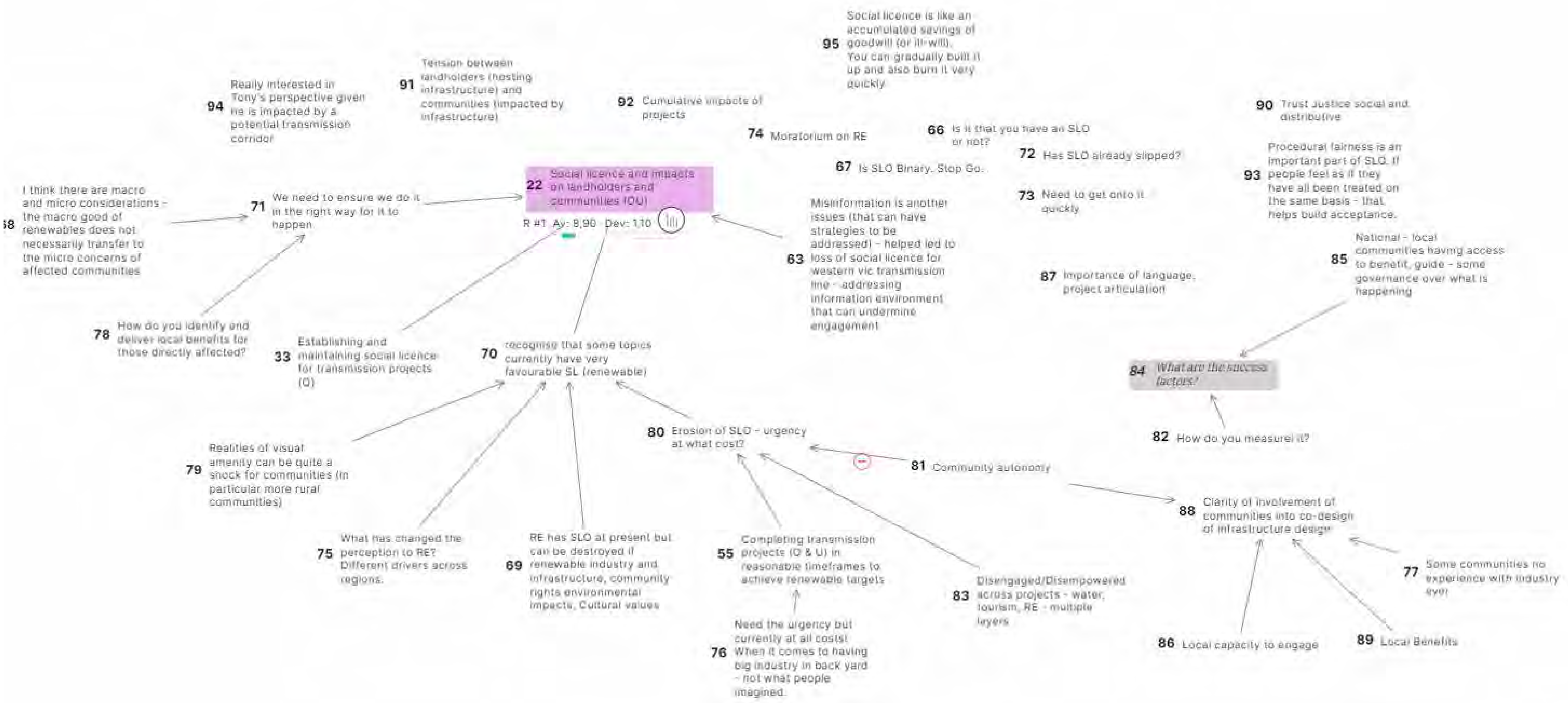
Causal Maps

Map 1: The initial capturing of information with rating scores (shown below each purple statement)

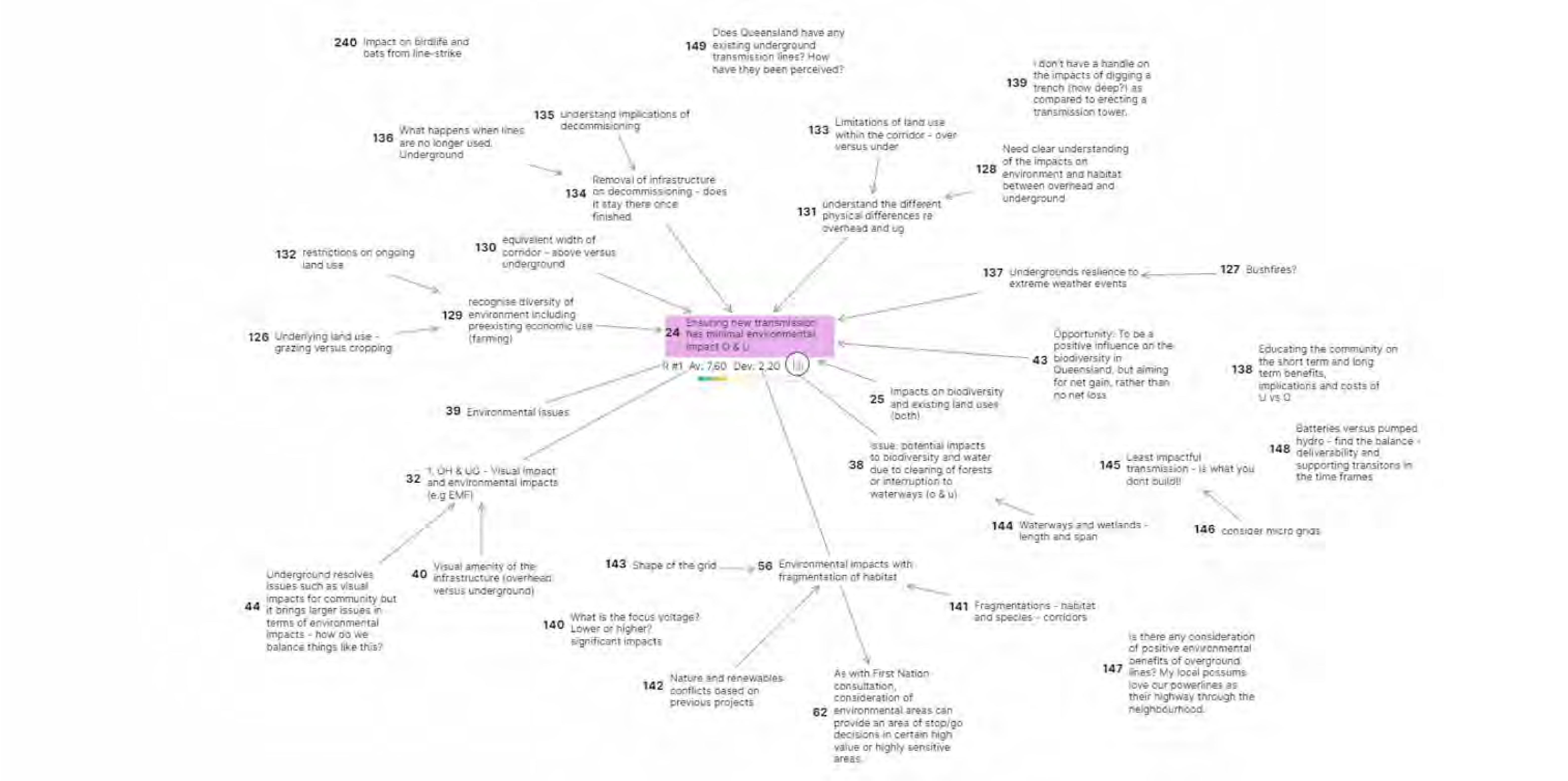


Note: themes are highlighted in purple (and each has a more developed map below)
Results of the Rating process are portrayed under each theme

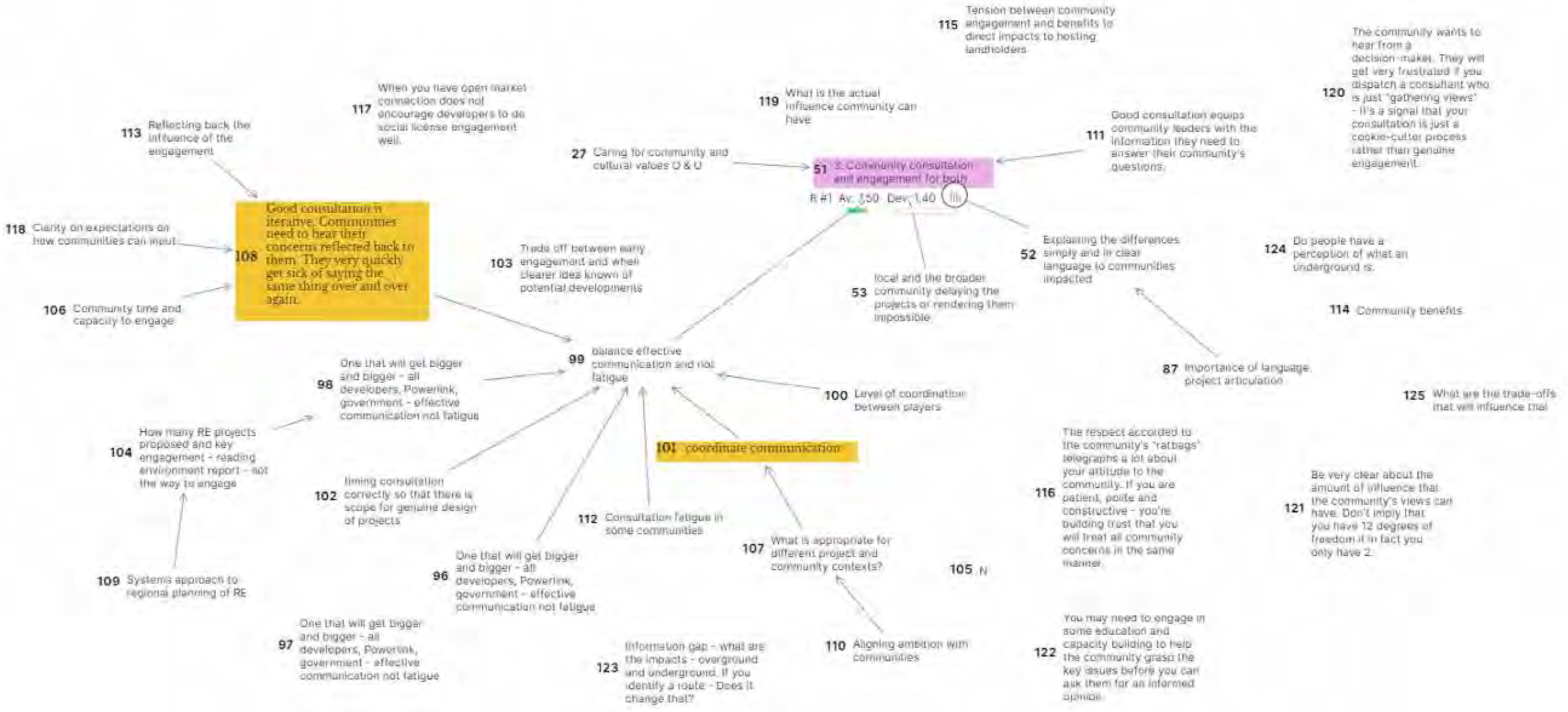
Map 2: Theme 1: material supporting the Social License theme



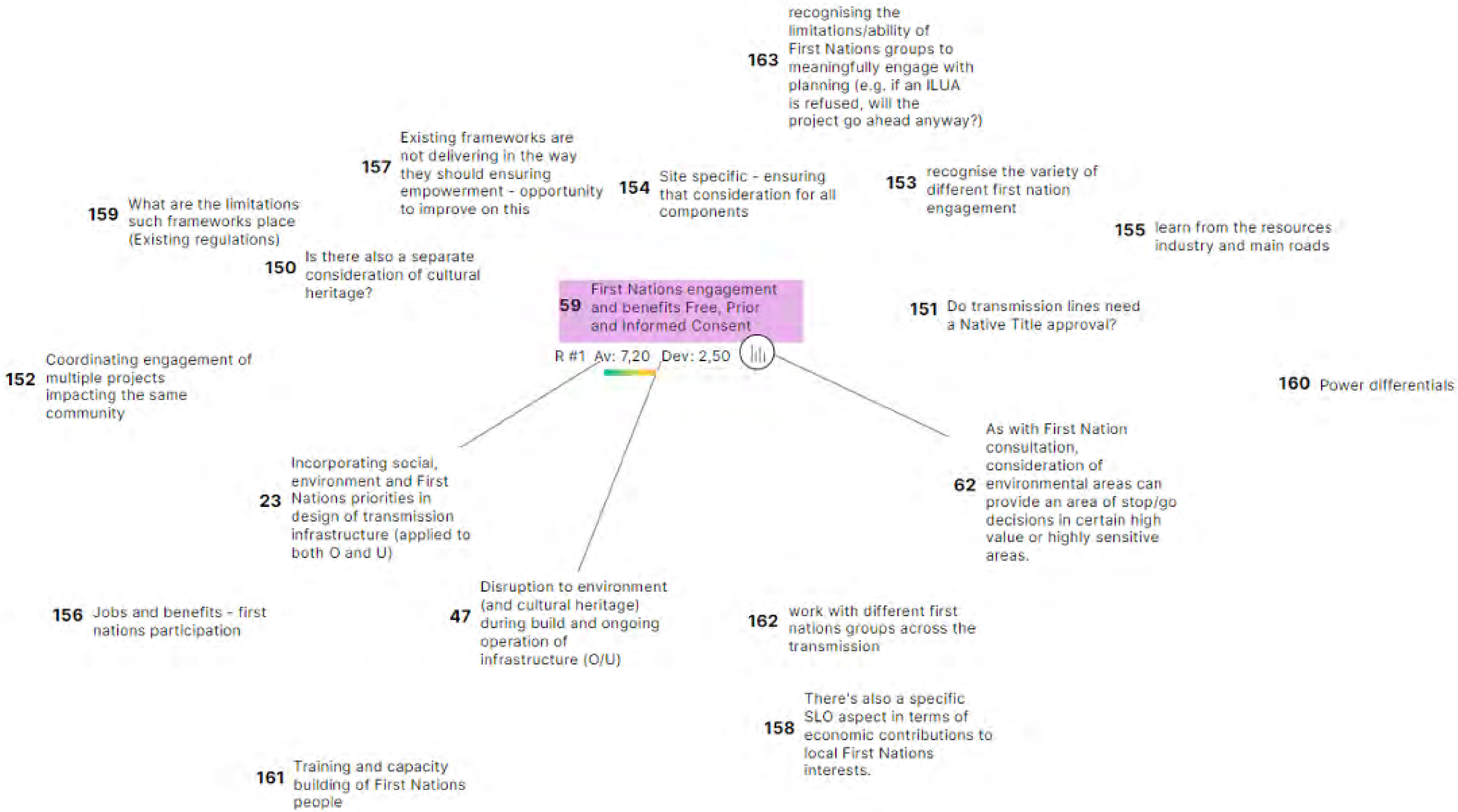
Map 3: Theme 2: material supporting the Environment theme



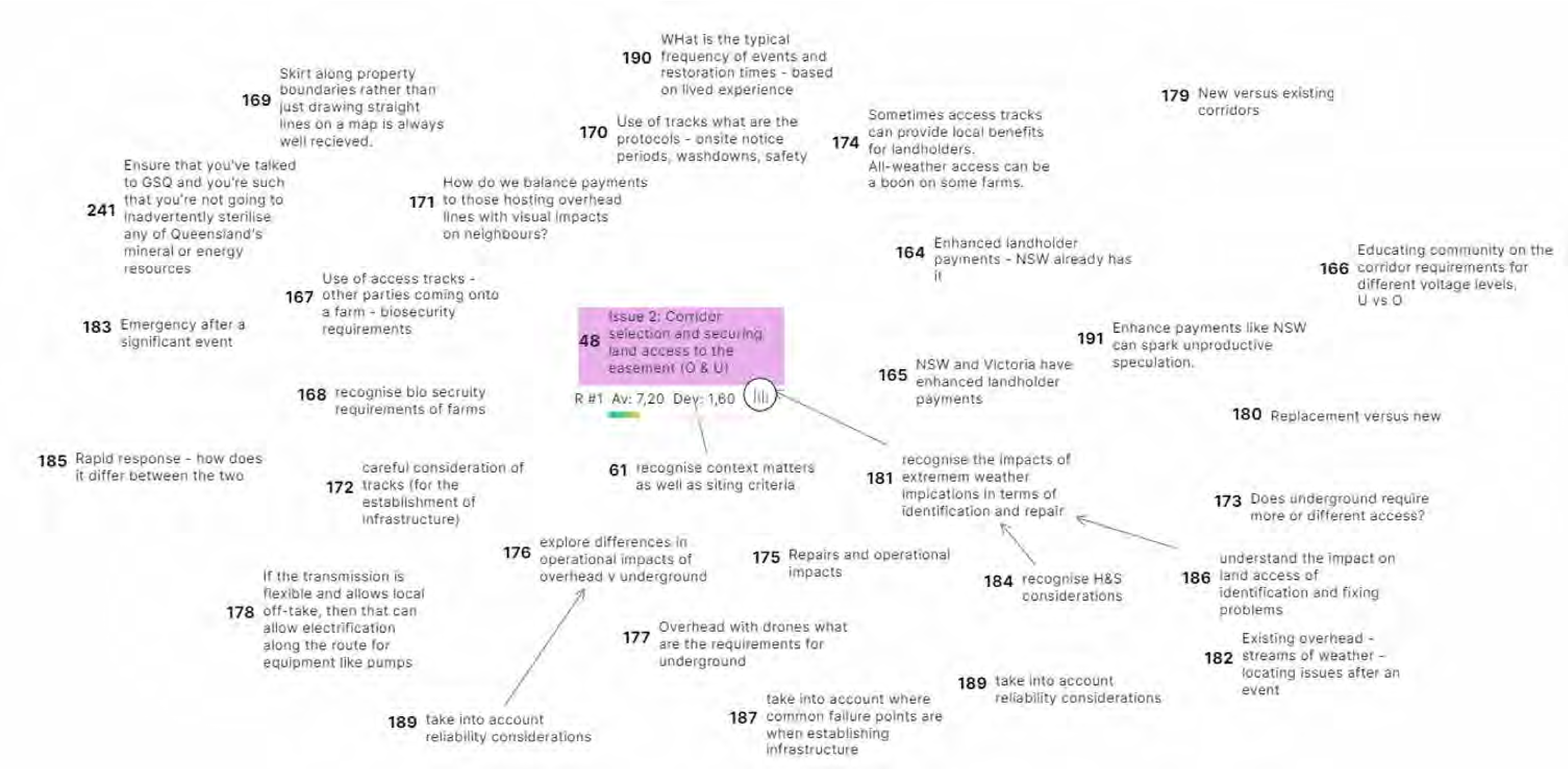
Map 4: Theme 3: material supporting the Community theme



Map 5: Theme 4: material supporting the First Nations theme



Map 6: Theme 5: material supporting the Access theme



Map 7: Theme 6: material supporting the Cost theme

198 Every electricity market in Australia is frantically trying to build transmission lines all at the same time. Rather than a bidding war to drive up costs – could we coordinate buying power and reduce everyone's costs?

194 Many communities will start from assuming that the budgets are endless. They need to understand that costs flow directly through to electricity prices.

200 A community will accept higher costs for transmission if it uses local staff or local components.

28 Whole of life cost
R #1 Av: 6,70 Dev: 2,90

192 What are the key decision points for choosing between the two

60 Powerlink given agency to consider sensible trade-offs between capex and opex in considering the timing as well as the total of whole of life costs.

193 Supply chain

50 Cost of build and ongoing operation (O/U)

202 Cost of easement / hosting of lines v cables may be different

195 Local labour

196 consider supply chain issues (labour and materials)

45 2. OH&UG Whole of life costing for both

201 There are serious sunk costs of building the wrong scale or location of transmission infrastructure.

46 Containing project costs through good project management adoption of new technology and construction methods.

30 Cost of renewable energy transition (U)

207 cost of environmental - eg avoiding impacts in wetlands

29 Cost impacts on consumers (OU)

197 What are the risks affecting certainty around Capex and Opex costs.

203 Transparency around the triggers for under-grounding ie extreme weather events, urban density to inform the cost-benfit analysis

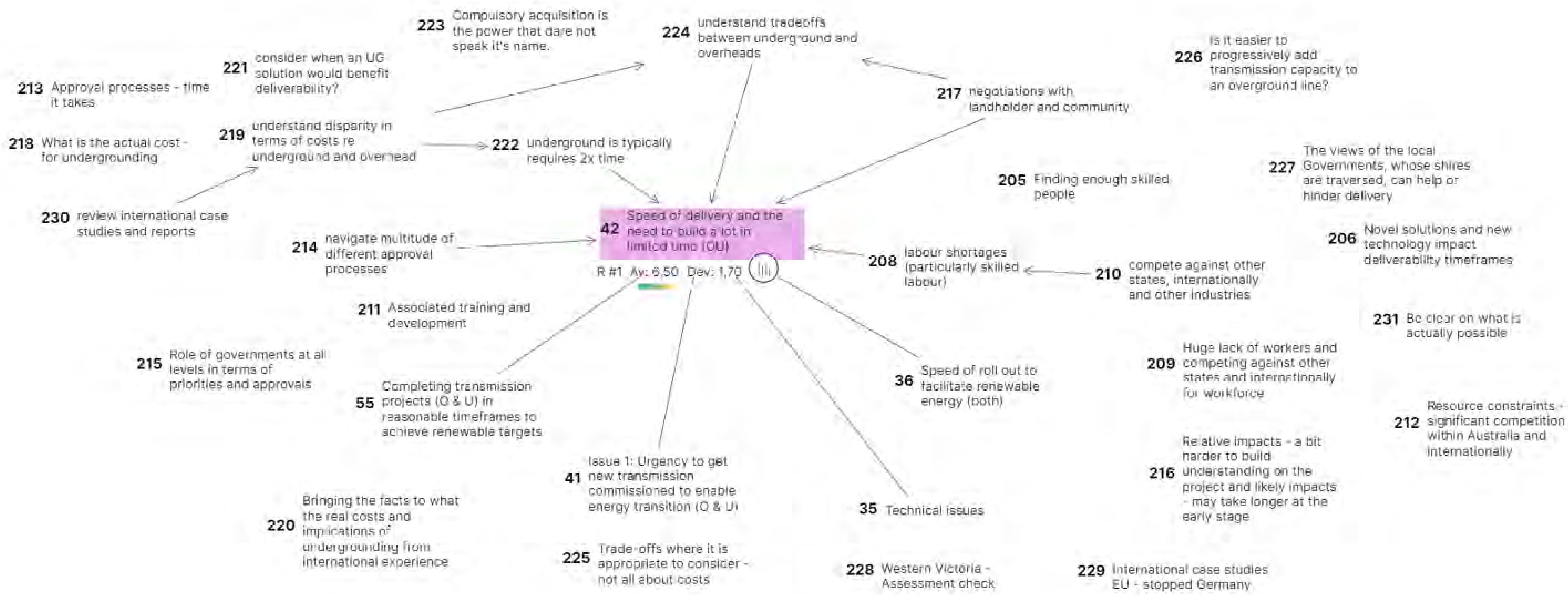
31 Significant cost difference - which flow back to electricity customers

34 Capital cost of initial build - trade off between underground cable and terminal substation impacts (U)

204 building on 202, the payments to landholder may be different depending on the impacts

199 Single Vs double circuit O structure

Map 8: Theme 7: material supporting the Delivery theme



Map 9: Theme 8: material supporting the Resilience theme.

198 Every electricity market in Australia is frantically trying to build transmission lines all at the same time. Rather than a bidding war to drive up costs – could we coordinate buying power and reduce everyone's costs?

194 Many communities will start from assuming that the budgets are endless. They need to understand that costs flow directly through to electricity prices.

200 A community will accept higher costs for transmission if it uses local staff or local components.

28 Whole of life cost
R #1 Av: 6,70 Dev: 2,90

192 What are the key decision points for choosing between the two

60 Powerlink given agency to consider sensible trade-offs between capex and opex in considering the timing as well as the total of whole of life costs.

193 Supply chain

50 Cost of build and ongoing operation (O/U)

202 Cost of easement / hosting of lines v cables may be different

195 Local labour

196 consider supply chain issues (labour and materials)

45 2. OH&UG Whole of life costing for both

46 Containing project costs through good project management adoption of new technology and construction methods.

201 There are serious sunk costs of building the wrong scale or location of transmission infrastructure.

30 Cost of renewable energy transition (U)

207 cost of environmental - eg avoiding impacts in wetlands

29 Cost impacts on consumers (OU)

203 Transparency around the triggers for under-grounding ie extreme weather events, urban density to inform the cost-benfit analysis

31 Significant cost difference - which flow back to electricity customers

34 Capital cost of initial build - trade off between underground cable and terminal substation impacts (U)

197 What are the risks affecting certainty around Capex and Opex costs.

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199 Single Vs double circuit O structure

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3.

Technical Aspects

Comparing high voltage overhead and underground transmission infrastructure (up to 500 kV)

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Abbreviations and Acronyms

Abbreviation	Description
AC	Alternating Current
ACSR	Aluminium conductor steel-reinforced cable (or conductor)
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AVP	AEMO Victorian Planning
CBA	Cost Benefit Analysis
CIGRE	International Council on Large Energy Systems
DC	Direct Current
EHV	Extra High Voltage—consensus for AC Transmission lines is 345kV and above
EIS	Environmental Impact Assessment
EIR	Environmental Impact Review
EIS	Environmental Impact Statement
ELF	Extremely low frequency
EMF	Electromagnetic Fields
ENA	Electricity Networks Australia
EPR	Ethylene propylene cable
EPRI	Electrical Power Research Institute
GIL	Gas Insulated Line
GC	Gas cable
HDD	Horizontal Directional Drilling
HPOF	High-pressure oil-filled cable

Abbreviation	Description
HTLS	High Temperature Low Sag Conductors
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ISP	AEMO's Integrated System Plan
NEM	National Electricity Market
OH	Overhead
OHTL	Overhead transmission line
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
REZ	Renewable Energy Zone
RIT-T	Regulatory Investment Test—Transmission
ROW	Right of Way (e.g. easement)
SCOF	Self-contained oil-filled cable
SLO	Social Licence to Operate
UG	Underground
UGC	Underground cable
UGTL	Underground transmission line
XLPE	Cross-linked polyethylene

Glossary

Term	Description
Impedance	The impedance in an AC electrical circuit or transmission line are a combination of characteristics which oppose current flow and result in voltage drop or rise and losses in the line. Impedance comprises of two components a) resistive, and b) reactive. The reactive component is a combination of inductance and capacitance.
micro-Teslas (µT)	A measurement unit for magnetic field strength (1µT = 10mG)
milli Gauss (mG)	A measurement unit for magnetic field strength (1µT = 10mG)
Right of Way	The general term used for a corridor secured for a transmission line. An easement provided a legal right of way on a property which may be privately or publicly owned. Transmission lines may also be installed on wider public road corridors.
Trefoil	Trefoil refers to a method of laying and arranging 3 single core cables in a triangular formation to form a 3-phase circuit.

1.

Introduction

This study aims to investigate the benefits and trade-offs between overhead and underground transmission line infrastructure, specifically focusing on issues associated with undergrounding new transmission infrastructure. It seeks to establish a clear and consistent approach to the evaluation of overhead lines and underground cable transmission, including the consideration of community concerns around the need for new transmission infrastructure to connect large renewable energy generation projects. It does this through systematic reviews of the literature as well as incorporating experiences of Transmission Network Service Providers (TNSPs) in Australia and overseas. The study has a particular focus on 500kV infrastructure which is expected to be the system voltage for high-capacity transmission lines in Australia going forward.

Historically, transmission networks in Australia developed from the need to transfer large amounts of power from large coal fired power stations, typically co-located near coal reserves, over long distances to major cities and industrial load centres. In contrast, the proposed large scale renewable generation facilities, mainly solar and wind farms, require greater land areas and are largely being located in greenfield areas with little or no existing transmission network infrastructure. These new developments are naturally creating community interest and concerns around a range of potential impacts, including but not limited to: visual amenity; environment; Traditional Owner lands; agricultural land use; and social licence to operate concerns. This has led to questions surrounding when it is appropriate to underground transmission infrastructure and the likely implications of doing so.

This chapter focuses on the technical aspects of overhead and underground transmission lines. To ensure the most up to date and objective information was used to form the basis of any comparisons, the research included both systematic literature reviews of published papers using the PRISMA methodology. The literature review focused on the technical and economic aspects of HV transmission infrastructure. The technical and economic literature review is contained in Appendix A of this chapter report. A purposeful search of additional published materials included: i) reference books and major reports from the leading electrical engineering research organisations of CIGRE and EPRI[1]; and ii) standards, reports, and reference material from electrical industry sources; Australian and international Transmission System Operators; the Australian Energy Market Operator (AEMO); the Australian Energy Market Commission (AEMC); and other federal, state, and local government reports.

[1] CIGRE Green Books Overhead Lines International Council on Large Electric Systems (CIGRE) Study Committee B2: Overhead Lines. Springer Reference.
CIGRE TB 680—Implementation of Long AC HV and EHV Cable System. CIGRE, 2017. EPRI Underground Transmission Systems Reference Book. Electric Power Research Institute, 2015.
EPRI AC Transmission Line Reference Book 200kV and above, 2014 Edition.
EPRI Underground Transmission Systems Reference Book: 2015.

2.

Comparison Factors—Overhead and Underground Cable Transmission Lines

There are several areas in which a technical comparison can be made between overhead and underground cable transmission lines. The main areas relate to the design and life cycle phases and include:

- System Design
- Construction and Installation
- Operation and Maintenance
- End of Life and Decommissioning

The main technical factors to be considered in the design of transmission line systems can be summarised as follows:

(a) Factors common to overhead and underground line design:

- Power transfer requirement
- Performance requirements – reliability, quality of supply, power system stability
- Redundancy e.g. single or double circuit
- Transmission voltage e.g. 132, 220, 275, 330, 400 and 500kV
- Electromagnetic fields
- Future requirements for additional circuits or upgrades.
- Corridor, right of way and easements requirements
- Life span requirement
- Environment, topography, and ground geology
- Land use e.g. urban, rural etc
- Vehicle access and traffic conditions

(b) Overhead lines:

- Overhead line structure types e.g. steel lattice towers, steel monopoles, single or double circuit per structure
- Structure heights and conductor span length
- Conductor size and number of conductors per phase
- Climatic conditions—seasonal temperatures, wind speed and direction, lightning and severe weather exposure

(c) Underground cables:

- Cable type e.g. conductor size, insulation, outer protective sheath
- Number of cables per phase
- Distance between cable joints and cable drum lengths
- Direct buried, ducts or tunnel installation
- Cable installation configuration—flat or trefoil formation, spacing and depth.
- Ground geology
- Ground temperature

Extra high voltage (EHV) is generally defined as transmission network operating at voltage levels greater than 345kV. In Australia, there is only a small network of 500kV transmission lines located mainly in Victoria and NSW. However, transmission voltages of 400kV or greater have been common in many countries and regions, since around the 1960s, including the regions of North and South America, Europe, and Asia. Based on this growing trend for higher voltage new transmission lines the comparison which follows, focuses on the 400 to 500kV range. However, where relevant, there are some references to lower voltage transmission lines. An overview of HVDC transmission lines will be provided in this section also.

3.

Transmission Lines in Australia

Most Transmission lines in Australia are rated at either 110, 132, 275, 330 or 500kV. The 110 to 132kV transmission lines are mainly operated by the larger Distribution Network Providers (DNSPs), while the 275 to 500kV transmission lines are operated by the Transmission Network Providers (TNSPs).

The first overhead 500kV transmission line in Australia was constructed in 1970 connecting Hazelwood Power Station to Melbourne. The 500kV network was later extended to Portland. The first 500kV line in NSW was constructed in the 1980s from Eraring Power Station to Kemps Creek. A network of 500kV lines has since been built in the central parts of NSW linking the major power stations in the Hunter Valley with the major load centres.

In contrast the installation of HV underground transmission lines of greater than 132kV in Australia has generally been limited to relatively short route lengths, mainly in higher density urban and CBD areas, where the lines are normally installed in road corridors. Some examples are listed in Table 1.

Table 1. Significant HV Transmission Cable Installations in Australia

Location	Voltage (kV)	Transfer Capacity (MW)	Length (km)	Year Completed	Route
Sydney South	330	750	28	2003	Urban area, 24.5 km in road corridor and 3.5 km in tunnel
Potts Hill-Alexandria	330	750	20	2023	Urban area, cable in conduits in road corridor
Cranborne Victoria	220	165	88	2012	Fringe urban in trenches and conduits (Connects desalination Plant)

4.

Characteristics of HVAC Overhead Transmission Lines

This section details the main system design characteristics and life cycle requirements for overhead transmission lines.

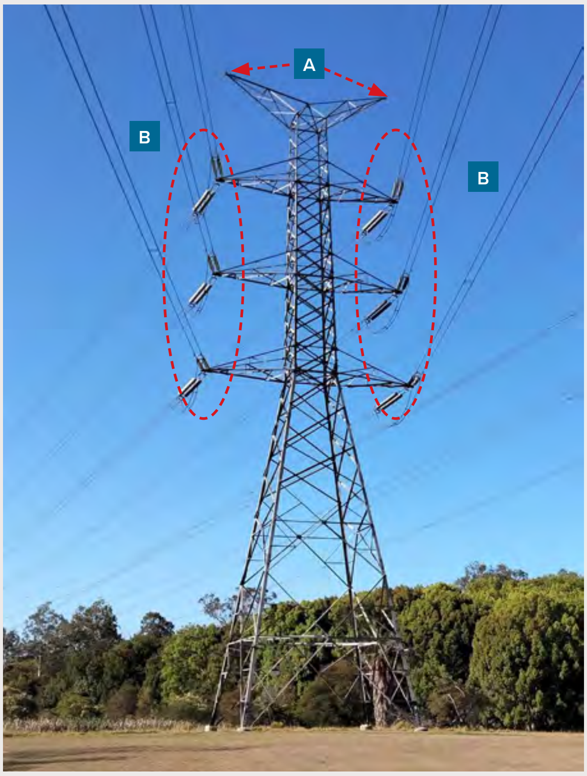
4.1 System Design – Overhead Transmission Lines

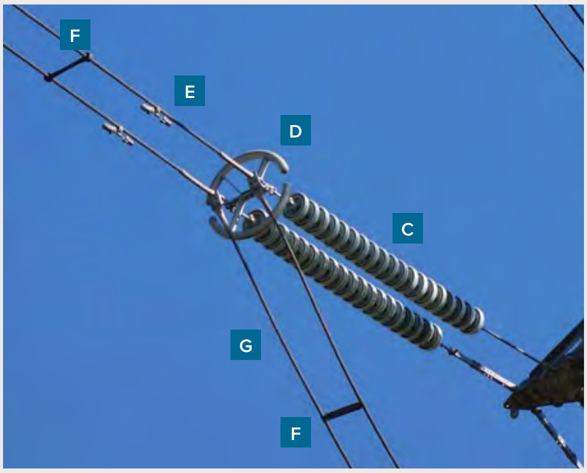
Transmission lines can be constructed as either a **single** or **double circuit** line. Each circuit will comprise of a 3-phase set of insulators and conductors. A typical transmission line tower is shown in Figure 1.

Tower structures – the most common and cost-effective structures are the steel lattice structure. The structures are constructed using prefabricated galvanised steel components which are assembled on-site and mounted on concrete **foundations** or footings.

There are two main types of tower constructions: (1) **Suspension towers** –with vertical insulator strings supporting conductors with no change in direction of the line, and (2) **Tension tower**s – with horizontal insulators strings in both directions of the line from the tower. Tension towers are placed at the ends of long sections of conductors or at change in directions of the line. Tension towers need to have higher strength steel construction and concrete foundations to support the higher tensile loads.

Structure Heights in Australia are determined by: (a) the clearances to ground requirements in State Regulation and Standards (AS/NZS7000); (b) the phase to phase and phase to earth wire clearance requirements in Standards (AS/NZS7000); (c) requirements to meet the





A Earth wires
B Phase conductor bundles
C Insulator strings
D Corona rings (aka grading rings)
E Vibartion dampers
F Spacers
G Bridging conductors (aka jumpers)

Figure 1. Transmission line components (275kV double circuit tension tower)

ICNIRP Electromagnetic field reference levels. At most transmission voltages the height is not affected by the 5kV/m ICNIRP electric field reference limit, but at 500kV, the limit becomes a factor and transmission designers typically increase the height of structures to comply with this limit. The typical height for a 500kV structure is 60 to 80m, whereas a 275kV structure[2] is around 40m to 50m.

Conductors used on overhead transmission lines are predominantly Aluminium Conductor Steel Reinforced (ACSR) which use a galvanised steel core with standard grade aluminium on the outer layers. An alternative is All-Aluminium Alloyed conductors (AAAC) which comprise alloyed aluminium (typically 1120-type) for the conductor strands. The strength to mass ratios for ACSR and AAAC are similar and result in similar spanning and sagging capabilities[3].

The maximum temperature for operating transmission conductors is typically in the range or 75°C to 90°C. The reason for this is to limit the effects of annealing which causes loss of strength of the conductors (see Figure 8 for annealing curves). However, some utilities have uprated their ACSR conductors to operate up to 120°C. This was based on better annealing performance of the ACSR with a steel core and a greater understanding of the operating characteristics of ACSR at elevated temperatures.

There have been a small number (around five) of transmission lines in Australia constructed with a high temperature low sag (HTLS) ACSR conductor. This type of conductor uses special high strength low sag steel cores with thermal resistant aluminium outer strands. The high temperature conductors can operate up to 200°C, which effectively can double the rating out of a transmission line. The high temperature conductors are very expensive (typically 1.5 to 5 times the cost of conventional ACSR—reference [1]) and require special fittings and connectors for the higher temperature.

Conductor Bundles When designing overhead powerlines, the designer is required to address corona discharge and will aim to keep the surface voltage gradient (SVG) on the conductor to below 16kV/cm. To achieve the SVG limit, it is common for there to be a bundle of 2 conductors for 275/330kV and 4 conductors for 500kV (See Figure 2). Each of the conductors in the bundles are limited by their thermal capacity. As an example, a quad bundle conductor with ACSR Drake

Figure 2. Transmission Line Quad Bundled Conductor with Spacer (Marcus Wong)

conductor (26/4.44 Aluminium and 7/3.45 Steel) has been calculated to have a rating around 2200 MVA per circuit. **Spacers** holding bundled conductors in place are installed at approximately 75 m intervals) to avoid conductors clashing during high winds and fault conditions.

Conductors are susceptible to fatigue damage from aeolian vibration[4] and **vibration dampers** are required to address aeolian vibration effects and ensure a long life for the conductors. Aeolian vibration occurs during light laminar winds and the effects are more predominant in flat rural countryside or over waterways. The vibration dampers are installed close to conductor attachment positions.

The configuration of the phase conductors is determined by (a) the phase to phase clearance and climbing clearance requirements in AS/NZS7000; (b) the requirement to keep the SVG on the conductor to below 16 kV/cm; (c) the justification due to prudent avoidance for compacting the conductors and reduce magnetic fields.

Earth Wires and Cross-member Widths effectively shield conductors to provide protection against damage from lightning strikes and are required on transmission lines to achieve an acceptable level of reliability. In general, there are two earth wires per structure with the earth wires generally directly above or close to being directly above the top conductor. A 500kV line

[2] https://www.powerlink.com.au/reports/our-transmission-network
https://www.transgrid.com.au/media/3tkdd5lr/easement-guidelines.pdf.

[3] AS/NZS 7000:2016 Overhead Line Design.
SA/SNZ HB 331:2020 Overhead line design handbook.

[4] Aeolian vibration is a type of motion caused by wind on conductors and overhead shield wires of transmission and distribution lines. Aeolian vibration is characterised by low amplitude (conductor diameter) high frequency (5 to 150 Hz).

Tension tower followed by suspension towers (Marcus Wong)

V string suspension towers (Irby Construction)

Figure 3. 500kV Double and Single Circuit Overhead Lines

is expected to be designed for a lightning outage rate similar to a 275kV line which would be of less than 0.3 outages per 100 km per year[5]. Fibre optic cables can be integrated into special types of earth wires – Optical Ground Wire (**OPGW**) to provide a telecommunication channel.

Corona rings at the ends of insulator strings help provide a smooth surface to mitigate against an electrical phenomenon called corona discharge which can cause noise and electrical losses.

Images of double circuit 500 kV lines are shown in Figure 3.

Insulators used on transmission lines are predominantly ceramic discs (porcelain or glass) with high strength capability (160 and 220kN tensile strength). The insulators are required to support: (a) conductor loads on suspension type structures; (b) tensile loads on angle and termination structures; (c) cascade longitudinal loads [2]. Given the high mechanical tensions in the transmission conductors, there are often multiple insulator strings (particularly for the termination structures).

Transmission Line Electrical Characteristics—A key characteristic of a transmission line is its surge impedance loading (SIL). The impedance in an AC electrical circuit (e.g., a transmission line) are characteristics of the circuit which oppose current flow and result in voltage drop or rise and losses in the line. The Impedance comprises of two main components a) resistive, and b) reactive. The reactive components are a combination of inductance and capacitance. The SIL for a lossless transmission line is where at the given power transfer, the reactive capacitance and inductance on the line are equivalent.

Figure 4. Live Insulator Change-out (North-western Energy UK)

[5] Data sourced from Powerlink Queensland.

Table 2. Typical Surge Impedance Loading for Transmission Line Voltages

Line Voltage	132kV	220kV	275kV	400kV	500kV
Surge Impedance Z0 (Ohms)	400	375	370	320	312
SIL (MW)	44	129	204	500	801

$$SIL = V_{LL}^2/Z_0;$$

Where V_{LL} is line to line voltage, and Z_0 is the characteristic impedance of the line.

Loaded below its SIL, a line supplies capacitive reactive power to the system, tending to raise system voltages. Above it, the line absorbs reactive power, tending to depress the voltage. The *Ferranti effect* describes the voltage rise towards the remote end of a very lightly loaded (or open circuit) transmission line. Typical SILs are given in the Table 2. This shows that doubling of voltage, results in approximately a quadrupling of the SIL.

Reactive compensation plant such as shunt reactors and static var compensators (SVCs) are installed at transmission line terminal substations to extend the critical lengths due to voltage limit effects described above.

Thermal and stability limits—Overhead transmission lines are limited by thermal, voltage and stability limits.

The thermal limit is the maximum temperature (under steady state and short circuit conditions) for operating the conductor and this is described in more detail in a later section on Power Transfer Capability.

There are 2 types of stability limits on transmission lines; (1) voltage stability and (2) transmission angle stability. Voltage stability is associated with the load on the system and is dependent on the power factor of the load, the power transfer and the impedance of the network. Voltage stability can occur on long radial transmission networks and is not usually encountered on highly meshed transmission networks. If the power transfer voltage stability limit is exceeded, there is potential for voltage collapse and generation plant disconnecting from the grid, resulting in widespread customer supply outages.

Transmission angle stability is associated with generation and can arise during disturbances such as faults on the transmission network. In normal operation the load angle (or rotor angle) on the transmission network is low and is much less than the 900 limit. In the event of a faults which can disconnect transmission lines, the load angle) will increase and if it exceeds the 900 limit, the system can become unstable and cause loss of generation.

4.2 Right of Way Corridor Requirements—Overhead Transmission Lines

'Right of Way' is the general term used for a corridor secured for a transmission line. An **Easement** provides a legal right of way on a property which may be privately or publicly owned. Transmission lines may also be installed on wider public road corridors.

The typical easement width for a 500kV line (single or double circuit) is 70m but could be up to 100 m depending upon other design factors. By comparison, a typical easement width for a 275kV line (single or double circuit) is 60m. However, the determination of the right of way or easement corridor width will depend on several factors. These can vary depending on local regulations, environmental considerations, and technical requirements. Some of the common factors that influence the width of the corridor include:

(a) Voltage and Line Configuration: The voltage level and configuration of the transmission line play a significant role in determining the corridor width. Higher voltage lines often require wider corridors to maintain safety clearances and reduce the risk of electrical arcing or interference.

(b) Safety Clearances: Safety regulations dictate the minimum distance that must be maintained between the transmission line and surrounding objects or structures. This includes considerations for the height of the towers, sag and sway of conductors, and any potential hazards in the vicinity, such as roads, railways, buildings, or water bodies. The corridor width is determined by adding appropriate safety clearances on either side of the transmission line.

(c) Electro Magnetic Field (EMF): Consideration is needed of prudent avoidance and recommended

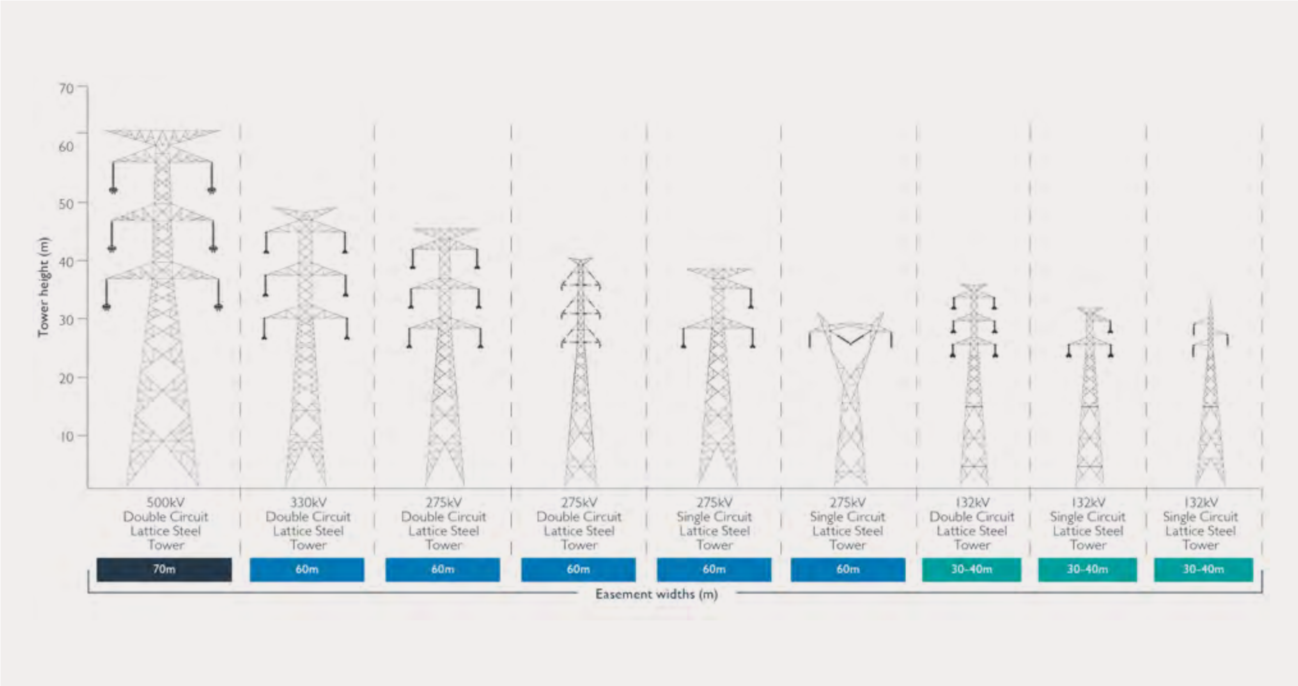


Figure 5. Typical OHTL Structure Types – Height and Easement Widths (Powerlink Queensland[6].)

guidelines from lead organisations—ENA, ICNIRP and ARPANSA (Refer section 7 Electromagnetic Fields).

(d) Environmental Considerations: Environmental factors, including protected areas, sensitive habitats, and ecological considerations, may influence the width of the corridor. In some cases, wider corridors are required to minimize the impact on wildlife migration, vegetation, or protected areas.

(e) Maintenance and Construction Access: Sufficient space is required to allow for maintenance and construction activities along the transmission line. The corridor width should accommodate the safe movement of personnel, vehicles, and equipment necessary for inspection, repair, and construction purposes.

(f) Future Expansion and Upgrades: When planning new transmission lines, the potential for future expansion or the need to upgrade the line capacity also needs to be considered. Providing a wider corridor can facilitate easier expansion or modification of the transmission line infrastructure in the future.

(g) Local Regulations and Standards: Different countries, states, or regions may have specific regulations and standards that dictate the required corridor width for transmission lines. Compliance with these regulations is essential and can influence the final determination of the corridor width.

The determination of the corridor width is often a collaborative process involving various stakeholders, including utility companies, landowners, government agencies, and environmental groups. Factors such as cost, public opinion, and specific project requirements can also influence the decision-making process. Typical corridor widths for various line voltages are shown in Figure 5.

[6] https://www.powerlink.com.au/reports/our-transmission-network

Figure 6. 275kV Double Circuit Compact Steel Pole

4.3 Aesthetic Overhead Transmission Structures

Over many years there have been developments by transmission line engineers and designers to improve the visual impact of transmission line support structures in the environment to gain more public acceptance (CIGRE [2]). Traditionally, transmission lines are constructed using lattice steel towers which are fabricated from galvanised angle structural steel. The need to develop more aesthetic structures emerged in the late 1960s when the demand for transmission line infrastructure resulted in more visual exposure to the general population.

General measures used to improve the aesthetics of transmission line structures include the following:

(a) Adopt compact pole top design—by utilising insulated crossarms (horizontal vee assembly or line post insulators) in place of steel crossarms and insulators strings which results in a lower tower height.

(b) Change the lattice steel structure to monopole steel or concrete—refer to Figure 6 showing typical double circuit 275 kV compact steel pole.

(c) Paint the structures—typically green in a treed environment, or a brown, rust colour in arid or desert areas.

(d) Dull the gloss of the galvanised steel structures and glossy aluminium conductors by sandblasting the structures and conductors prior to erection. The sandblasting of the conductors has an additional benefit—it reduces the hydrophobicity (water repelling property) of the conductors and minimises the risk of the water droplets on the surface of the conductors causing corona discharge resulting in audible noise.

Figure 7. Examples of Aesthetic Design Transmission Line Structures (CIGRE 2017 [2, pp. 905–908])

Aesthetic Transmission Line Structures—CIGRE 2017 [2, pp. 905–908] have reported on a number of examples of innovative and artistic transmission line structures aimed at improving public acceptance. Most of the aesthetic structures are single circuit, utilising single or double pole steel with round or curvy shapes. The crossarms are a variety of different shapes and are often coloured to blend in with the environment. Blue is a colour regularly used to match the colour of the background sky. Poles are often left the galvanised steel colour—which matches the colour of clouds. Development of aesthetic structures involves additional time and cost for a project, so only tends to be used where the need is justified. Some examples are shown in the photos below.

Besides adding time and cost to the project the other major trade-offs with using aesthetic structures or using lower height structures are as follows:

1. Compacting of the phase conductors with the use of aesthetic/innovative structures may not meet the clearance requirements of AS/NZS7000 [3] and restrict climbing access and maintenance.
2. There will be a trade-off with reducing the height of the structure and compliance with the ARPANSA electric field reference levels.
3. There will be a trade-off with reducing the height of structure and reduced span length with reduced span lengths resulting in more structures on the line route.
4. There will be a trade-off in easement requirements when using a wider delta configuration as opposed to the standard vertical formation on a double circuit transmission line. A standard 500kV double circuit line will typically have an overall width of 20 metres, whereas the delta configuration will be 48 metres. This will lead to an additional 30 metres in easement widths.

4.4 Power Transfer Capability

One of the most significant advantages of overhead transmission lines compared to underground transmission cables is the line power transfer capability or rating and the short-term overload capability.

The line power transfer capability is mainly dependent on the resistance of the conductor/cable (material and size), the assumed ambient temperature, the maximum allowable temperature of the conductor above ambient, assumed wind speed and direction.

For example, if we assume a conductor with a maximum allowable temperature of 75°C, for a summer day at noon when the assumed ambient temperature is 40°C, the allowable temperature rise for the conductor is 35°C. For a winter evening, if the assumed ambient temperature is 10°C, the allowable temperature rise increases to 65°C. This has a significant increase on the line rating as illustrated in the examples below.

When calculating ratings, the transmission utilities tend to apply a conservative approach and for normal summer noon ratings, assume the maximum summer temperature, in range of 35°C to 40°C, with a corresponding low wind speed, typically in the range of 0.5 to 1.0m/sec. For emergencies, some transmission utilities assume a higher wind speed for example up to 2.0m/sec.

Dynamic ratings can be determined and applied by use of real time measurements of temperature, wind speed, and conductor sag. (This is described below also).

Typical Power Transfer Rating—Examples

The power transfer capability or rating on a powerline is proportional to the square of voltage. If the voltage doubles, the power transfer goes up four times. The typical MW ratings across a range of overhead transmission voltages are:

- 132 kV—100 to 300MVA
- 275 kV—300 to 1000MVA (twin conductors)
- 500 kV—2000 to 3000MVA (quad conductors)

The factors which influence the line ratings are: (inputs to the Heat Balance Equation)

- Current flow and resistance of conductor (I2.R)
- Solar radiation (typically 1100W/m^2)
- Ambient temperature and maximum conductor temperature
- Wind speed (m/sec)
- Emissivity and absorption values (typically 0.5 for rural weathering and 0.85 urban weathering – where more pollution on conductors is expected)

Line rating calculations have been calculated by the authors for typical 275kV conductors: sulphur and twin phosphorus and shown in Table 3. The assumed parameters for the rating calculations are:

- Solar radiation = 1100 W/m^2
- Emissivity and absorption = 0.5 (assumed rural)
- Maximum temperature of conductors = 75 0C
- Summer noon ambient temperature—35°C, wind speed—0.7m/sec
- Summer noon ambient temperature—35°C, wind speed—2.0m/sec
- Winter evening ambient temperature—10°C, wind speed—0.7m/sec
- Winter evening ambient temperature—10°C, wind speed—2.0m/sec

Table 3. Typical 275kV Overhead Transmission Line Power Transfer Ratings

Conductor (code name)	Summer Noon Normal (MW)[1]	Summer Noon Emergency (MW)[2]	Winter Evening Normal (MW)[3]	Winter Evening Emergency (MW)[4]
Single Sulphur	500	680	670	920
Twin Phosphorus	735	980	990	1300

1. Summer noon ambient temperature—35°C, wind speed—0.7m/sec
2. Summer noon ambient temperature—35°C, wind speed—2.0m/sec
3. Winter evening ambient temperature—10°C, wind speed—0.7m/sec
4. Winter evening ambient temperature—10°C, wind speed—2.0m/sec

To limit the effects of long-term annealing[7], the maximum temperature for a conductor is set. Annealing is dependent on both the operating temperature and the duration of time at the operating temperature (see Figure 8 for typical annealing loss for aluminium conductor). Conductors which are operated at 80°C or less will generally lose 2 to 3% of strength with time. However, if operated under short time emergencies above 100°C, may lose 5% of their original mechanical strength.

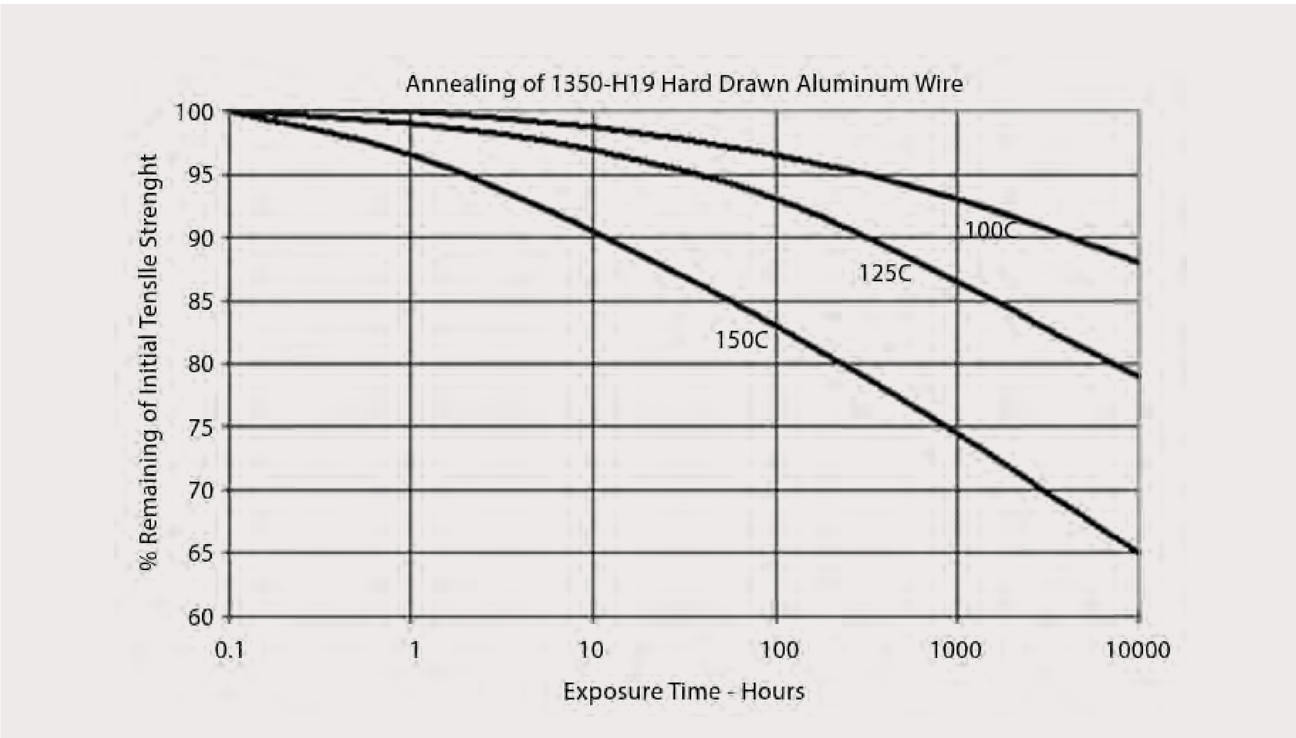


Figure 8. Typical Annealing Curves for Aluminium Wires, Drawn from "Rolled" Rod, of a Diameter Typically Used in Transmission Conductors (The Aluminium Association 1982)

[7] The loss in mechanical strength of the conductor.

Table 4. Example of Overhead Transmission Line Dynamic Ratings

Conductor	Summer Noon Normal (MW)[1]	Summer Noon Dynamic Ambient Change (MW)[2]	Summer Noon Dynamic Ambient and Wind Change (MW)[3]
Single Sulphur	500	570	1046

1. Ambient temperature—35°C, wind speed—0.7m/sec
2. Actual temperature—25°C, wind speed—0.7m/sec
3. Actual temperature—25°C, wind speed—4m/sec

Dynamic Ratings

Transmission utilities have been introducing dynamic line ratings for overhead transmission lines where actual conductor temperatures and wind speeds are measured, or conductor sags are monitored.

To evaluate the impact of using dynamic ratings, additional calculations were performed for a summer noon day but with a reduced actual temperature of 25°C and the wind speed in the range of 0.7m/sec to 4m/sec (see Table 4).

Summary

Overhead transmission lines can be uprated by increasing the maximum operating temperature, varying the assumptions for ambient temperature and wind speeds based on location, season and environment. There is a significant variability in line ratings between the summer and winter seasons (around 30%), but the largest variability is caused by wind. It is practicable to achieve higher ratings with overhead transmission lines using dynamic rating capability. Ratings of two times or more are practicable.

The Literature Review (Appendix A) also found that power transfer capability of existing overhead infrastructure could be increased in cost-effective ways by upgrading/uprating as follows:

(a) Expand current overhead transmission line into multi-circuits, multi-voltage lines.

(b) Replace ACSR conductors with HTLS conductors.

(c) Convert existing AC line into a hybrid AC/DC line.

It should be noted that an underground transmission line cannot be upgraded/uprated like an overhead transmission line.

4.5 Reliability Performance

Most of the overhead transmission lines in Australia, perform to a high level of reliability—typically forced outages are less than 1.0 incident per annum per 100km per year. In general, a higher system voltage line has better reliability performance – this is mainly due to measures to address lightning performance (e.g use of two earthwires, longer insulation and lower footing resistances). For example, using the above design measures, it is possible to design a 500kV overhead line to achieve a forced outage performance rate not greater than 0.5 outages per 100km per year.

In Victoria, the electricity system code [4] outlines the performance standard of forced outage rate due to primary failure and lightning/storms for overhead transmission lines. The requirement is less than 1.0 incident per annum per 100 circuit km. For a double circuit line of 100km length, the requirement is 2.0 incidents per annum. There is also a requirement for a secondary failure to be less than 0.5 incidents per annum per 100 circuit km [7].

Structural Failures—More recently, there have been 2 incidents of structural failures to overhead transmission lines. These occurred in Victoria and South Australia. The first was the six tower failures on the 500kV double circuit line in Southwest Victoria on 31 January 2020 that supplied power to the Portland aluminium smelter. In this instance, it was reported that the wind speeds were more than 160km/hr. The second was on the 28 September 2016, with one single circuit and one double circuit tower failure on the Victoria to South Australian inter-connector. It was reported that there were tornadoes with wind speeds in the range of 190–260km/hr.

In the 1990s, in Queensland, there were several double circuit 275kV transmission tower failures in the Esk ranges. One of the incidences resulted in a cascading failure of 6 towers, after one tower failed mainly due to severe uplift wind conditions. The section of transmission line had been built on the ranges and the towers were reported to have experienced a 1 in 80-year wind on a cold day (where tensions on the conductors were higher than normal). The tension on the conductors is dependent on the temperature. Under hot conditions, the conductors elongate, and conductor tensions reduce, whereas under cold conditions, the conductors contract and conductor tensions increase.

Figure 9. Fallen 500kV Double Circuit Tower, Victoria (Zinfra Pty Ltd.) and 275kV tower, South Australia (ABC News: Dean Faulkner)

While transmission structure failures have occurred in recent times, these failures are considered rare and the failure rate of transmission structures in Australia is in the order of 0.85 in 175,000 per annum [5] or 0.0012 per 100 km per annum (based on 70,000 km of overhead transmission lines in Australia).

Repair times for overhead transmission lines will in general, be of shorter duration compared to underground cable transmission. Even in the cases illustrated above, where towers have fallen, temporary line diversions can usually be constructed within a week, thereby allowing permanent repairs to be subsequently completed without causing continued disruption.

The literature review (Appendix A) highlighted a study which reviewed the Estonian transmission system has compared the reliability (in terms of outage rate) for different voltages (110kV, 330kV) and for steel and concrete structures:

- The concrete structures have tended to have a better performance than steel (There was however no explanation given for this trend).
- Outage times for the higher system voltage lines tended to be longer.
- Outage times tended to be longer where access to the line was further from public roads.

4.6 Construction Phase

An Environment Management Plan (EMP) will generally be implemented for transmission line projects. Requirements for this plan will have been identified in the overall Environmental Impact Study during the planning phase of the project. In general, the key activities and sequence for construction of an overhead transmission line are:

1. Construction surveys
2. Corridor clearing and site access tracks.
3. Excavation and construction of structure foundations
4. Structure assembly
5. Conductor stringing
6. Fitting of insulators hardware and fittings
7. Final inspections
8. Testing and commissioning

Time frames for the construction phase of an overhead line will of course vary depending upon factors such as route length, geography, environment, and packaging of segments of the project for concurrent work. A typical overhead transmission line construction of 100 km will generally take from 1 to 2 years to complete.

4.7 Operation and Maintenance

Policies, plans, and strategies for operation and maintenance of transmission lines form a major part of a utility's overall life-cycle asset management regime. The basic categories of maintenance activities for overhead transmission lines are [2]:

(a) Periodic inspections and condition-based assessments may include ground based or aerial based inspections, detailed inspections of structures, and assessment of vegetation growth near the lines.

(b) Periodic maintenance includes activities such as vegetation management, painting of steel strictures, and insulator washing.

(c) Preventative maintenance or defect repairs usually involves repairs or replacement of defective or damaged components identified from inspections, e.g., insulators, clamps, spacers, excessive conductor sag.

(d) Emergency restoration or repairs are done after a failure

Maintenance tasks are carried out by highly trained personnel. Application of modern technologies such as drones and robotics are being introduced and trialled in some areas [6].

4.8 Increasing the Utilization of Existing Overhead Transmission Lines

An advantage of overhead transmission lines compared to underground cables is that there are options to increase the utilization of the transmission line during its lifespan. CIGRE publication 353 "Guidelines for Increased Utilization of Existing Overhead Transmission Lines" [7] identified 4 main categories of areas for the utilisation of existing overhead transmission lines as follows:

1. Uprating is defined as increasing the electrical characteristics of a line due to, for example, a requirement for: higher electrical capacity or larger electrical clearances.
2. Upgrading is defined as increasing the original mechanical strength and or electrical for increased applied loads such as wind, ice and any load case combination or increasing electrical performance such as pollution or lightning performance.
3. Refurbishment is defined as being the extensive renovation or repair of an item to restore the intended design working life. Life extension is an option of refurbishment which does not result in the complete restoration of the original design working life.
4. Asset Expansion is defined as increasing the functionality of transmission line, e.g. utilising structures for 3rd party assets such as mobile phone antennas and fibre optic cables.

Table 5. Categorisation of CIGRE 353 Case Studies and Cost Impact

Utilisation Description	Uprating	Upgrading	Refurbishment	Asset Expansion
Painting of steel towers			Minor cost	
Attaching conductors at higher location on tower	Minor cost			
Line voltage uprating	Moderate cost			
Increasing temperature of conductor	Minor cost			
Raising height of structures	Moderate to High cost			
Upgrade towers to higher wind speed (change steel members)		Minor cost		
Reinforcement of wood pole K-frame			Minor cost	
Reinforcement of concrete foundations			Moderate costs	
Upgrading of insulators		Moderate cost		
Increasing capacity of line (changing conductors)		Moderate to high cost		
Installation of optic fibre to line				Minor cost
Installation of mobile antennas to towers				Minor cost

The CIGRE publication also considers the economics of the various categories of increasing utilisation and identifies 2 key points in asset lifespan:

1. Technical end of life—where the line fails to perform within the normal operating requirements without abnormal maintenance or when the line is no longer fit for the original purpose) and
2. Optimal time for renewal where the cumulative net present value of future annual costs of the transmission line, (including maintenance, losses and risk costs, per years of service of is equal to the minimum long run average costs of a renewal project.

The optimum time for renewal and the technical end of life are intrinsically linked as the optimum time for renewal. This is influenced by factors such as the original design, construction and workmanship of the asset, operating environment (e.g. degradation due to ultra violet radiation, extreme ambient temperature, lightning, wind and ice exposure), maintenance quality and subsequent requirements to comply with new safety or design standards and codes.

There were a number of case studies for each of the asset renewal options, with some being low cost (e.g. painting of towers), some having moderate costs (replacement of insulators and tower members) and some having high costs (upgrading of line by replacing the conductors with higher capacity high temperature conductors). Table 5 summarises and categorises the case studies and identifies the likely cost of the changes.

The majority of the case studies involving minor costs only achieve an incremental increase in electrical or structural ratings or life extension of the transmission line.

Where moderate or high costs are expended, such as (a) changing of conductor to a higher capacity high temperature conductor or (b) adding extensions to height of the structures, or (c) change voltage on the line, will generally result in a significant up-rating of the line.

Feasibility of uprating HVAC lines to a higher voltage

A case study from Brazil had the highest benefit to cost ratio and involved uprating line by re-insulating from 69kV to 138kV to achieve a 100% increase in line capacity at a cost of 20% of a new line.

Given the age when the up-rating of the transmission line is being considered (around 50 years) and the up-rating is not likely to increase the expected life of the transmission line (being in the range of 70 to 80 years), an economic study will need to be performed to determine if the benefits are greater than the costs.

In the past, some utilities in Australia have considered up-rating conductors on aged transmission lines to high temperature conductors and found the economics did not support the up-rating option. It was more economic to pull down the existing line and build a new line with the high temperature conductors.

Some of the cases which involve either (a) attaching conductors at a higher location on the crossarm/tower or (b) increasing temperature of conductor are generally incurred at a minor cost and would tend to show a positive benefit to cost ratio.

In general, uprating existing HVAC lines to a higher voltage, e.g. 275kV to 500kV, will not be economically feasible if significant modifications to the existing structures are required such as:

- Increasing reach of earthwire cross-arms for effective lightning protection
- Increasing strength of structures, conductor cross-arms to support additional bundled conductors (from double to quad bundled
- Increasing height to meet ground clearance requirements for the higher voltage.

HVAC transmission line conversion to a HVDC Line

There is also an option of converting existing HVAC transmission circuits to HVDC to achieve a higher rating, typically between 50% and 100%. One such approach is being undertaken on the UltraNet project by Amprion and TransnetBW in Germany, where an existing 380kV AC line is being converted to a ±-380kV line with a metallic return—refer to Figure 10. This new HVDC line has a 2GW capacity.

4.9 End of Life and Decommissioning

CIGRE's Green Book (2017) [2] suggest an estimated lifetime of 60 to 120 years, for overhead transmission lines if well maintained. This assumes that major components such as conductor fittings, insulators and corrosion protection are replaced or addressed during that time. Maintenance policies and practices including inspection and testing are key factors that influence the lifetime of transmission lines.

Decommissioning of overhead transmission lines requires a comprehensive approach that considers a range of factors to ensure the process is conducted in a responsible and efficient manner to minimise any negative impacts on the environment and surrounding communities. Key factors include:

(a) Safety and Environmental Impact: Measures must be taken to ensure the safe removal of equipment, structures, and conductors. These need to be carried out in compliance with

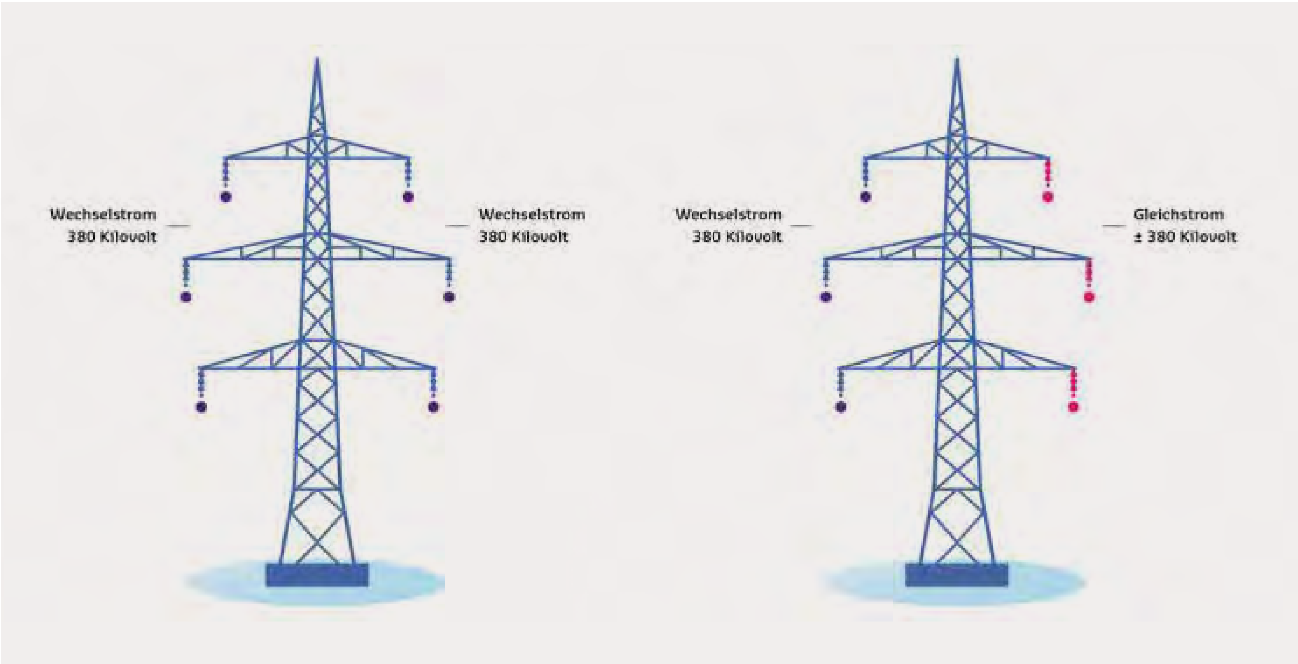


Figure 10. Ultranet Project—HVAC to HVDC Conversion (Amprion[8])

environmental regulations to prevent any harm to human health or the environment.

(b) Removal and Disposal of Equipment: Towers, conductors, insulators, and other equipment need to be carefully dismantled and transported to designated facilities for recycling, reuse, or proper disposal. Maximisation of the recovery of valuable materials and minimisation of waste are also important.

(c) Site Remediation: Site remediation may be necessary to restore the land to its original condition or repurpose it for other uses. This may involve activities such as grading, erosion control, vegetation restoration, or land reclamation. Environmental assessments may be required to ensure compliance with local regulations and mitigate any potential impacts.

(d) Stakeholder Engagement: Stakeholder engagement is crucial throughout the decommissioning process. Communication with local communities, landowners, regulatory agencies, and other relevant stakeholders needs to be established to provide adequate information about the works to address any concerns that might arise. This can include notifying residents about the decommissioning activities, coordinating road closures or traffic diversions, to minimise any potential disruption or inconvenience caused by the process.

(e) Transmission System Reliability: Decommissioning of overhead transmission lines should be carefully planned to minimise any impact on the reliability of the overall transmission system.

(f) Regulatory Compliance: Compliance with applicable regulations and permits is essential during the decommissioning process.

(g) Cost and Financial Planning: Decommissioning overhead transmission lines can involve significant costs, including equipment removal, site restoration, and any required environmental assessments.

[8] https://www.amprion.net/Grid-expansion/Our-Projects/Ultranet/

05.

Characteristics of HVAC Underground Transmission Lines

This section details the main system design characteristics and life cycle requirements for underground transmission cables.

5.1 Types of Transmission Cables

Fluid-Filled Cables were the first underground transmission cables developed around 100 years ago. Comprised of a conductor with layered paper tape insulation which was impregnated with an insulating oil and kept under positive pressure by a hydraulic system including tanks located along the cable route to suit the route profile. Gas-filled pressurised cables were another a common fluid-filled cable design but was found to be only suitable for lower transmission voltages. The last two decades have seen most fluid-filled cable systems decommissioned and replaced.

Cross Linked Polyethylene (XLPE) Insulated Cables have become the dominant technology for high voltage cables. A typical HV cable construction in shown in Figure 11.

XLPE insulated cables have many advantages over previous cable types which include:

- not containing fluids that could leak and cause environmental harm;
- requiring less maintenance compared to fluid-filled cables;

Figure 11. Typical Underground Transmission Cable Construction (Wuxi Lonheo International Trade Co., Ltd.)

Figure 12. HV Gas Insulated Transmission Line (Siemens)

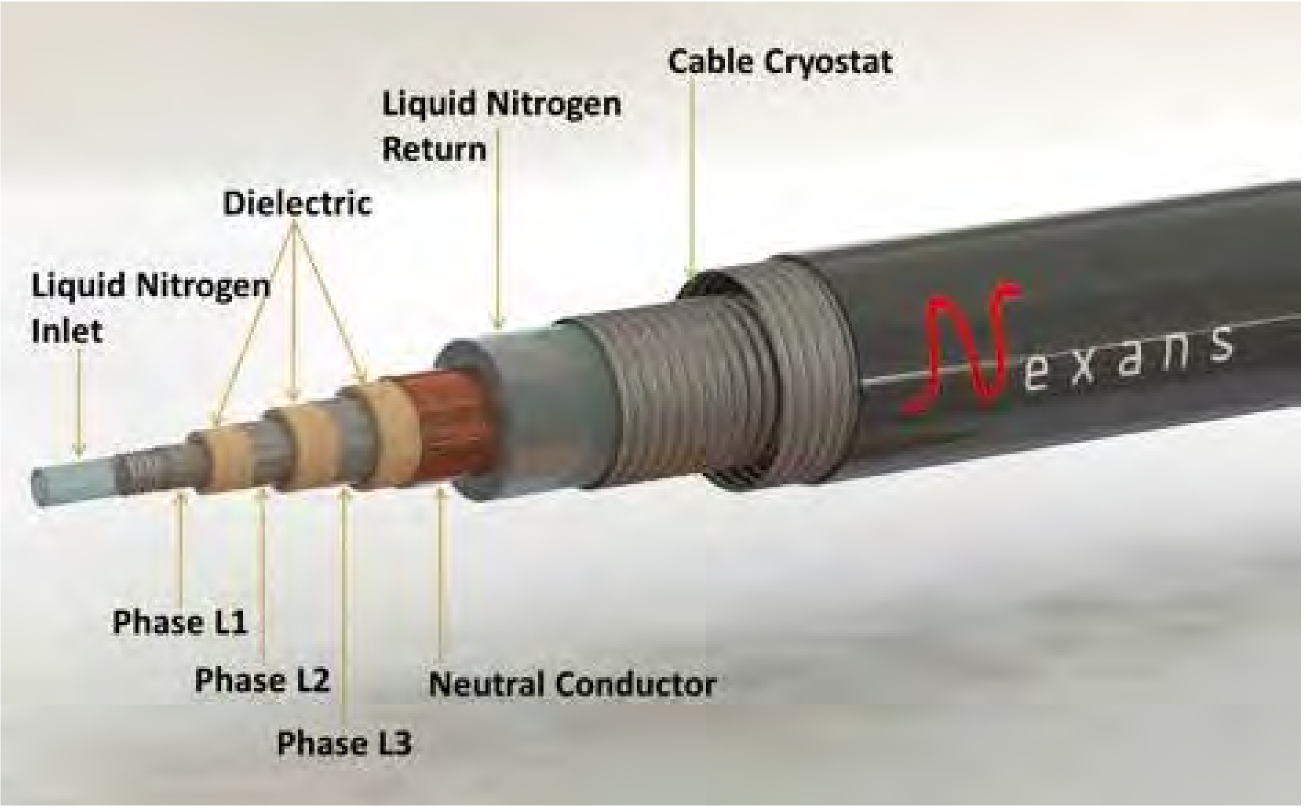


Figure 13. Design of a High Temperature Superconducting (HTS) Cable for AC Operation with 3 Phases Cooled by Liquid Nitrogen (Nexans)

- having improved fire resilience and performance;
- having lower dielectric losses and are therefore cheaper to operate;
- being more economical to manufacture compared to other designs.

The world's first 500kV XLPE system was commissioned in Japan by Hitachi in 1988 [8]. XLPE cable technology has considerably matured since that time and has become the dominant and most economical technology for EHV cables.

Gas Insulated Lines (GILs) were invented in the early 1970's with the objective of providing a high-capacity transmission system with maximum safety for equipment and personnel in energy tunnel systems. This target was reached by replacing flammable insulation materials (e.g. XLPE and fluid-filled cables) with non-flammable and non-toxic insulating gas such as nitrogen (Energinet [9]). These systems have been used in Europe in special limited applications. Disadvantages of the system are the additional installation and maintenance requirements associated with the gas-filled system. The construction of this systems is illustrated in Figure 12.

Super-Conducting Transmission Lines (SCTLs) are currently a developmental technology that offers lower losses, higher power transfer, compact size requiring much reduced corridor width and low electromagnetic field emissions [10]. An example of a superconducting cable is shown in Figure 13. There are several short route length (100 to 2500m) trial installations around the world in USA, China, Japan, Russia, Korea and Germany [11]. Superconductors are materials that, when cooled below a certain critical temperature, can conduct electric current without any resistance, resulting in extremely efficient electrical transmission, and significant increases in thermal rating and transfer capability. This technology however is not yet considered to be viable at this point in time for transmission line projects.

For this report only XLPE cable systems have been considered for the comparison with overhead transmission because this is now the dominant HV cable technology used by transmission utilities around the world and in Australia.

5.2 Long HV Underground Cable Transmission Installations

There are many significant underground transmission cable projects from around the world that have been reported in various publications including by CIGRE TB680 2017 [12]. A summary of these is provided in Table 6.

Table 6. Long HV Underground Cable Installations-Onshore, 275kV or Greater (adapted from CIGRE 2017 [12])

Ref	Country	Tear	Name	No. of Circuits	Voltage (U0 0	Power	System Length (Total)	Conductor Size	Conductor Material	Insulation type	Cable type
1	United Kingdom	1967	New Cross	2	275 kV	800 MVA	22 km	1613 mm²	Copper	SCFF	3 x1 core
2	United Kingdom	1967	Wimbledon	1	275 kV	760 MVA	21 km	1613 mm²	Copper	SCFF	3 x1 core
3	USA	1967	NYC-1967	1	345 kV	650 MVA	21 km	1267 mm²	Copper	HPFF	3 x1 core
4	USA	1968	NYC-1968	1	345 kV	650 MVA	21 km	1267 mm²	Copper	HPFF	3 x1 core
7	USA	1974	NYC-1974-1	1	345 kV	650 MVA	28 km	1267 mm²	Copper	HPFF	3 x1 core
8	USA	1974	NYC-1974-2	1	345 kV	650 MVA	28 km	1267 mm²	Copper	HPFF	3 x1 core
9	USA	1978	NYC-1978	1	345 kV	650 MVA	29 km	1267 mm²	Copper	HPFF	3 x1 core
11	Canada	1984	BC Hydro - Vancouver	2	525 kV	1200 MVA	38 km	1600 mm²	Copper	SCFF	3 x1 core
12	Denmark	1997	Copenhagen; Southern Cable Route	1	400 kV	975 MVA	22 km	1600 mm²	Copper	XLPE	3 x1 core
13	Spain -Marocco	1997	Spain-Morocco Interconnection	1	400 kV	700 MVA	28 km	1600 mm²	Copper	SCFF	3 x1 core
14	Australia	2000	NSW - Transgrid	1	330 kV	750 MVA	28 km	1600 mm²	Copper	SCFF PPLP	3 x1 core
15	Japan	2000	Shin - Toyosu Line	2	500 kV	1800 MVA	40 km	2500 mm²	Copper	XLPE	3 x1 core
19	Japan	2005	Nishi Osaka - Ozone Line	1	275 kV	322 MVA	19 km	1500 mm²	Copper	XLPE	3x1 core
22	United Kingdom	2005	St Johns Wood	1	400 kV	1600 MVA	26 km	2500 mm²	Copper	XLPE	3x1 core
23	Saudi Arabia / Bahrain	2006	GCCIA Interconnection	2	400 kV	1200 MVA	51 km	2000 mm²	Copper	SCFF	3x1 core
24	Spain -Morocco	2006	Spain-Morocco Interconnection	1	400 kV	700 MVA	33 km	1600mm²/ 800 mm²	Copper	SCFF	3x1 core
28	USA	2008	Middletown – Norwalk	2	345 kV	600 MVA	38 km	1500 mm²	Copper	XLPE	3x1 core
29	China	2009	Hainan - Guangdong	1	525 kV	740 MVA	32 km	800 mm²	Copper	SCFF	3x1 core
55	Japan	2014	Chiba -Katsunan Line	2	275 kV	860 MVA	30 km	2000 mm²/ 2500 mm²	Copper	XLPE	3x1 core

Ref	Country	Tear	Name	No. of Circuits	Voltage (U0 0	Power	System Length (Total)	Conductor Size	Conductor Material	Insulation type	Cable type
61	Italy	2015	Sorgente-Rizziconi	2	380 kV	2000 MVA	47 km	2500 mm^2/ 1500 mm^2	Copper / Aluminum	XLPE / SCFF PPLP	3x1 core
62	Netherlands	2015	Randstad	2	380 kV	5280 MVA	20 km	2500 mm^2	Copper	XLPE	3x1 core
68	Japan	2016	Kawasaki - Toyosu Line	3	275 kV	1710 MVA	22 km	2500 mm^2	Copper	XLPE	tri-core cable
71	Norway	2017	Kollsnes - Mongstad	1	420 kV	300 MVA	30 km	1200 mm^2	Copper	XLPE	3x1 core
75	Japan	1995	Katsunan -Setagaya Line	3	275 kV	1380 MVA	33 km	1200 mm^2/ 1400 mm^2/ 1600 mm^2	Copper	XLPE	tri-core cable
76	Japan	1995	Yokohama - Kohoku Line	3	275 kV	2220 MVA	20 km	2000 mm^2/ 2500 mm^2	Copper	XLPE	3x1 core
77	Japan	1993	South Route by CEPCO (Chubu)	2	275 kV	1180 MVA	28 km	2500 mm^2	Copper	XLPE	3x1 core
78	Japan	1999	West Route by CEPCO	2	275 kV	1280 MVA	23 km	2500 mm^2	Copper	XLPE	3x1 core
79	Korea	T.B.A.	Nam Pusan - Buk Pusan	3	345 kV	520 MVA	22 km	2000 mm^2	Copper	SCOF	3x1 core
80	USA	T.B.A.	Yonkers - East Garden City	1	345 kV	693 MVA	42 km	1267 mm^2	Copper	HPFF / SCFF	3x1 core

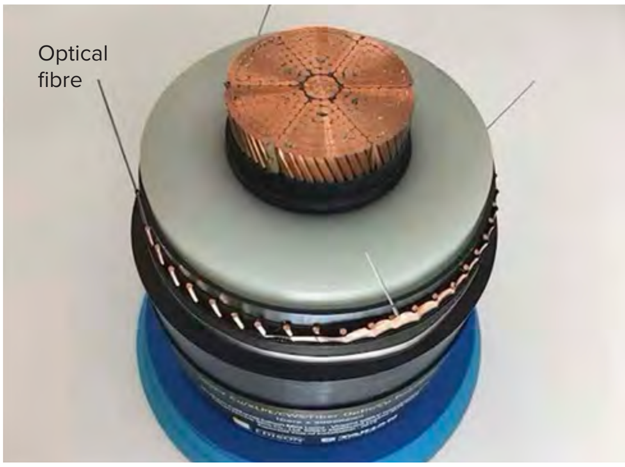


Figure 14. 500kV 2500mm Copper Conductor XLPE Cable with Laminated Copper Sheath and Embedded Optical Fibre Cable (T&D World[9])

5.3 XLPE Cable and Accessories—Design Factors

Conductors used on underground transmission cables are predominantly copper because of its higher conductivity to aluminium and small cross-section for the equivalent rating. Copper is also considered more corrosion resistant compared to aluminium and has a longer life. The early 500kV transmission cables had a cross sectional area of 800mm^2 but in recent times conductor sizes up to 2500mm^2 are common. A typical 500kV UGTL cable is shown in Figure 14.

This cable can achieve a rating or around 600MW single circuit and 1200MW double circuit. If power transfers of over 2000MW are required, there may need to be two sets of cables per phase per circuit. The embedded fibre optical cable is used for distributed temperature sensing (DTS) along the cable route to identify sites of overheating which can lead to electrical failure of the cable. The fibre optical cable can be installed on the conductor core (to directly measure the core temperature) or on the surface of the cable (to indirectly measure the core temperature). DTS monitoring equipment is normally installed at the substations which the cables terminate.

XLPE Insulation—In the early years of manufacture using XLPE, there was poor quality control in the manufacturing process. This caused (a) protrusions on the conductor shield; (b) contaminants in the insulation, including conductive and insulating particles, which have a significant effect on conductivity of insulation; (c) voids in the insulation, which permit electrical discharges. When put into service in environments subject to moisture, if there were ingress of water (via the joints/conductors or diffusion in the insulation), there was initial “water treeing”, which led to electrical treeing and finally breakdown of the insulation. These issues have been addressed by design and manufacturing improvements. The maximum operating temperature of the XLPE is in the range of 80°C to 90°C. Insulation thickness for cables rated at 400/500kV tend to be in the range of 27 to 32mm [13] .

Electrical Operating Stress (kV/mm) on a cable’s insulating shields is a major influence on the cable design and its service life. The design of HV cables in the 400 to 500kV range generally results in higher electrical stresses, but the installation thickness and overall diameter of the cables have to be designed to accommodate flexibility and practical installation. Data sourced from EPRI [8] shows that the electrical stresses with XLPE insulation shields increase with voltage levels—refer Figure 15. The electrical stresses on a 500kV nearly double compared to the values for 220kV

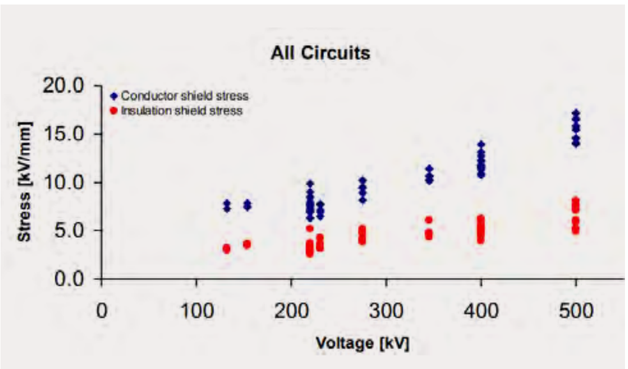


Figure 15. Conductor and Insulation Shield (Screen) Stresses Increase with Voltage (EPRI -2002 [8])

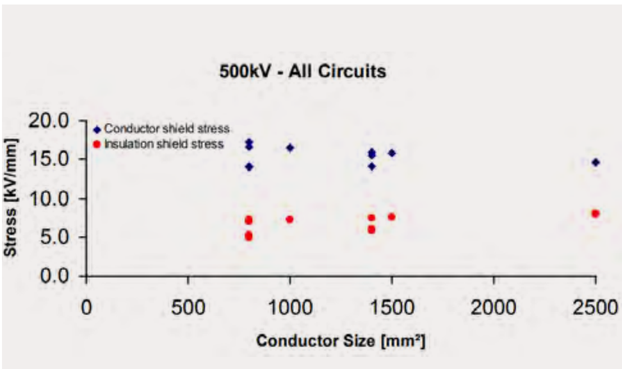


Figure 16. Variation in Conductor and Insulation Shield Stresses with Conductor Size at 500kV (EPRI 2002 [8])

[9] Engineering a 500-kV Underground System | T&D World (tdworld.com).

at around 15 kV/mm for the conductor and 8kV/mm for the insulation shield.

Smaller conductor sizes can be seen to have higher conductor shield stresses, while insulation shield stresses remain similar [8] as shown in Figure 16.

The breakdown voltage of XLPE varies significantly with temperature. It has an electrical breakdown voltage of around 50 kV/mm at room temperature but will reduce by 25% at 90°C and if increased from 90°C to 130°C will reduce by another 40% [13]. These factors influence the selection of cable conductor size and installation design to achieve the desired normal and emergency power transfer rating.

Cable Joints and terminations are essential components in a transmission cable system. Joints are required as cable is typically manufactured in continuous lengths of 500m to 1000m for transport logistics and also to suit site project specific requirements for joint bay location. Maximum lengths can be up to 1000m for transmission cables. This length range allows for transport of cable from factory to site on large drums or reels, so joints are required at regular intervals along the route.

Cable joints and terminations are required to meet the same electrical performance as the cable and an ideal joint would result in no mechanical, thermal or electrical discontinuity in the cable. In practice, joints have a larger radial dimension compared to the cable, and this leads to longitudinal components of stress in the joint component. Joints can also be a point for moisture ingress which can accelerate electrical breakdown and failure of the cable insulation.

Today's HV transmission cable accessories are manufactured using high quality materials, sophisticated production equipment and quality control. Prefabricated or pre-moulded joints and stress cones for terminations are now used extensively with HV transmission cables including at voltages of 400 to 500kV. A systems approach is required with accessories being purpose designed to match the cable. A diagram of typical XLPE cable joint is shown in Figure 17.

Cable terminations are required at the termination points of the cable usually in a substation or at overhead to underground transition points in a hybrid transmission line. Terminations for outdoor locations are air insulated of porcelain or composite insulator construction as shown in Figure 18. Gas insulated terminations are used where cables are required to connect directly to a transformer or gas insulated switchgear (GIS)—see Figure 19.

Joints and terminations are assembled on site by highly trained and qualified personnel. The environment for this work must be protected from the weather, clean and dust-free.

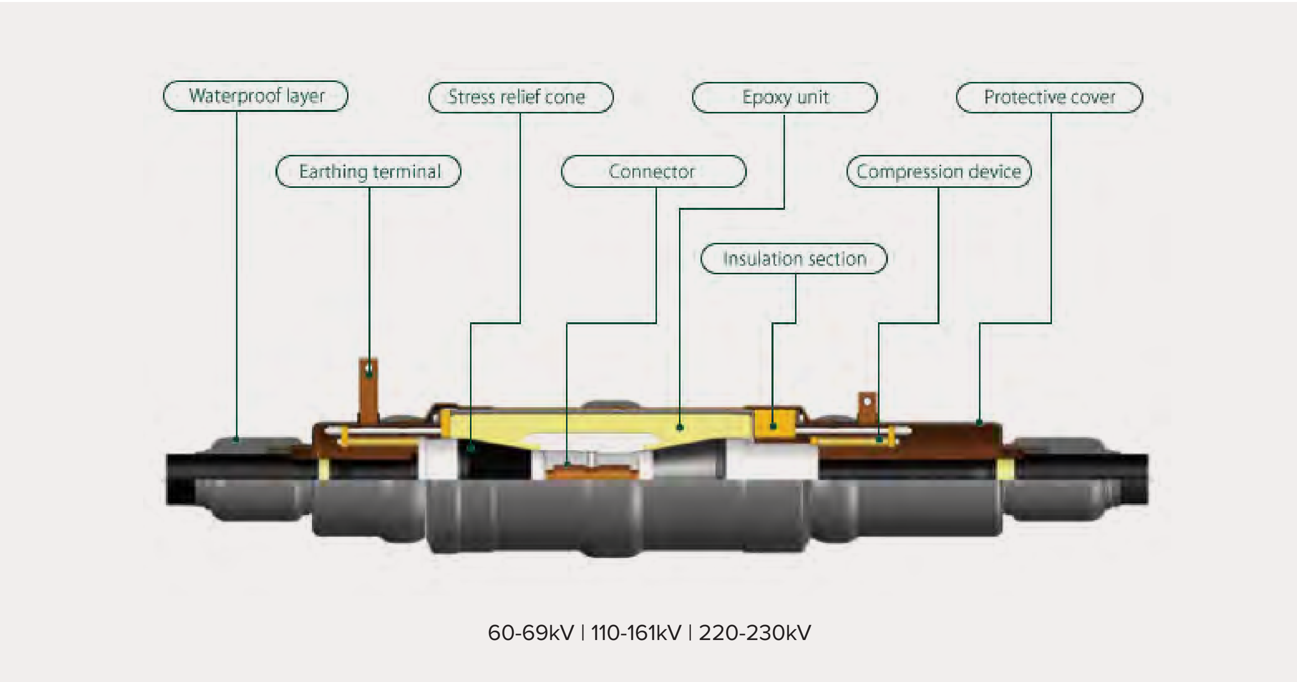


Figure 17. Prefabricated XLPE Straight Cable Joints (SWCC Corporation[10])

[10] https://www.swcc.co.jp/eng/products/siconex/cable_joint.html.

5.4 Transmission Cable System Design and Implementation

Critical Length—In contrast to overhead lines the impedance of an underground transmission cable is highly capacitive in nature—across the insulation, which is between the conductor and the external metallic sheath. The maximum length of AC transmission cable is limited by the capacitive charging current since charging current increases proportionally with length. As the length of cable is increased, a point is reached where the total charging current equals the cable rating. This point is known as the "Critical Length". The Critical Length can be calculated by equation below from EPRI 2015 [13]

$$Critical\ Length = I / Ic$$

Where:
I = normal rating, in amps
Ic= charging current, amps/m

The maximum feasible cable length must be significantly less than the Critical Length to transmit a reasonable amount of power. EPRI 2015 [13] provides examples. The values for XLPE cable from this reference are provided in Table 7.

Table 7. Critical Length for XLPE Underground Cables at Different Voltages (EPRI—2015)

Voltage (kV)	Critical Length (km)
138	193
230	130
345-400	85
500	76

Note: assumes 1600 mm^2 cable with XLPE insulation

Reactive Compensation Plant—Transmission cable capacitance causes voltage rise from the sending end to the receiving end. If the transmission cable capacitance is not compensated by inductance, the voltage at the receiving end would be higher than the voltage at the sending end. The effect can be most noticeable at times of low system load.

Reactive compensation is provided by supplying inductive power, which acts in the opposite way to capacitive power and consequently cancels it

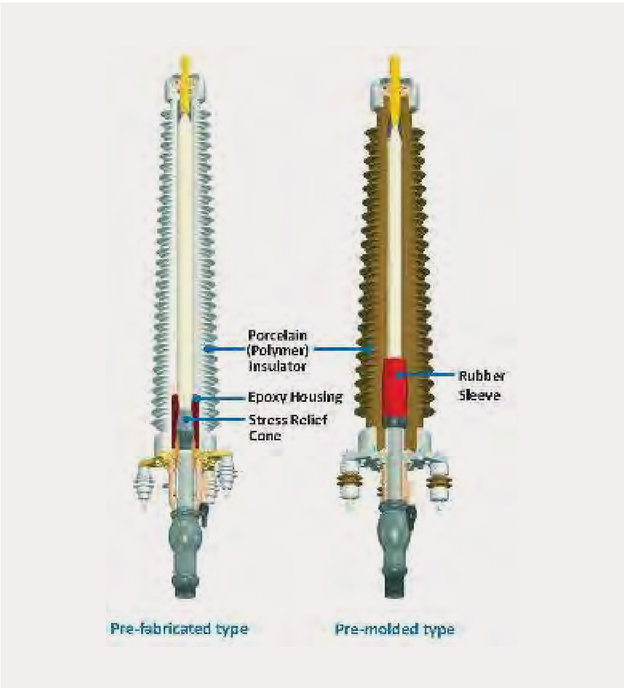


Figure 18. Outdoor XLPE Cable Termination (LS Vina Cable & System[11])

Figure 19. Typical HV Gas Insulated Switchgear (GIS) with cable terminations Installed in Horizontal Position (Nexans / Frederic Lesur)

[11] https://lsvinacns.vn/outdoor-terminations.

out. Small amounts of capacitive reactance, say, in a short route length of cable of a few kilometres, can in most cases be compensated by the inherent inductance of generators and overhead lines in the system nearby. However, for longer route lengths, reactive power compensation plant in the form of passive compensation plant such as shunt reactors or active compensation plant such as static Var compensator (SVC) or STATCOM is required. The reactive compensation plant is normally installed at the terminal substations, but for long cable routes reactive compensation may be required points along the route to avoid unacceptable voltage rise at times of low load.

CIGRE -2017 [12] provides a guide for the amount of reactive compensation required per km cable route transmission cable. Reactive power compensation quantity is normally expressed in Mega Volt-Amperes Reactive (MVAr). From the CIGRE 2017 reference, as an example for a 400kV 2000mm^2 conductor cable, reactive compensation of 9.5MVAr/km would be required. The actual amount of reactive power compensation required would be determined in the planning phase of the project based on the system specific studies.

In comparison with an equivalent overhead line, an underground transmission cable line is estimated to produce 8 to 10 times more reactive capacitive power (Energinet [9]). This is therefore a significant cost in an underground transmission system.

Harmonic Filters and Resonance Mitigation Techniques—CIGRE 2017 [12] reports that low levels of harmonic distortion are present in the electricity supply voltage wave form mainly from: a) power electronic equipment by end users; b) HVDC connections; c) solar and wind farms. The addition of a long EHV transmission cable to a network can amplify the effect of exiting harmonics present in the supply systems. This is due to the high levels of capacitance in EHV transmission cables that can cause resonance with the inductance of the external system in power grid at a particular frequency. Inter-harmonics could also be from switching actions, especially transformers and cables.

Resonance can cause damage to components of the grid and must be avoided. This is mainly done by passive filters or in special cases by means of active filters.

The requirement for harmonic filters for the transmission line would be assessed in the planning phase of the project.

Cable Sheath Bonding—The effect of induced voltages in the outer metallic sheath of a cable must be considered in the cable system design. Induced sheath voltages are a function of the route length, phase currents, mean diameter of the metallic sheath, spacing between phase cables, supply frequency, and laying configuration of cable (e.g. flat, tre-foil etc.). Sheath bonding arrangements are required: 1) to protect people working on the cables from un-safe voltages; 2) to protect the cable from damage due to transient over-voltages that may occur during system disturbances or faults.

There are 3 main types of bonding arrangements for transmission cables. These are described below and illustrated in Figure 20, Figure 21 and Figure 22.

Figure 20. Solid Bonded Cable System (Electrotechnik[12])

[12] https://elek.com.au/articles/sheath-bonding-design-guide-for-hv-cables/

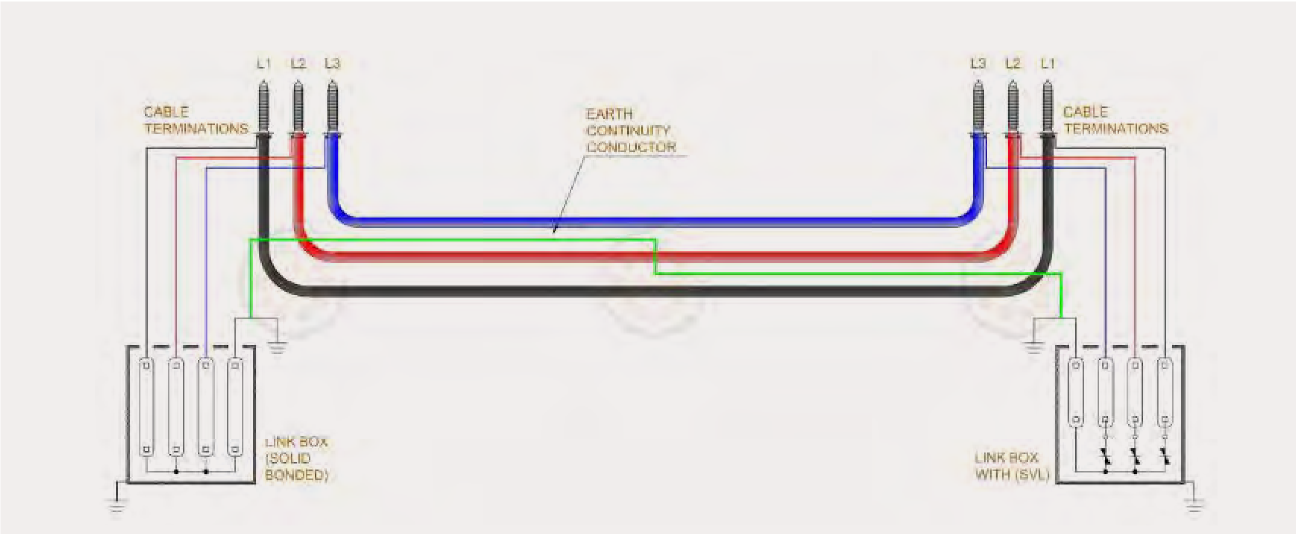


Figure 21. Single-point Bonded System (Electrotechnik[12])

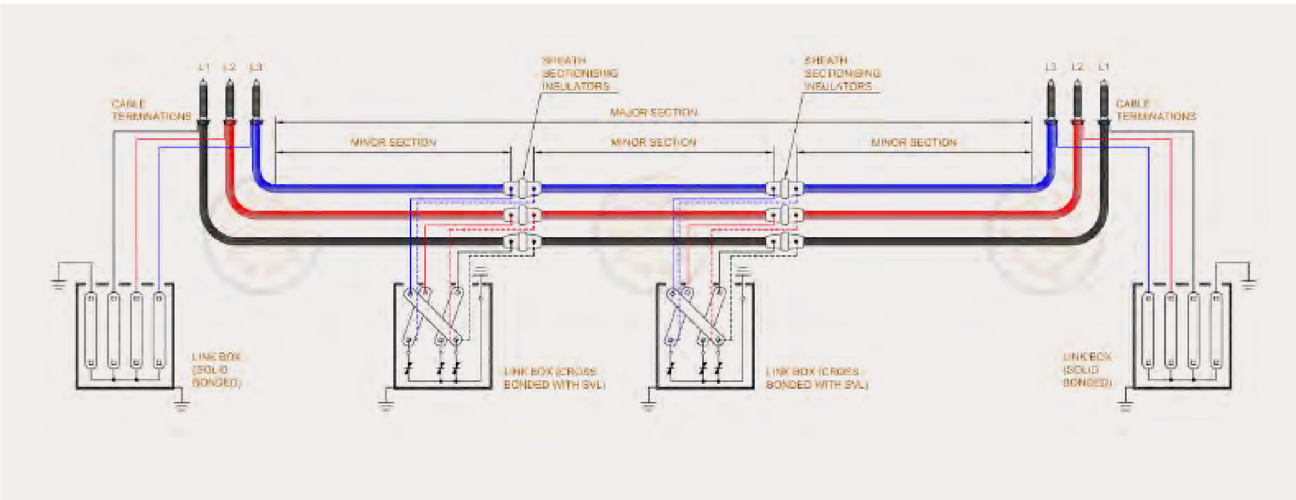


Figure 22. Cross-bonded System (Electrotechnik[12])

a) Solid bonding—with solid bonding there will be a continuous induced current flowing in the sheath, and this can be quite high (due to the close mutual coupling) with the phase conductors. This will significantly reduce the power transfer rating of the cable and result in additional losses. Therefore, this method is only used for very short lengths of underground cable.
b) Single point bonding—typically used for relatively short cable lengths, otherwise electromagnetic induction will produce a significant un-safe voltage on the cable sheath under steady state conditions. Transmission cables typically have a sheath voltage limit of 65V. Additional earthing points in the middle of a cable route may be required if this limit is exceeded.
c) Cross-bonding—transmission cables of reasonable lengths will generally utilise cross-bonding in the installation. With cross-bonding, the cable length is broken up into thirds and the sheath bonding rotates from, say, A phase to B phase to C phase at each third section. With cross-bonding, the electromagnetic induced voltages are cancelled in the cable. Circulating currents in the sheaths are also minimised reducing losses compared to solidly bonded systems. There are some variations with cross-bonded systems. Physically transposing the phase cables at the cross-bonding points will provide additional reduction in induced voltages and currents further.

To protect cables sheaths from phase to earth faults, surge protection devices, Sheath Voltage limiters (SVLs) are used in the link boxes and at termination structures.

Induced Voltages on Nearby Services—As with overhead transmission lines, underground transmission cables can induce voltages in nearby metallic services such as pipelines and other cables that run parallel. This can result in un-safe voltages on the services and damage such as corrosion of the metallic services. Bonding systems as described above can be employed to limit the induced voltages.

On-line Monitoring of Cable Temperature Performance—Modern XLPE transmission cable systems are designed with means of monitoring performance including cable temperatures. Temperature monitoring can be implemented by either:

(a) Discrete temperature sensors placed at hot spots or locations where the calculated thermal rating of the cable is known to be a limiting factor.

(b) Continuously along the cable—known as Distributed Temperature Sensing (DTS). This is normally achieved via a system using an optical fibre cable along the cable. The optical fibre can be integrated into the cable construction (see Figure 14).

Temperature data can be logged and analysed in real time for grid operations or used to review assumptions and parameters for installation and environmental conditions.

Matching overhead and underground transmission line ratings in a hybrid system based on continuous ratings can be economically unattractive, due to the larger cross sections or numbers of cables per phase for underground cables that is needed [12]. Consideration of the thermal inertia of underground cable and application of cyclic or short-term emergency ratings can result in a more optimal economic solution considering number of cables per circuit, conductor sizes, cable installation configuration.

5.5 Underground Cable Installation Methods

Transmission cable routes can comprise one or more different installation methods depending upon different factors and requirements along the route. The main installation methods are detailed below.

Cable Tunnel Installation is the most expensive option and is usually only justified in highly congested areas such as CBD areas or a section of a cable route into a major substation, that is shared by multiple circuits. Tunnels require extensive planning, design, and construction work as well as coordination with local authorities and other utilities. However, there are some advantages of tunnelling such as the opportunity to improve power transfer capability and providing a ready corridor for future cables.

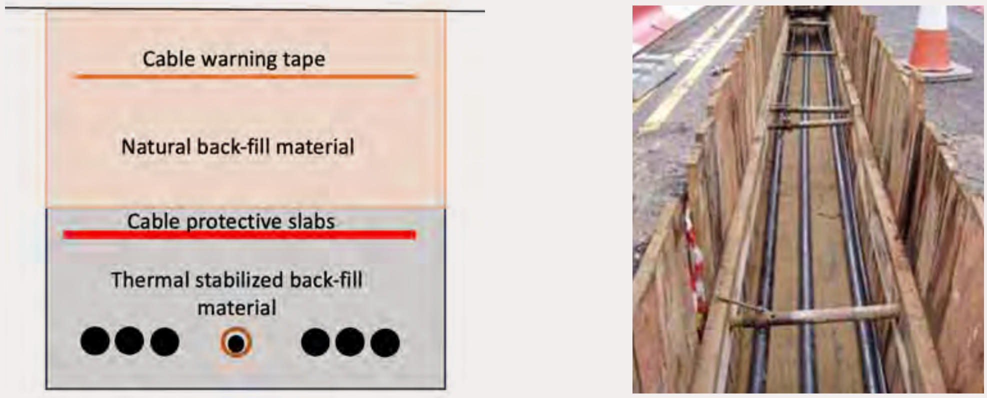
Direct Buried Cable Installation is usually the least cost option and common in Europe and the UK,

Figure 23. Cable Tunnel Installation (Nexans / CIGRE 2017 [12])

particularly in areas where cables are not under public roads. Direct buried sections require that the cable trench should remain open for the complete section between joint bays until all cables are installed, which can take up to 4 weeks or more. Depending on the project the length of these trenches may be up to 1000 metres or more. On completion of excavation works the trench is backfilled with special backfill materials and protective slabs are placed above the cables in the trench. Direct buried cables can offer improved power transfer capability compared buried duct installation with equivalent cable as thermal transfer from the cable is not reduced by air spaces around a cable within a duct.

The main disadvantages of direct buried systems include the fact that the trench must remain open for the cable installation work, which can be an inconvenience and safety hazard for pedestrians and vehicle drivers in the area. It also requires that the local council and/or road authorities agree to the installation and timeframes. As well, any installation of replacement or additional cables in the future requires complete re-excavation of the trench.

Buried Conduit or Duct Installation involves the use of ducts or conduits made from PVC or heavy-duty polyethylene (HDPE) and is the most common method for installation of underground cables. While buried duct cable installation is more expensive than direct buried cables it does have several advantages. For example, the trenching and duct installation for a section of cable between 2 joint bays, can be carried out progressively along the route, including re-instatement, thereby not requiring the total route section trench to be left open for long periods of time. Spare ducts can also be installed in the trench to allow for future network upgrades in an economic staged approach without having to re-excavate the whole route again.

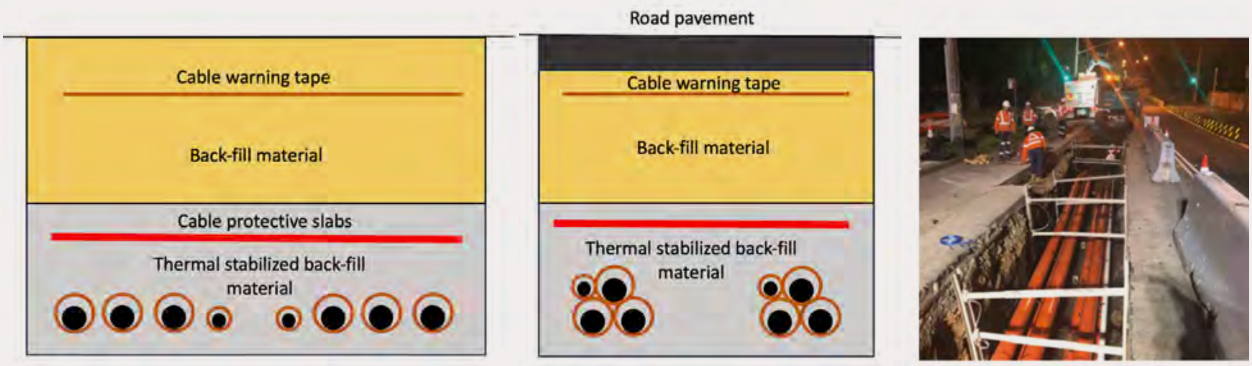


Direct Buried Cable
Flat - spaced

Figure 24. Diagram and Photograph of Direct Buried Cables and Trench (emfs.info[13])

Horizontal Directional Drilling (HDD) [12], is a steerable trenchless method of installing underground conduits and cables in a shallow arc along a prescribed bore path by using a surface-launched drilling rig, see Figure 26. A key benefit of this method is that is has minimal impact on the surrounding area. HDD is used when trenching or excavating is not practical. It is suitable for a variety of soil conditions and jobs including road, landscape, and water way crossings, with different types of heads used in the pilot-hole process depending on soil conditions. The bore profile can be designed to avoid other services and obstacles.

The elevations of the bore vary from a shallow open pit level and are then guided to the required depths across the crossing and finished at the ground level at the other end. A directional drilling machine drills the bore, and the cable conduit is drawn back through the bore. The depth of the bore can be monitored and adjusted accordingly as per the bore profile drawing during the drilling process.

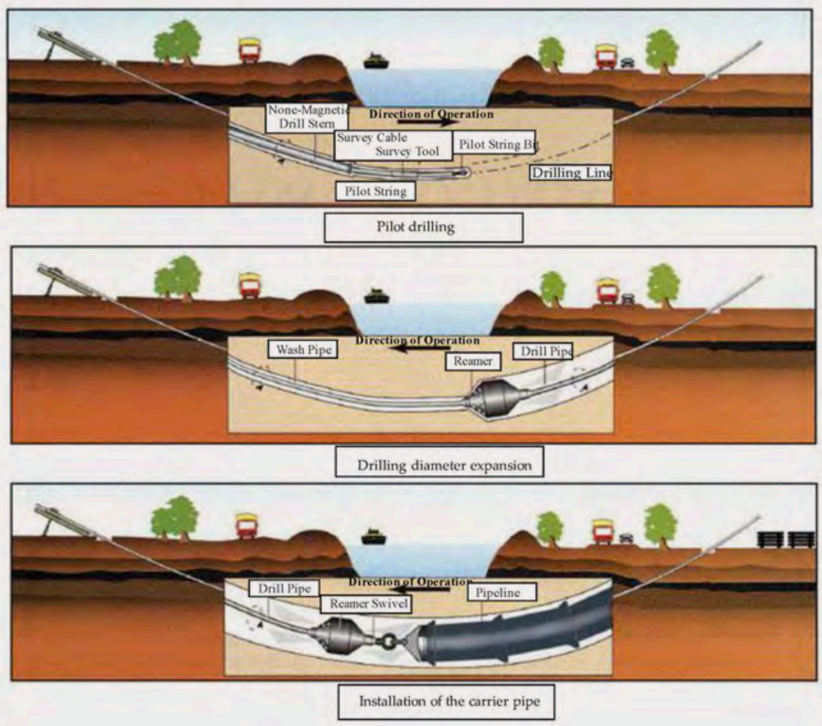


Cable in Ducts
Flat - Spaced

Cable in Ducts
Trefoil - touching

Figure 25. Diagram and Photograph[14] of Cable Duct / Conduit Installation (Photograph: TransGrid)

[13] https://www.emfs.info/sources/underground/types/.
[14] april-2021-project-update-newsletter-inner-west.pdf (transgrid.com.au).



Pilot Drilling:
Installing a pilot hole drilled from the surface at a pre-determined angle and along a prescribed path. During the pilot bore, a sonde (transmitter) and a tracking (receiver) device are utilized to be able to precisely locate and steer the drill string underneath the surface.

Reaming
Enlarges the pilot hole to achieve the required size. Reaming is usually performed in stages until the final desired diameter of hole is reached.

Pipe pullback
The pipe is connected to the drill string and then pulled from the exit pit side towards the entry pit side on the same pre-reamed path.

Figure 26. Horizontal Directional Drilling (HD DRILLING CONTRACTORS[15])

Sleeve bore or micro-tunnelling is like HDD. In most micro-tunnelling operations, the machine is launched through an entry eye and cable conduits are pushed behind the machine. This is a process that is often called pipe jacking. As the machine advances, more tunnel liner or conduit is pushed from the starting shaft, through the entry eye. Voids between the sleeve & conduits are filled with grout.

One disadvantage with HDD is that the cable profile will result in a greater burial depth which will de-rate the power transfer capacity. This can be mitigated by using special flowable fill material with low thermal resistivity to fill voids between the cable and constraining conduits.

Management of Thermo Mechanical Forces—Power cables, joints, and terminations are subject to thermo-mechanical forces due to the nature of cyclic loading that occur in a power grid over a daily and weekly basis. The design of a cable installation needs to analyse the thrust forces that apply in the different parts of the installation so that suitable construction methods to control and mitigate the risk of cable failures due to mechanical forces can then be applied in the design.

Installing cables in a wave formation often known as “snaking” (see Figure 23) is one way of mitigating thermo-mechanical forces. Constrained clamping of cables at points most exposed to thermo-mechanical thrust forces risk, is another method used.

Locations where snaking and clamping of cables are employed include the 15 to 25m sections at the entries of joint bays, inside cable tunnels, bridge structures, substations, and at cable termination points in substations or overhead to underground transitions.

Underground to Overhead Transition Structures

Hybrid overhead and underground transmission lines require overhead to underground transition structures at either end of an underground route segment. The size of these structures increases as the system voltage increase. The designs can be aesthetically improved depending on the locations. Examples of different overhead to underground transitions stations are shown in Figure 27.

To improve the aesthetics of the transition structure, there are designs where the underground cables are installed directly on the transmission tower or pole and

[15] https://www.hddrilling.co.za/what-is-horizontal-directional-trenchless-drilling.

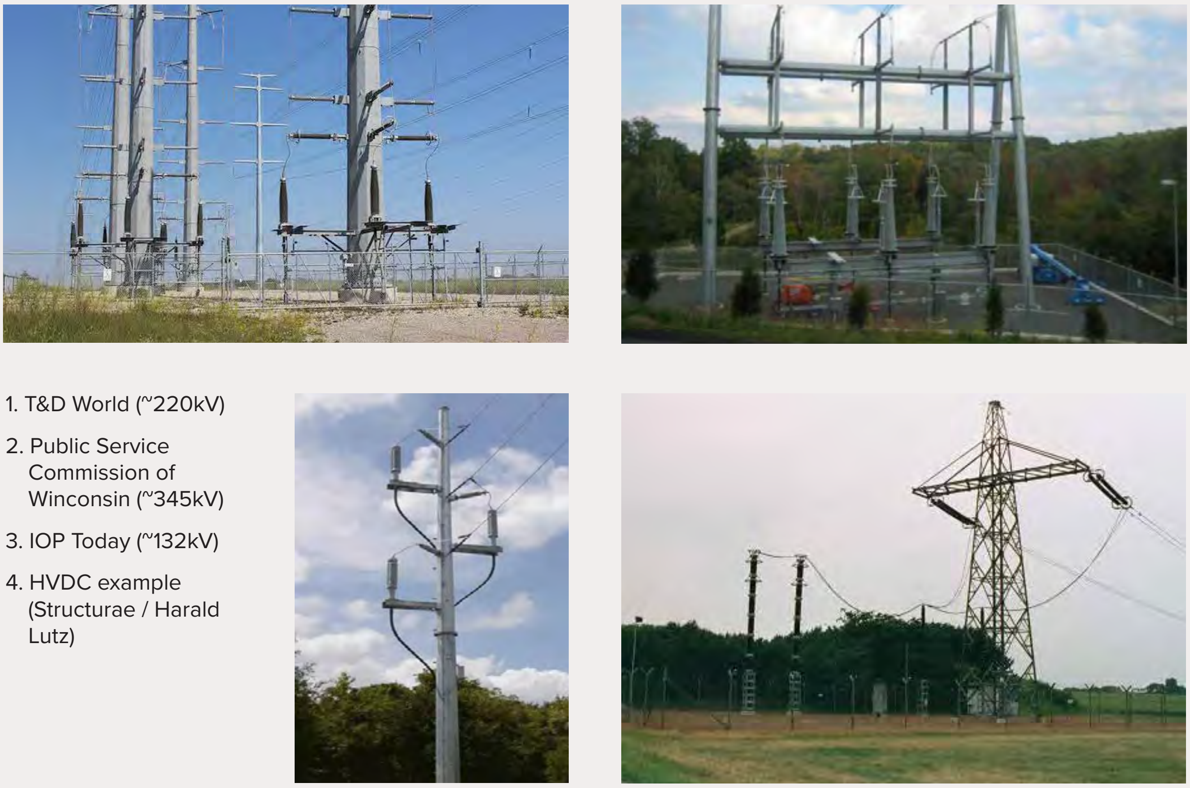


Figure 27. Examples of Overhead to Underground Transmission Line Transitions

the surge arresters are also mounted on the structure. This may be suitable for transmission voltages of 132kV and below, but is generally restricted at 275/330kV and above for the following technical reasons:

- There is a generally a maximum height for making off the cables for safe working (for the cable jointers).
- The cables add significant weight and larger wind area for the structure (and may overload the capability of the structure).
- The UGTL cable termination will restrict access to the tower for maintenance.

5.6 Right of Way and Corridor Requirements

Transmission cable routes can vary and may be under public roadways, as well as on public or private lands. Underground cables can also be installed within an existing overhead line corridor or easements. Determining the right of way or easement corridor width for underground transmission cable lines involves considering a range of factors. Because underground cable systems are buried this immediately affects the corridor width. Factors influencing the determination of the corridor width include:

(a) Traffic Management, Safety and Security: All the logistics associated with the construction works need to be fully assessed for route options. Cable joint locations are also critical as those locations remain active worksites for the longest durations during the works - covering cable hauling in and jointing.

(b) Safety and Clearance Requirements: Clearances and safety considerations are essential to avoid physical and electrical interference with other utilities or potential hazards. The corridor width should accommodate required clearances from existing infrastructure such as water pipelines, gas lines, sewer systems, and other underground utilities. It should also ensure safe distances from structures, roads, railways, or other sensitive areas.

(c) Ground and geological conditions: The soil and ground conditions along the route influence excavation requirements, safety and environmental measures that may be required for the installation. These factors also influence the overall cost and feasibility of undergrounding.

(d) Cable Installation Arrangement and Method: The type and configuration of the underground cable system plays a crucial role in determining the corridor width. Factors such as the number of cables, their diameter, and the arrangement (single or double circuits) and power transfer capability, impact the space and the width of corridor required for installation, maintenance, and future expansion.

(e) Cable Protection and Depth: Underground cables require appropriate protection to ensure their integrity and prevent damage. The trench and corridor width needs to accommodate protective measures such trench shoring during construction and protective slabs above cables or ducts.

(f) EMF: EMF levels for underground cables tend to reduce more rapidly with distance from the line compared to overhead lines. However, consideration of prudent avoidance and recommended guidelines from lead organisations—ENA, ICNIRP and ARPANSA are important factors for influencing required corridor widths (Refer separate section on EMF in this report)

(g) Access and Maintenance Requirements: Adequate space is necessary to ensure access to the underground cable system for ongoing maintenance, repair, and monitoring purposes. The corridor width should allow for safe and convenient movement of personnel, equipment, and vehicles required for these activities. This includes considerations for vertical access points such as manholes or vaults.

(h) Environmental and Land Use Factors: Environmental considerations such as protected areas, environmentally sensitive regions, cultural heritage, and ecological requirements may influence the corridor width. Additionally, the specific land use and land ownership conditions can impact the determination of the corridor width, including considerations of private property boundaries or public access requirements.

(i) Future Expansion and Flexibility: Planning for future expansion or upgrades is crucial when determining the corridor width for underground transmission cable lines. Providing additional space within the corridor allows for potential cable system expansion, accommodating increased capacity or incorporating future technological advancements.

(j) Regulatory and Industry Standards: Compliance with local regulations, codes, and industry standards is essential in determining the corridor width for underground cable lines. These standards may specify minimum clearances, separation distances, or recommended practices that influence the width of the corridor.

The determination of the corridor width for underground transmission cable lines involves coordination among various stakeholders, including utility companies, landowners, regulatory agencies, and engineering professionals. It aims to balance technical requirements, safety considerations, environmental impacts, and future needs while adhering to applicable regulations and industry best practices.

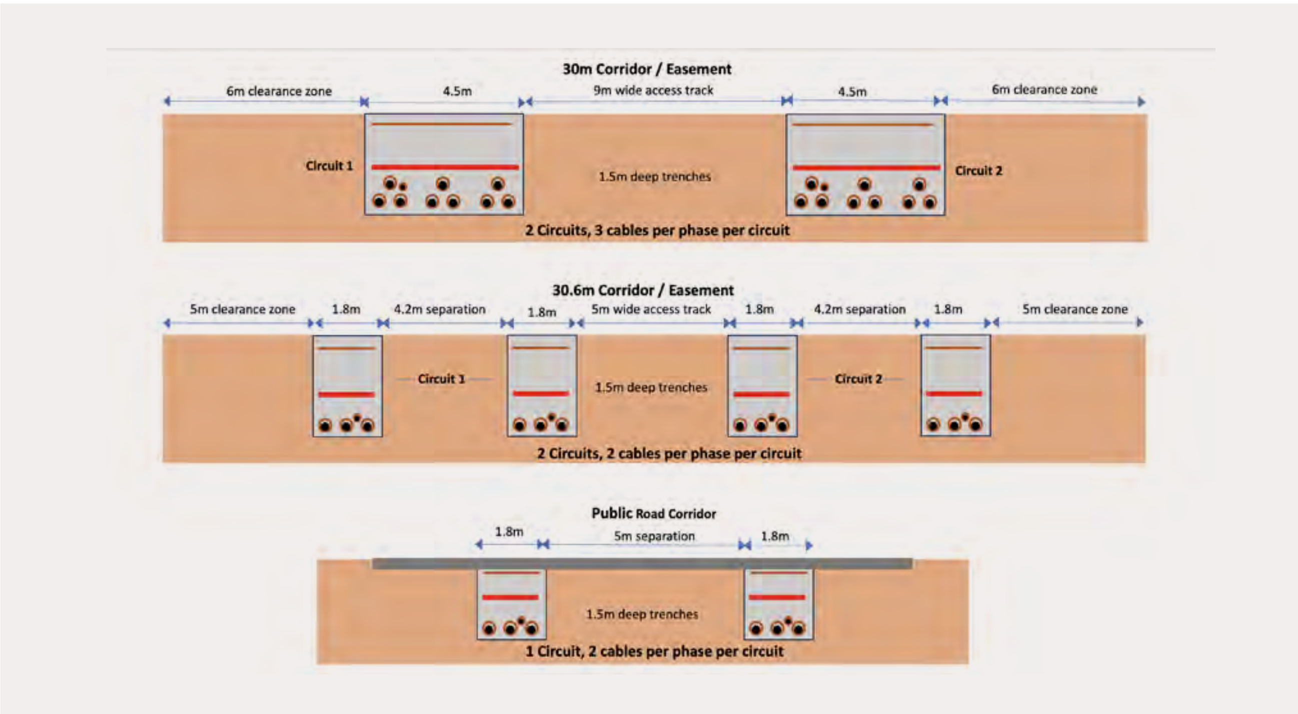


Figure 28. Indicative Installations and Corridors for 500kV Underground Cables

400kV and 500kV Underground Cable Corridor Examples

Examples of corridor requirements for 400kV and 500kV underground cable projects are found in some of the references for this report:

- 400kV double circuit (2 x 2200MVA) arrangement comprising 4 trenches occupying a total corridor width of 21m (CIGRE 2017 [2])
- 400kV AC Interconnector, Idomlund Denmark to German border [9, p. 40] - a total corridor width of 36m was required to accommodate construction and a 30m wide right of way for ongoing operation for a 2500MVA double circuit underground transmission line.
- Western Renewable Link Underground Construction Summary [14] identified a requirement for a nominal 30m wide easement for a double circuit underground installation.

Indicative 500kV double circuit underground line corridors are shown in Figure 28. The general requirements for a 2 x 2500MVA line are:

- Trench, cable laying configurations (flat or tre-foil) and separation between cable groups are determined based on power transfer requirements and spatial constraints.
- A vehicle access track is needed for construction and maintenance.
- A buffer zone of 5–6m at each side of the corridor is needed for work access and EMF prudent avoidance. This can be varied based on estimated EMF levels and future access requirements.
- Trenches separated by 5 to 6m to allow for access, construction shoring, and separation of circuits to meet the power transfer rating requirements.
- Additional width for temporary work zones may be required during construction, e.g., for large volumes of stockpiling and installation of drainage.

In some locations where under boring or HDD is required, the easement width may need to be increased to accommodate the drilling equipment and greater separation of the trenches to meet power transfer rating requirements.

5.7 Power Transfer Capability

The transfer capability of underground cables is a function of several factors:

- conductor type (copper or aluminium);
- conductor cross-sectional area (mm^2);
- conductor resistance (Ohms/m);
- installation method—direct buried, ducts or open air (e.g., tunnel);
- maximum operating temperature (typically 900C for XLPE insulation);
- laying configuration (flat or tre-foil);
- cable burial depth;
- metallic sheath material (copper or aluminium) and method of bonding (single point or cross-bonding);
- backfill and ground thermal resistivity;
- the ground and ambient temperatures;
- spacing between adjacent cable circuits.

The maximum operating temperature of the conductor in the cable is limited by the temperature performance limits of the insulating materials. There are 2 types of cable temperature limits that are referred to in the industry. For XLPE cables these limits are as follows: (reference EPRI 2017 [13]):

1) maximum normal (continuous) temperature—90°C
2) maximum emergency temperature—105°C

Transmission system operators apply the higher operating temperature of 105°C for short term emergency rating purposes. This allows the cable to have higher power transfer rating in an emergency such as an outage of another circuit in the network. The emergency rating can be applied for a short period, typically 2 hours, to allow operators time to take controlled actions to restore the network, followed by a period of loading at 50% of the maximum continuous rating.

The power transfer capability for the underground transmission cable is specified by the utility and the cable and installation is then designed to meet that requirement.

Most of the above factors are considered in the design with the main variable factors which influence dynamic ratings of underground cables are the maximum operating temperature, the ground temperature, and the ambient air temperature. Because underground cables are buried at depths of 1 to 2 metres below ground, the ground temperatures are relatively constant at these depths.

Underground cable ratings are not affected by annealing (conductors are already annealed) but limited by the maximum temperature for operating the XLPE insulation.

The XLPE key properties remain relatively stable at temperatures below 80°C. If this temperature is exceeded, it can cause accelerated ageing of the insulation and significantly reduce its life. The insulation may go through irreversible chemical changes which effect electrical breakdown strength and make it susceptible to electrical failure.

XLPE has an electrical breakdown voltage of around 50kV/mm at room temperature, but will reduce by 25% at 90°C and if increased from 90°C to 130°C will reduce by another 40% [13].

Utilities have typically restricted overload capability to a maximum temperature of 105°C. A temperature rise from 80°C to 105°C will only produce an additional 30% of extra cable rating.

A list of EHV underground cable projects is provided by CIGRE, 2017 [12, p. 170]. The list indicates that for 400–500kV cable projects utilising 2500mm^2 copper conductor XLPE cable, normal continuous power transfer capacity are in the range of 1600 to 1800MW per circuit. [12] The list indicates that for 400 – 500 kV cable projects utilising 2500mm^2 copper conductor XLPE cable, normal continuous power transfer capacity are in the range of 1600 MW to 1800 MW per circuit.

5.8 Reliability Performance

The CIGRE publication –Technical Brochure 815—Update of Service Experience of HV Underground and Submarine Cable Systems (2020) [15] provides a recent and comprehensive analysis of underground transmission cable reliability performance. The reporting period was for 10 years ending December 2015. The report covers both fluid-filled cables (GC, SCOF, and HPOF) and extruded cables (XLPE, PE, EPR). Because XLPE cable, installed on land, is the most used around the world and likely to be used in Australian projects the results and analysis of XLPE cables are detailed below only. The CIGRE report did report higher failure rates for fluid-filled cables compared to extruded cables, partly attributable to greater age of the fluid-filled cable grouping.

Cable failures can be categorised as:

(a) internal failures of cable, joints or terminations involving conductor, insulation, screen, over-sheath, moisture barrier, with potential causes being:
   - lightning, transient or switching surges—which are higher than the rating of the surge protection;
   - water ingress—generally at joints, which can lead to a reduction of sheath resistivity and electrical breakdown on the cable;
   - manufacturing defects;
   - localised hot spots leading to thermal or electrical failure;

(b) external failures including:
   - third party mechanical damage e.g., dig-ins, vibration from machinery;
   - corrosion;
   - environmental impacts such assoil erosion or tree roots;
   - wildlife impacts from burrowing animals and termites.

Cable Failure Rates reported by CIGRE in 2020 for XLPE transmission cable installed on land are summarised in Table 8. These failure rates are only for the cable component of the system, failure rate of the accessory components is reported separately. Note that no failures were reported for 500kV cables, largely attributable to the relatively small amount of this cable in service, i.e. 291kms out of 227,554kms in this CIGRE survey.

The report also concluded that for internal faults in XLPE cables, insulation system failures are the major cause (64 %), followed by over-sheath failures (18 %).

Table 8. Failure Rates of HV XLPE Land Cables—Faults/100km-year (Adapted from CIGRE—2020)

	All voltages	60–109kV	110–219kV	220–314kV	315–499kV	500kV and above[1]
Internal failures	0.0686	0.0702	0.0199	0.229	0.0511	0
External failures	0.0368	0.0211	0.0717	0.0403	0.0511	0
Unknown origin failures	0.0055	0.0026	0.0139	0	0	0
All failures	**0.111**	**0.0939**	**0.108**	**0.269**	**0.102**	**0**

1. The 500kV failure rates are based on a relatively small quantity (171km) of installed cable reported in the CIGRE 2020 report.

Table 9. Number of External Faults Reported for XLPE Land Cables (Adapted from CIGRE—2020)

Failure Type	Installation Mode	
	Direct Buried	Ducts
External—Total	31	30
External—Abnormal System Conditions	1	0
External—Other Physical External Parameters	3	3
External—Third Party Mechanical Damage	27	27
External—Corrosion	0	0

Table 10. Failure Rates of Accessories for Extruded Cables (XLPE, EPR, PE) on Land—Faults /100 Units—Year (adapted from CIGRE—2020)

Component	All voltages	60–109kV	110–219kV	220–314kV	315–499kV	500kv and above[1]
Joint	0.0047	0.0021	0.0160	0.0266	0.113	0
AIS Termination Fluid Filled Porcelain	0.0107	0.0018	0.0111	0.570	0	0
AIS Termination Fluid Filled Composite	0.132	0.0362	0.0307	0.344	0.833	0
AIS Termination Dry Porcelain	0.0036	0.0040	0	0	0	0
AIS Termination Dry Composite	0.0880	0.111	0	0	0	0
GIS or Transformer Termination Fluid Filled	0.0127	0	0.0265	0.0347	1.00	0
GIS or Transformer Termination Dry	0.0068	0.0039	0.0114	0.155	0	0
Other Components	0	0	0	0	0	0

1. The 500kV failure rates are based on a relatively small quantity (171km) of installed cable reported in the CIGRE 2020 report.

The results summarised in Table 9 from the CIGRE 2020 report show that 3rd-party damage is the most common cause of external failures for XLPE cable installations. The report did note, however, that the external failure rate has decreased around 40% for XLPE cables since previous CIGRE report (TB379) on this topic was published. This indicates better positioning and Geographic Information System (GIS) mapping of cable systems today than before. However, better protection of the cables via the use of ducts and/or warning tapes can also be a possible explanation for the reduction in the external failure rate. "Dial before you dig" programs have also improved over that period with messaging in media and improved on-line information access.

Cable Accessory Failure Rates from the CIGRE 2020 report in Table 10 show the failure rate for internal faults involving the cable accessories. The results show that cable terminations tend to be more prone to failure than joints with fluid filled terminations being most prone, particularly at the higher voltages. As with cable failures, due to the relatively limited quantity of 500kV cables in service, there were no failures reported.

The report also commented that most faults in XLPE cable systems occur within the first 10 years of operation, with a very large number of faults occurring during the first two to three years of operation. Most failures in XLPE cable systems during the first 10 years of operation are found in accessories, whereas failures in the latter years of operation occur in the cable.

Outage and Repair Times data from the CIGRE 2020 report shows that the outage times in days for repairs for extruded cables (XLPE, EPR, PE) on land ranged from 9.3 to 33.9 days. The longer outage and repair times for underground transmission cable compared to overhead transmission lines is a disadvantage from a reliability perspective.

5.9 Construction Phase

Underground installation methods were described in section 5.5 Underground Cable Installation Methods.

An Environment Management Plan (EMP) needs to be implemented for any underground transmission line project. Requirements for this plan will have been identified in the overall Environmental Impact Study in the planning phase of the project.

Open cut trenching is the most common method of constructing an underground transmission cable system. Excavation equipment is used to remove any asphalt road surface, concrete, topsoil, and normal soil to the required depth of the cable (typically 1m to 2 m). This will lead to large stockpiles of material which will have to be removed to an appropriate dump site.

Trenches are dug in sections along the line route (typically the cable drum lengths are between 500—1000m), and after the trench is dug, there is the need to shore up the trench—to maintain the trench sides and provide safety to the workers. There is also often a need to install steel covers (for driveway access and worker crossings) along the trench sections. Trenches will need to be left open for long periods and will suffer from rain and water ingress. Any such water needs to be pumped out and treated before disposal.

The steps in a typical underground cable transmission installation after trenching are:

1. installing a layer of bedding sand;
2. installing the conduits on the bedding sand (if using ducts);
3. installing a backfill material (typically weak mixed concrete) with good thermal properties (for much of the trench volume);
4. positioning cable pulling equipment and cable drums at the ends of the trench section;
5. installing the cables in the conduits;
6. reinstating the ground surface to the condition it was originally in or better;
7. making off the joints in the joint bays.

There are likely to be major obstacles along the cable route, such as waterways, major highways/motorways, railroads where under boring or horizontal directional drilling is required to minimise impact on the service corridor.

Construction Timeframes for an underground transmission cable line will vary depending upon factors such as route length, geography, environment, and packaging of segments of the project for concurrent work.

ENTSOE and Europecable reported [16]:

"The average installation time per km (direct buried in urban area) is 1.5 months/km for opening the trench per circuit, cable laying and closing the trench. For the cable laying alone, 1–2 days per km and per phase is required. Installation times indicated here refer to working with one civil work team only. By increasing the number of teams, installation times can be reduced. Also, if there are more systems in the same trench timing will only increase by approximately 10–20%."

The case studies found in the Chapter 7 report of this study of this report also provide a comparison of construction timeframes for various projects of relatively short lengths (5.6 to 26km), which are in the range of 2 to 4 years.

5.10 Operation and Maintenance

Policies, plans, and strategies for operation and maintenance of transmission lines form a major part of a utility's overall life-cycle asset management regime.

The basic categories of maintenance activities for underground transmission lines include:

(a) periodic line route patrols and visual inspections to identify risks such as:
   - construction activities involving excavation near cables;
   - changes in environmental conditions—waterways, soil erosion, vegetation;
   - terminations;
   - easement / corridor clearances;
- cable tunnels, bridge structures etc.;

(b) periodic testing and maintenance: this includes components such as:
   - outer sheath tests;
   - cross-bonding system—link boxes, surge voltage limiters (svls);

(c) preventative maintenance or defect repairs:
   - repair or replacement of defects identified from patrols, inspection, or testing;
   - locating and repairing sheath faults or damage;

(d) emergency restoration or repairs after a failure:
   - cable dig-ins;
   - sheath faults;
   - joint or termination failures.

Table 11. Typical Duration of Repair Works for Cable Joint Failure under a Road (adapted from CIGRE 2017)

No.	Task	Duration (Days)
1	Fault location	1
2	Road traffic management	1
3	Excavate to confirm fault location	1
4	Excavation of joint bay	1
5	Remove faulty joint	1
6	Excavate joint bays	2
7	Lay new cable	1
8	Install new joints (2)	4–14
9	Reinstate road	1
10	Test and put into service	1–2
	Total	**14-25**

One of the major disadvantages of underground cable transmission lines compared to overhead lines is that repair times for major failures involving joints or terminations are significantly longer. For example, the work typically required to replace a failed joint involves a number of activities [12] that can take up to 25 days as shown in Table 11. By comparison with overhead transmission, as stated in 4.5 Reliability Performance, most repairs, including fallen structures can be restored within one week.

The literature review (Appendix A) reported that asset management is a crucial part of operations and maintenance of underground cable system. In numerous instances, it is challenging to assess the physical conditions of underground cable assets due to their installation locations that are either hard to reach or inaccessible [17]. Also, existing tests used to determine the remaining lifespan of an underground cable circuit necessitate obtaining an actual cable sample from the field and conducting laboratory testing. However, acquiring samples from an existing underground cable circuit is typically difficult and usually only possible after a cable fault has taken place [17]. Non-destructive in-situ testing of cable insulation can also be undertaken.

5.11 End of Life and Decommissioning

Expected Lifetime of HV Transmission Cables

Most references [12] [2] support an estimate of on average of at least 40 years for XLPE cables based on tests and operating experience. XLPE transmission cables have been in service since the mid 1970s. The reasons for end of life of a cable system are typically:

- Network planning analysis determines that continued operation of the underground cable circuit is not the most economic option to meet network demand forecasts.
- Service condition result poor reliability or reduced transfer capacity.

Maintenance policies and practices including inspection and testing are also a key factor. Replacement of cables in tunnel systems or ducts is a practical economic option compared to direct buried cable systems which cannot be replaced without extensive excavation works.

End of Life Works

Decommissioning an underground cable transmission line involves several requirements and activities to ensure the safe and efficient removal of the infrastructure. Some common requirements and activities associated with the decommissioning process include:

(a) Planning and Coordination: A comprehensive decommissioning plan needs to be developed, outlining the objectives, timeline, resources, and stakeholders involved in the process.

(b) Safety Assessments: This involves assessing risks such as electrical hazards, hazardous materials, structural integrity, and ensuring compliance with safety regulations.

(c) Equipment Removal: Where it is necessary to remove cables, the physical removal of underground cable infrastructure is a key activity. In most cases the redundant cables can be removed from ducts, allowing the ducts to be reused. In other cases, such as direct buried cables it is often not economically feasible to remove all of the cable unless there are specific environmental factors.

(d) Cable Disposal: Proper disposal of the decommissioned cables is essential. Recycling or proper disposal methods should be followed to minimize environmental impact. This may involve separating cables into different material types, such as copper or aluminium conductors, for recycling. Compliance with environmental regulations regarding waste management and hazardous materials is also crucial. With cables, in some cases it may be feasible to obtain scrap value, e.g. copper and aluminium conductors.

(e) Site Restoration: The decommissioned site should be restored to its original condition or repurposed appropriately. This may include backfilling the excavated trenches, re-establishing the land contours, restoring vegetation, and implementing erosion control measures. Site restoration activities should adhere to environmental regulations and any specific requirements set by local authorities.

(f) Documentation and Reporting: Comprehensive documentation of the decommissioning process is important. This includes recording project details, safety procedures, equipment removed, disposal methods, and any environmental monitoring carried out during the process. Reporting to relevant regulatory bodies, utility companies, or stakeholders may also be required.

(g) Stakeholder Communication: Effective communication with stakeholders throughout the decommissioning process is vital. This includes notifying affected parties, such as landowners, local communities, and regulatory agencies, about the decommissioning activities, timelines, and any potential impacts. Providing regular updates and addressing concerns helps maintain transparency and foster positive relationships throughout the process.

(h) Regulatory Compliance: Compliance with applicable regulations and permits is essential throughout the decommissioning process. This may include obtaining permits for excavation, waste disposal, environmental monitoring, or any other specific requirements set by local authorities.

(i) Safety and Environmental Monitoring: Monitoring activities during the decommissioning process are important to ensure compliance with safety and environmental standards. This may involve monitoring air quality, water quality, noise levels, or other environmental parameters. Safety monitoring should also be conducted to ensure the well-being of workers and to prevent any accidents or incidents.

It is important to note that the specific requirements and activities for decommissioning an underground cable transmission line may vary depending on local regulations, project specifications, and environmental considerations.

6.

HVDC Transmission Lines (Overhead and Underground)

This section provides an overview of HVDC overhead and underground transmission infrastructure.

6.1 Overview of HVDC Transmission Technologies

High-Voltage Direct Current (HVDC) transmission systems are a proven alternative technology to AC systems for transmitting large amounts of electrical power over long distances. To date the application of HVDC transmission has mainly been with submarine cables or transmission system interconnectors that have no requirement for other circuit connections along the route.

The main components of a HVDC transmission system include:

(a) Converter Stations: These stations are located at the endpoints of the transmission line and are responsible for converting AC power to DC power (rectification) at the sending end and converting DC power back to AC power (inversion) at the receiving end.

(b) Transmission Line: HVDC transmission lines are typically made of overhead lines, underground cables, or a combination of both. They carry the DC power between the converter stations.

Figure 29. Single Circuit Guyed HVDC Overhead Transmission Line (Left) and Self-Supporting HVAC Transmission Line (Right) (AlternativeUniversity.net[16])

Some of the key characteristics and advantages of HVDC transmission systems compared to AC transmission systems are as follows:

(a) Lower Transmission Line Losses: HVDC systems have lower line losses compared to AC systems, especially over long distances. This is because the conductors for HVDC tend to be larger cross-sectional area with lower resistance compared to equivalent rated AC lines and also there is no reactive power losses. However, energy losses in the converter stations may be significant, depending on the size and type of technology.

(b) More compact overhead line structure or towers normally requiring 2 conductors (or bundles) per circuit. An example is shown in Figure 29. Note that only 2 main conductors are required on the DC line compared to 3 phases on the AC line. The AC tower structure is consequently much larger.

(c) More compact underground cable trench profiles due to the reduced number of cables and conductors for the same power transfer rating. An example is shown in Figure 30.

(d) Interconnection of Asynchronous AC Systems: HVDC allows the interconnection of AC systems that operate at different frequencies or have different characteristics. It enables power transfer between systems that would otherwise be incompatible, facilitating the integration of renewable energy sources or the interconnection of grids between different regions.

(e) Controllability and Stability: HVDC systems offer better controllability and stability compared to AC systems. The ability to regulate power flow and control voltage helps in managing power grids and improving system reliability.

(f) Lower Environmental Impact: HVDC transmission lines have a smaller footprint and emit lower electromagnetic fields compared to long-distance AC lines. Additionally, the use of underground cables reduces visual impact and environmental concerns.

[16] https://alternativeuniversity.net/aec/electricity/hvdc/.

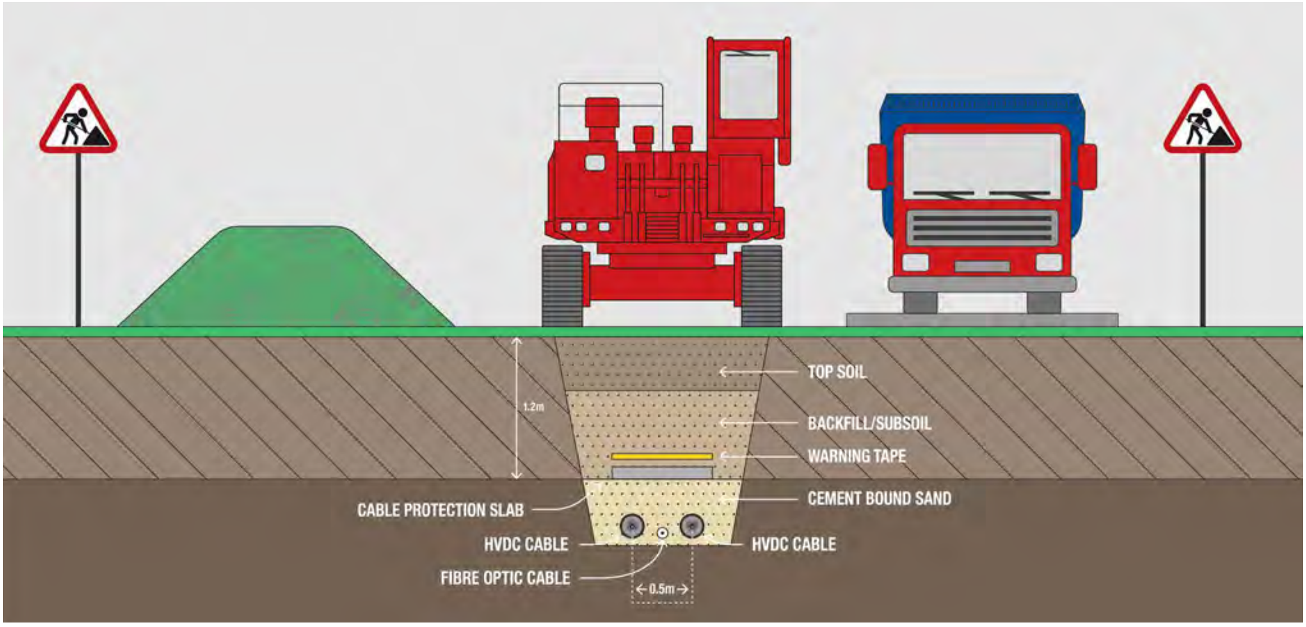


Figure 30. Example of HVDC Single Circuit Underground Cable Installation (gridlinkinterconnector.com David Barber)

(g) EMF for HVDC systems is discussed in the section 7 Electromagnetic Fields of this report. EMF from HVDC are static fields and generally lower than similar voltage AC transmission lines.

(h) Efficient for Long-Distance Transmission: HVDC is particularly suitable for transmitting electricity over long distances, such as across continents or seas (using submarine cables). It can transmit power over thousands of kilometres without significant losses. DC conductors and cables can carry significantly more current for the same conductor or cable size.

However, there are some disadvantages with HVDC when compared to HVAC transmission in Australia:

(a) HVDC systems are generally more expensive to build compared to AC systems due to the requirement for large AC/DC converter stations and specialized equipment contribute to higher initial costs (The economics and break-even distance for HVDC compared to HVAC is discussed later in this report).

(b) Intermediate connections for loads or generation along a line route will require additional converter stations, increasing the cost of project.

(c) There is limited experience with the design and operation of HVDC transmission in Australia.

(d) Design related impacts such as longer insulator strings compared to AC, measures required to mitigate increased corrosion risk, and noise levels from the lines and equipment at converter stations [18] must all be considered.

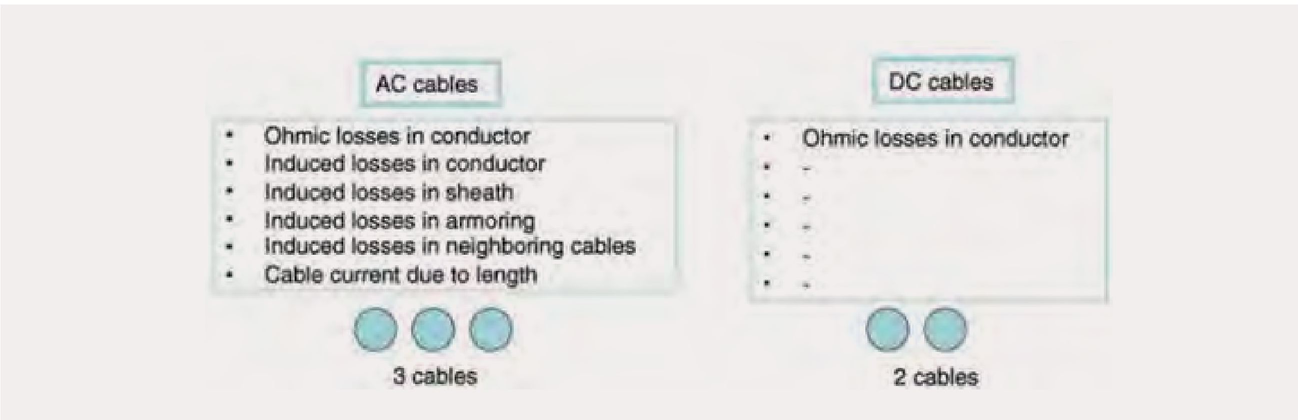


Figure 31. Comparison of HVDC and HVDC Cable (Extruded Cables for High-Voltage Direct-Current Transmission [19])

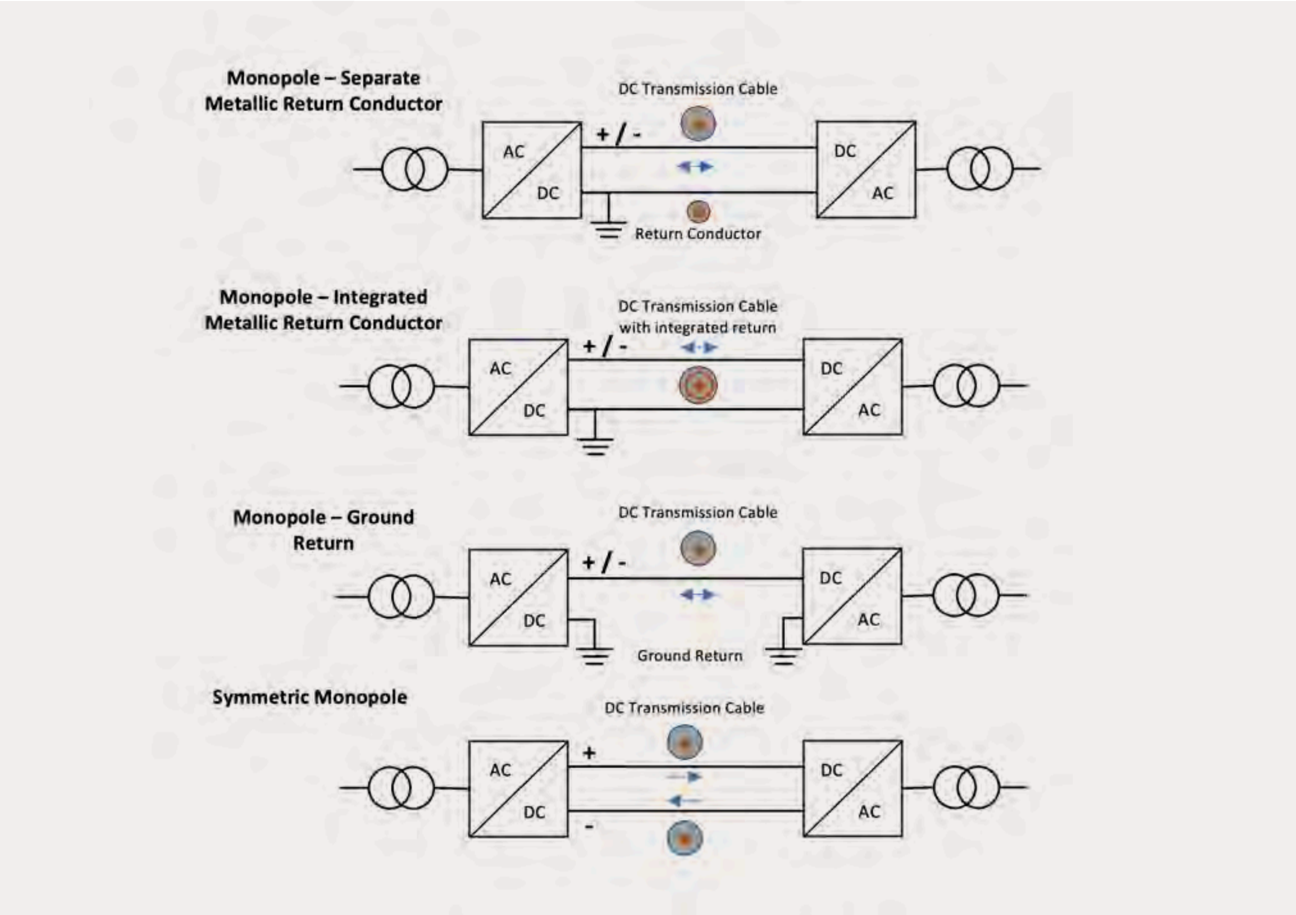


Figure 32. Monopole HVDC Configurations

Both AC and HVDC transmission systems have their own applications and are used based on factors such as distance, power capacity, grid interconnections, and cost considerations. The choice between AC and HVDC depends on the specific requirements and constraints of the power transmission project.

The Literature Review (Appendix A) reported that advantages of HVDC cable over HVAC cable are shown through Figure 31 [19]. A very thorough comparison between the HVAC and HVDC system is presented in [20]. The results show the additional sources of losses in HVAC cables compared to HVDC.

6.2 HVDC Transmission Systems Topologies

There are several types of HVDC systems and topologies, each having advantages and disadvantages depending upon the application requirements.

Monopolar HVDC Systems

Monopole DC links are most applicable to power transmission over long distances, with submarine cables. An example is the Basslink interconnector between Victoria and Tasmania, which is approximately 300km long with a capacity of 500MW at 400kV DC. Examples of network topologies for monopole systems using cables are shown in Figure 32.

With a Monopole HVDC system, there are important design considerations for the ground electrodes as follows [21]:

1. Current—both DC and harmonic currents flow in the ground electrodes.
2. Ground potential rise (GPR)—current flow across a ground resistance generates a voltage on the structures. These need to be electrically safe.
3. Electrical resistance—needs to be low to ensure low voltage to remote earth.
4. Potential gradient—gradients in ground need to be electrically safe.
5. Long life—components need to be selected for long life.
6. Reliability—ground electrodes are generally sectionalised into discrete parts to facilitate maintenance.

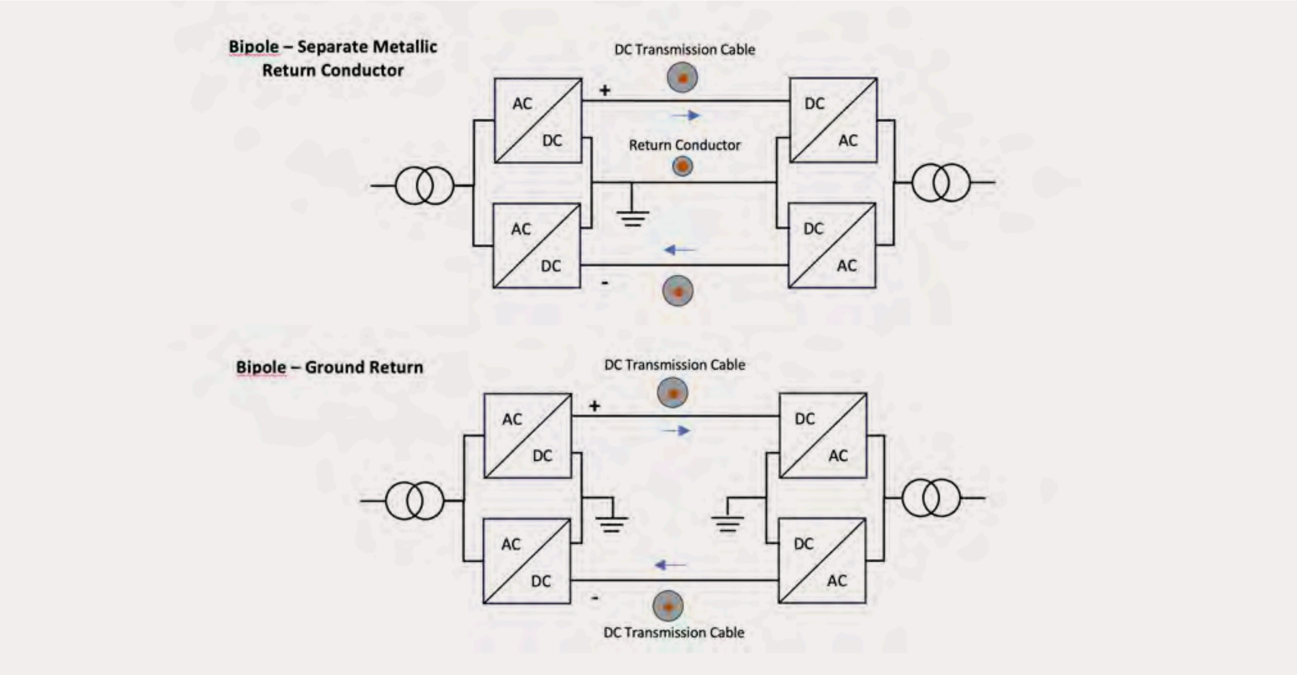


Figure 33. Bipole HVDC Configurations

Bipolar HVDC Systems

A bipolar DC link caries DC current via separate positive and negative cables with a return conductor carrying any imbalance which should ideally be zero. This configuration is applicable for higher transfer capacities and provides additional security of supply. Typical configurations are shown in Figure 33.

Homopolar HVDC System

Homopolar DC links are like bipolar links but have the same polarity in each cable. The configuration is simpler and lower cost with reduced insulation in the cables [22]. However, the disadvantages with the homopolar arrangement are reduced power transfer capacity and power flow control capability. An example of this configuration is shown in Figure 34

Induced Voltages and currents from HVDC Lines

Both AC and DC power lines can cause induced voltages and currents in nearby metallic structures which can create a hazard with un-safe touch voltages or cause damage by corrosion. The Canadian Association of Petroleum Producers, 'GUIDE - Influence of High Voltage DC Power Lines on Metallic Pipelines [23] reports that induced voltages can occur by three modes: (1) capacitive coupling, (2) inductive coupling, and (3) conductive coupling.

Steady state induced voltages from capacitive and inductive coupling effects from HVDC lines are static (i.e. not alternating current) and less than equivalent rated HVAC lines. During fault conditions there can be momentarily high induced voltages.

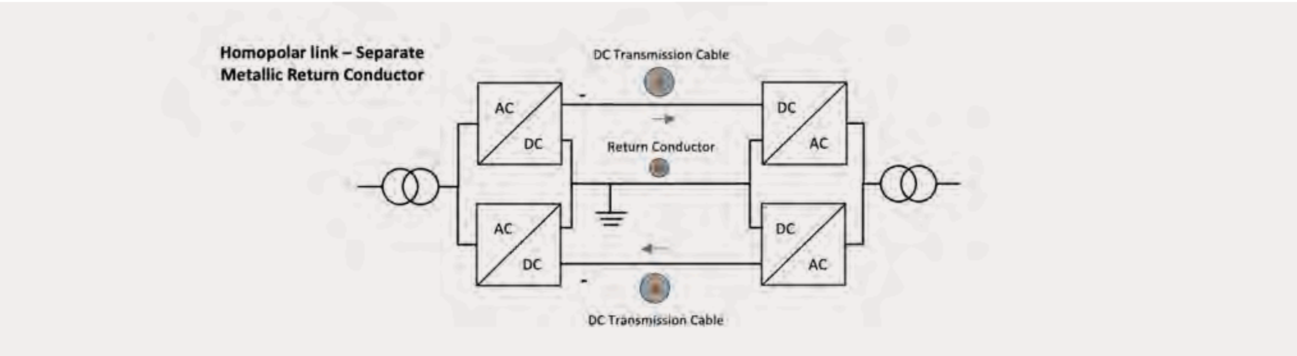


Figure 34. Homopolar HVDC Configurations

Conductive coupling effects can occur through discharge of current through grounding electrodes, leading to ground potential rises.

Although the levels and effects of HVDC induced voltages are generally less than equivalent HVAC rated lines, induced voltage in nearby metallic objects must be addressed in the design of a HVDC overhead or underground transmission line.

Figure 35. HVDC Converter Station (ABB[17])

6.3 HVDC Converter Technologies

There are several converter technologies used in HVDC transmission systems. The choice of converter technology depends on project requirements considering factors such as power transfer, system requirements, associated HVDC configuration and cost considerations. The main types of converters used in HVDC transmission are:

(a) Line-Commutated Converter (LCC): LCC is the most established and widely used converter technology in HVDC systems. It utilizes thyristor-based converters that operate on line-commutation principles. LCC converters provide robust and reliable operation and are suitable for high-power, long-distance transmission applications.

(b) Voltage-Sourced Converter (VSC): VSC-based converters have become the most used technology in recent years, particularly for applications such as offshore wind farm connections and grid interconnections. VSC converters use insulated-gate bipolar transistors (IGBTs) or integrated gate-commutated thyristors (IGCTs) to generate the desired voltage waveform. VSC technology provides benefits, such as better controllability, reactive power support and the ability to independently control active and reactive power flow.

(c) Modular Multilevel Converter (MMC): MMC is a specific type of VSC technology. It utilizes a modular structure with multiple sub-modules connected in series to form a high-voltage waveform. MMC offers advantages such as scalability, fault tolerance, reduced harmonics and improved control flexibility.

(d) Current-Source Converter (CSC): CSC-based converters were commonly used in early HVDC systems but have been largely replaced by LCC and VSC technologies. CSC converters utilise current-source inverters and require external capacitors to provide the required voltage waveform. While CSC technology offers certain benefits, such as inherent short-circuit protection, it has limitations in terms of control and reactive power capabilities.

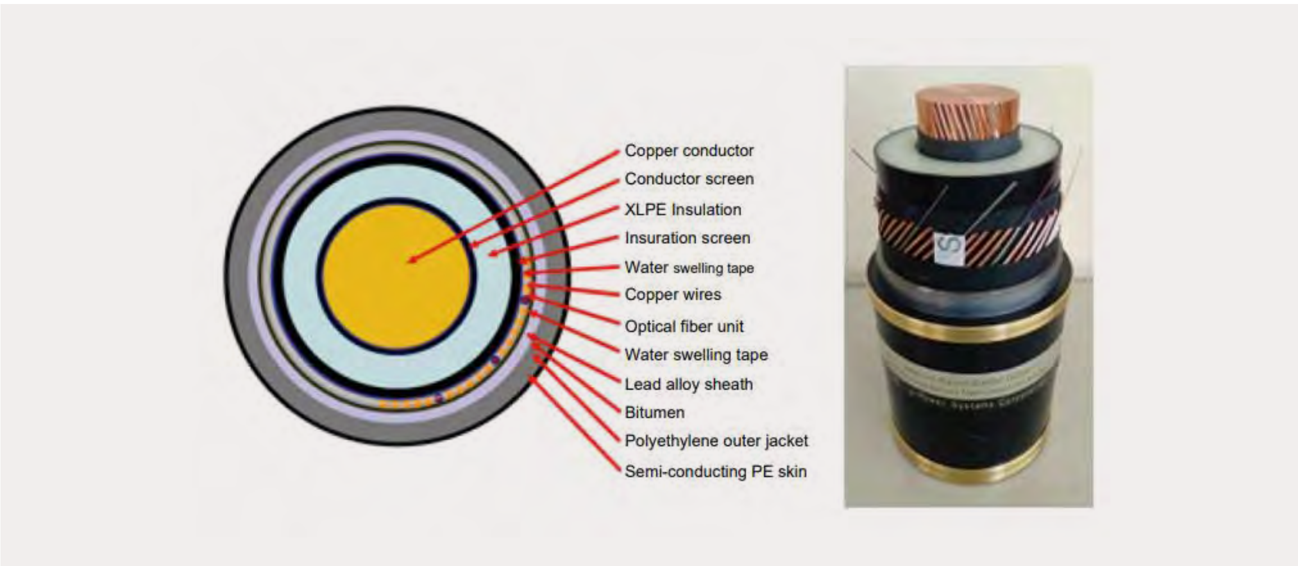


Figure 36. HVDC Land Cable (Sumitomo)

[17] https://new.abb.com/news/detail/45972/abb-completes-upgrade-of-first-major-hvdc-link-in-us-transmission-history

Table 12. HVDC Transmission Lines in Australia

Name	Route Length	Voltage	Power Rating	Year	Type	Other Details
Directlink (NSW)	59km	80kV	180MW	2000	VSC / IGBT	Underground and above ground polymeric cables
Murraylink (Vic—SA)	176km	150kV	200MW	2002	VSC / IGBT	Underground XLPE cable
Basslink (Vic—Tas)	370km	400kV	500MW	2006	LCC /Thry	Monopolar system, Submarine cable

An example of a HVDC converter station is provided in Figure 35. The converter stations have a large land requirement, for example the converter stations for the Suedlink project will occupy around 7 hectares (Tennet [24])

6.4 Design

The design of HVDC cables has many similarities to HVAC cables. The key differences are [13]:

- Mechanical design for submarine cables
- Insulation design for DC electrical stresses
- Special requirements for accessories i.e., joints and terminations
- Design issues relating to DC ground return current.

The two main types of cables are characterised by the insulation medium i.e.

- Mass impregnated (MI)—insulation material is layered paper tape impregnated with a high viscosity fluid.
- Polymeric insulated cable includes XLPE.

HVDC XLPE cable is now the most used for onshore or land projects. A typical HVDC XLPE cable is shown in Figure 36.

The literature review (Appendix A) provided a finding that HVDC cables may show better reliability than their AC counterpart due to their better performance at elevated temperatures and fields, minimal space charge retention, favourable material compatibility, and reliable and robust accessories.

6.5 HVDC Transmission Line Projects

Basslink submarine cable, and the relatively small capacity Directlink and Murraylink transmission lines are the only completed HVDC transmission projects in Australia (refer Table 12). In other parts of the world, such as Europe, America, and Asia, HVDC has been used extensively for inter-regional transmission connectors, offshore and onshore renewable zone interconnections. In Europe, regulatory drivers for HVDC are also promoting the adoption of HVDC underground transmission. The Changji-Guquan project [25] in China was the world's first UHV DC (ultra-high voltage DC) at +1100kV, 12GW capacity over 3324km, completed in 2016. The Suedlink HVDC 4000 MW 700km project in Germany is significant because it is all underground cable.

The literature review (Appendix A) provided a list of recent international large HVDC transmission projects with year, voltage, power, distance, type, and supplier is provided in Table 13.

Table 13. International HVDC Projects [26]

Name of the Project	Country	Year	Voltage (kV)	Power (MW)	Distance (km)	Type	Supplier
Three Gorges-Shanghai	China	2006	500	3000	1060	Thy	ABB
Estiink	Estonia-Finland	2006	150	350	105	IGB	ABB
NorNed	Netherland-Norway	2008	450	700	580	Thy	ABB
Yunnan-Guangdong	China	2010	800	5000	1418	Thy	Siemens
SAPEI	Italy	2011	500	1000	435	Thy	ABB
BorWin1	Germany	2012	150	400	200	IGB	ABB
Mundra-Haryana	India	2012	500	2500	960	Thy	Siemens
Zhoushan	China	2014	200	400	134	IGB	NA
AL-link	Aland-Finland	2015	80	10	158	IGB	ABB
Western Alberta TL	Canada	2015	500	1000	350	Thy	NA
Nord: Balt	Sweden Lithuania	2015	300	700	450	IGB	ABB
Skagerrak 4	Denmark Norway	2015	300	700	244	IGB	Nexans, ABB
Jinsha River II-East China	China	2016	800	6400	NA	Thy	NA
DolWin2	Germany	2016	320	900	135	IGB	ABB
SydVastlanken	Sweden	2016	300	720	260	IGB	Alstom
Western HVDC Link	UK	2017	600	2200	422	Thy	Prysmain Group, Siemens
Xinjiang-Anhui	China	2017	1100	10000	3333	Thy	NA

6.6 The Future of HVDC Transmission in Australia

There are many HVDC transmission lines currently in the planning or construction phase around the world. The Marinus Link 1500MW, 250kM undersea cable from Victoria to Tasmania is currently in planning and approval phase and is the only large HVDC transmission project in Australia.

The relatively small number of HVDC transmission projects in Australia compared to other parts of the world historically indicates that the Australian industry will need to increase the knowledge, skills and experience base in grid planning, design, construction, operation, and maintenance of HVDC transmission if this technology is to be utilised on a larger scale.

A recent report on HVDC systems titled "Western Victorian Transmission Network Project—High Level HVDC Alternative Scoping Report" [27] was commissioned by Moorabool Shire Council and authored by Amplitude Consultants. This report provides an example of how HVDC could be an option in a current project. The consultants were engaged to investigate an alternative HVDC option utilising underground cable to the AEMO preferred Western Victoria Transmission Network Project (WVTNP) Option C2, which includes the erection of new 220 kV and 500 kV overhead transmission lines refer Figure 37.

The features of the HVDC proposal were:

- 78km of underground cable in a three metre wide trench
- Three converter stations, located at Bulgana, Sydneham and North Ballarat
- Base case for N-1 Reliability planning criteria
- Rating of around 2700 MVA, voltage of 525kV dc

The key findings and commentary on this report are summarised as follows:

- High level base case cost estimate circa $2.7 billion, which was 5.7 times the cost of AEMO preferred AC OHTL WVTNP option C2. Converter stations range from $536 to $710M each. Prior cost ratios of HVDC to HVAC OHTL had been in the range of 10:1.
- Lowering the N-1 planning capability can significantly lower capital costs (particularly with sizing of cables and cost of converter stations).
- HVDC can facilitate a staged approach to renewable development. For example, if a double circuit HVDC is required for the long term, and only half the capacity is required for the medium term, the initial converter stations installed can be rated for this lower capacity (which equates to one circuit of the double circuit). It would still be prudent to install the double circuit cables (or have conduits installed for the second circuit).
- The staged approach may be prudent, because the total output from a renewable zone is not certain and the expected capacity factors (of around 30%) for wind turbine may not be realised.
- The reduced underground trench (3-metre width) and corridor/easement requirements for HVDC have significant benefits compared to underground AC and overhead AC transmission. It is possible to locate the HVDC cables on existing overhead easements and on road reserves.

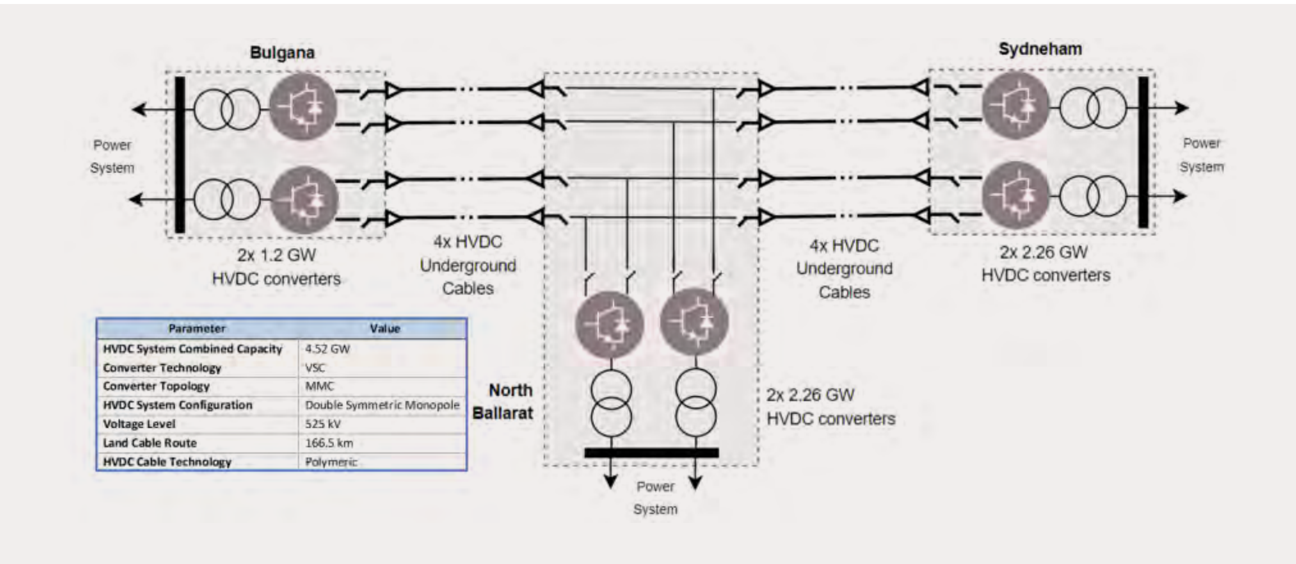


Figure 37. Option of using HVDC technology (Amplitude Consultants [27])

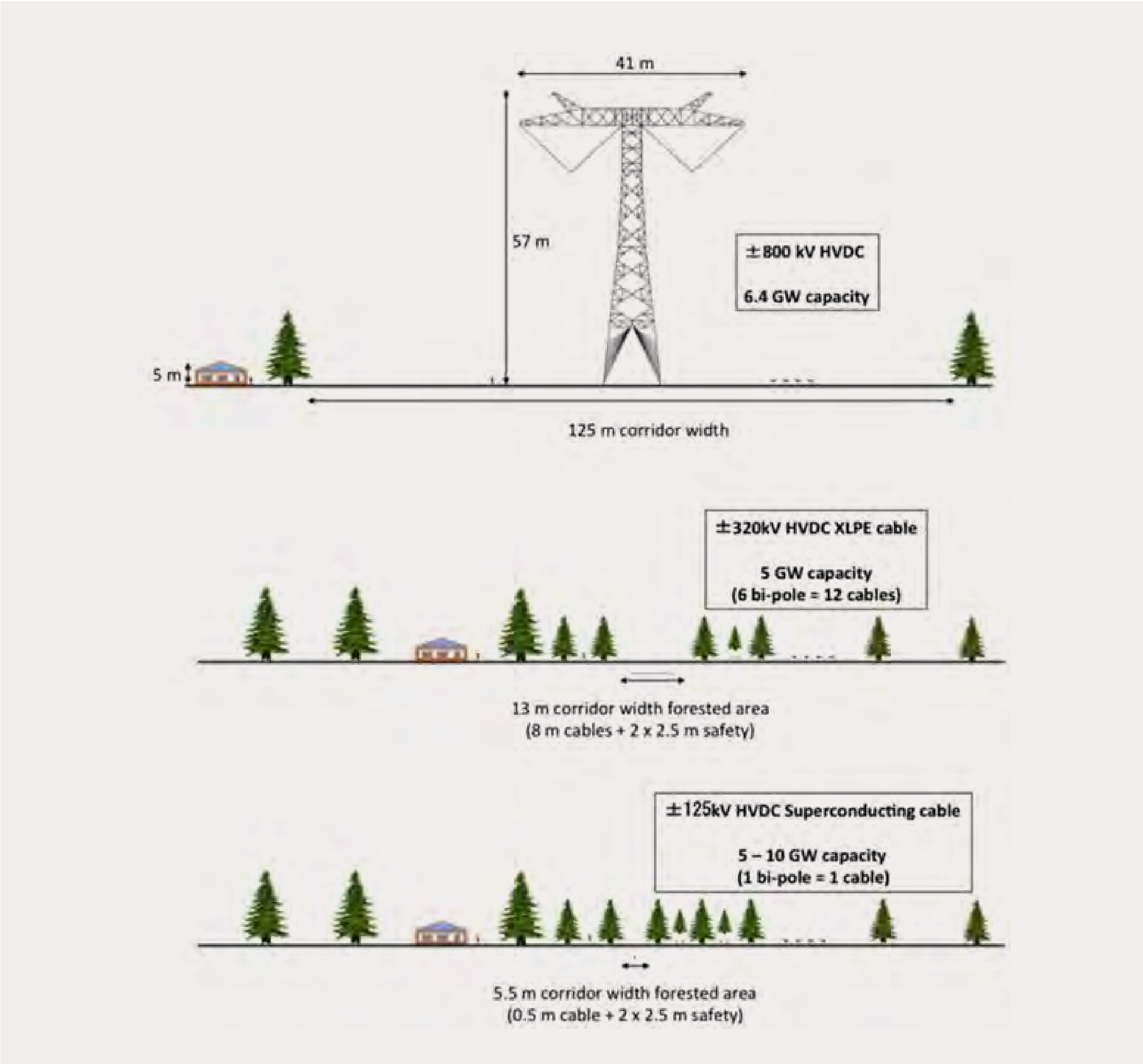


Figure 38. ROW and Power Transfer Capacity Comparison between Different Power Transmission Lines (Thomas et al [11])

6.7 HV Superconducting Cables

Super-Conducting Transmission Lines (SCTL) are currently a developmental technology that offers many advantages compared to existing overhead transmission and underground transmission cables, including: lower losses, higher power transfer, compact size requiring very reduced corridor width and low electromagnetic field emissions [10]. SCTL require a circulating cooling medium of liquid nitrogen within the cable. At this stage the technology is not considered to be at a mature stage of development necessary for commercial application.

The literature review (Appendix A) reported several advantages of superconducting power lines compared to the most modern underground standard HVDC cables (320 kV XLPE HVDC) [11]. The most notable is the compact size and reduced ROW corridor requirements and significantly reduced losses for long route lengths compared to HVAC and DC cables. A corridor comparison is shown in Figure 38.

6.8 Summary and Conclusions – Technical Aspects of HVAC and HVDC Transmission

A summary and comparison of the technical aspects of HVAC and HVDC overhead and underground transmission lines presented in this section is provided Table 14. Comparison of HV Overhead and Underground Cable Transmission Lines.

7.

Electromagnetic Fields

7.1 Introduction

Electromagnetic fields (EMF) is the term used to describe the combination of electric and magnetic fields that are generated by electrically energised or charged objects, including power lines, cables, appliances, and electronic devices. These fields are present everywhere in our environment, including the Earth's natural magnetic field. There is much information available on EMF from many sources. Scientific research on the health effects of EMF from powerlines has occurred since the 1970s.

There are several key organisations and authorities that provide guidance for industry.

Energy Networks Association (ENA)—is the peak national body representing electricity transmission and distribution businesses in Australia. ENA published its EMF management handbook in 2016 [28]. The purpose on the EMF Management Handbook is to provide, industry-wide information for guidance to the Australian Electricity Distribution and Transmission Industry and public on EMF. The ENA states in the handbook [28, p. 3]:

> *"Based on the findings of credible public health authorities, the body of scientific research on EMF does not establish that exposure to EMF at levels below the recognised guidelines cause or contribute to any adverse health effects. Some scientists however believe there is a need for further scientific research, although the World Health Organization has found that the body of research on EMF already is extensive."*

Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)—is the Australian government's primary organisation responsible for protecting people and the environment from the harmful effects of radiation. ARPANSA operates under the Australian Radiation Protection and Nuclear Safety Act 1998. ARPANSA advises on its website[18] that:

> *"The scientific evidence does not establish that exposure to extremely low frequency (ELF) EMF found around the home, the office or near powerlines and other electrical sources is a hazard to human health".*

> *"There is no established evidence that ELF EMF is associated with long term health effects. There is some epidemiological research indicating an association between prolonged exposure to higher than normal ELF magnetic fields (which can be associated with residential proximity to transmission lines or other electrical supply infrastructure, or by unusual domestic electrical wiring), and increased rates of childhood leukaemia. However, the epidemiological evidence is weakened by various methodological problems such as potential selection bias and confounding. Furthermore, this association is not supported by laboratory or animal studies and no credible theoretical mechanism has been proposed."*

International Commission on Non-Ionizing Radiation Protection (ICNIRP)—is an independent scientific organisation that provides guidelines and recommendations on the protection against non-ionizing radiation. This includes EMF from various sources such as power lines, radiofrequency fields (RF) from wireless devices, and optical radiation (e.g., from lasers). The primary role of ICNIRP is to develop and promote guidelines for limiting exposure to non-ionizing radiation to protect human health and ensure the safety of the public and workers. ICNIRP advises that [29, p. 824]:

> *"It is the view of ICNIRP that the currently existing scientific evidence that prolonged exposure to low frequency magnetic fields is causally related with an increased risk of childhood leukemia is too weak to form the basis for exposure guidelines. In particular, if the relationship is not causal, then no benefit to health will accrue from reducing exposure."*

World Health Organization (WHO)—undertakes and sponsors research on the health impacts of radiation including EMF. Considerable information and technical resources are available on their website[19].

[18] Source: ARPANSA Electricity and Health, ARPANSA Extremely Low Frequency Electric and Magnetic Fields www.arpansa.gov.au.
[19] https://www.who.int/.

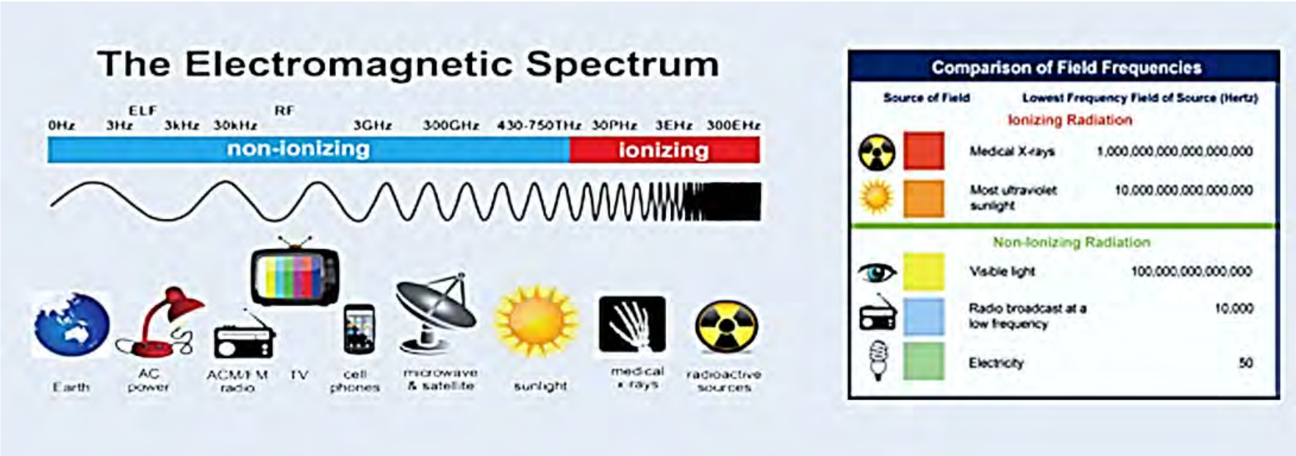


Figure 39 . The Electromagnetic Spectrum (ENA [28, p. 5])

7.2 How the Australian Electricity Network Operators approach EMF

Australian network operators including TNSPs broadly adopt the approach recommended by ENA as outlined in their handbook. The ENA's position on EMF has been adopted in the light of authoritative reviews having concluded that no adverse health effects have been established from exposure to EMF below the recognised international guidelines.

ENA recognizes that even, so some members of the public continue to have concerns about the issue. The ENA position on EMF includes [28, p. 3]:

- *"...recommending to its members that they design and operate their electricity generation, transmission and distribution systems in compliance with recognised international EMF exposure guidelines and to continue following an approach consistent with the concept of prudent avoidance,*
- *monitoring engineering and scientific research, including reviews by scientific panels, policy and exposure guideline developments, and overseas policy development, especially with regard to the precautionary approach,*
- *communicating with all stakeholders including assisting its members in conducting community and employee education programs, distributing information material including newsletters, brochures, booklets and the like, liaising with the media and responding to enquiries from members of the public, and*
- *cooperating with bodies established by governments in Australia to investigate and report about power frequency electric and magnetic fields."*

ENA's policy includes designing and operating electricity generation, transmission and distribution systems in compliance with relevant Australian guidelines and in an approach consistent with prudent avoidance i.e. no cost and very low cost measures that reduce exposure while not unduly compromising other issues should be adopted.

7.3 EMF—The Science, Health and Safety

Electromagnetic fields can be classified into two types:

(a) Non-ionizing radiation: This is electromagnetic fields (**EMF**) with frequencies below the ionizing radiation range, and includes, visible light, radio waves, and microwaves. Examples of non-ionizing radiation sources include power-lines, household electrical wiring, cell phones, and Wi-Fi routers.

(b) Ionizing radiation: This is higher-energy electromagnetic radiation (**EMR**) that can remove tightly bound electrons from atoms and molecules, leading to ionization. Ionizing radiation includes X-rays and gamma rays. Unlike non-ionizing radiation, ionizing radiation has sufficient energy to cause damage to biological tissues and DNA, and prolonged exposure to high levels of ionizing radiation can increase the risk of cancer and other health effects.

EMF is sometimes confused with **EMR**. The differences are illustrated in Figure 39.

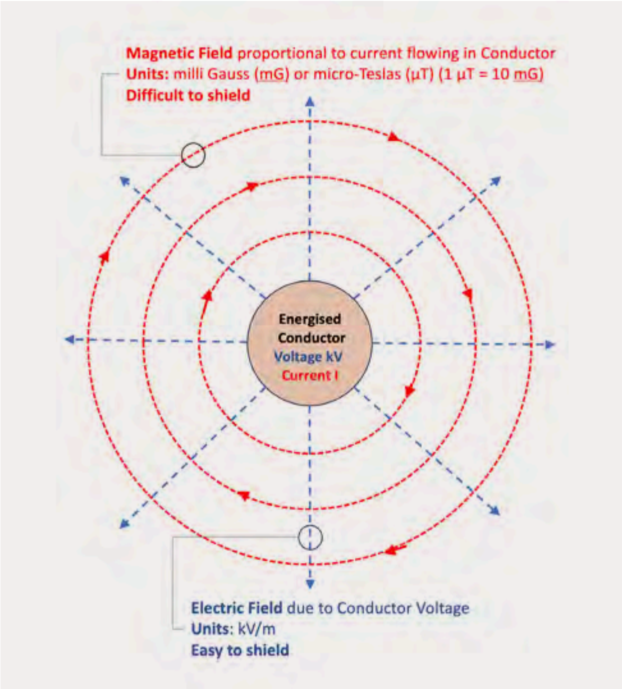


Figure 40. Simple Representation of Electric and Magnetic Fields from a Conductor

TABLE 5-1 BASIC RESTRICTIONS AT 50HZ FOR IEEE AND ICNIRP.

	IEEE 2002	ICNIRP2010
GENERAL PUBLIC		
Exposure to head	0.0147 V/m	0.02 V/m
Exposure elsewhere	0.943 V/m (heart) 2.10 V/m (hands, wrists, feet) 0.701 V/m (other tissue)	0.4 V/m (rest of body)
OCCUPATIONAL		
Exposure to head	0.0443 V/m	0.1 V/m
Exposure to rest of body	0.943 V/m (heart) 2.10 V/m (hands, wrists, feet, other tissue)	0.8 V/m (rest of body)

Figure 41. EMF—Basic Restrictions at 50Hz from IEEE and ICNIRP (ENA [28, p. 15])

EMF refers to two types of fields — Electric and Magnetic as illustrated in a simplified representation in Figure 40.

EMF Guidelines and Exposure Limits

The two international recognised exposure guidelines are ICNIRP:2010 and International Committee on Electromagnetic Safety, Institute of Electrical and Electronics Engineers (IEEE): 2002

ARPANSA's advice is [28, p. 14] "The ICNIRP ELF guidelines are consistent with ARPANSA's understanding of the scientific basis for the protection of people from exposure to ELF EMF."

ARPANSA directly references ICNIRP 2010 as a guideline for exposure and indicates the IEEE:2002 guideline provides an alternate set of guideline limits applicable to electric and magnetic field exposure.

Electric Fields are produced by the voltage in the powerline and magnetic fields by the current flowing in the powerline. The higher the voltage is, the higher is the electric field. Electric fields can be shielded by most objects, including trees and buildings. Electric fields tend to drop off quickly with distance. The units commonly used for electric field strength are volts per metre (V/m) of kilovolts per metre (kV/m).

Underground cables with metallic outer sheaths (i.e. transmission cables) bonded to earth will have no external electric fields.

Magnetic Fields are proportional to the current in the powerline, the higher the current the higher the magnetic field. When there is no current flow, there is no magnetic fields. Magnetic fields also drop quickly with distance. In general, the magnetic fields will decrease as follows:

- Single current—1/n
- Double circuit un-transposed—$1/n^2$
- Double circuit transposed or coil (e.g., transformer)—$1/n^3$

The units of magnetic field are commonly in milli Gauss (mG) or micro-Teslas (µT) with 1µT = 10mG.

Basic restrictions are the fundamental limits on exposure and are based on the internal electric currents or fields that cause established biological effects. The basic restrictions are given in terms of the electric fields and currents induced in the body by the external fields. If basic restrictions are not exceeded, there will be protection against the established biological effects. The basic restrictions include safety factors to ensure that, even in extreme circumstances, the thresholds for these health effects are not reached.

These safety factors also allow for uncertainties as to where these thresholds lie. The physical quantity used to specify the basic restrictions is the tissue induced electric field. The Basic Restrictions relating to 50Hz are shown in a Table 5-1 from the ENA EMF Management Handbook (see Figure 41).

TABLE 5-2 MAGNETIC FIELD REFERENCE LEVELS AT 50HZ FOR IEEE AND ICNIRP.

	IEEE 2002	ICNIRP 2010
GENERAL PUBLIC		
Exposure general	Not specified	200 μT*
Exposure to head and torso	904 μT	Not specified
Exposure to arms and legs	75,800 μT	Not specified
OCCUPATIONAL		
Exposure general	Not specified	1,000 uT*
Exposure to head and torso	2,710 μT	Not specified
Exposure to arms and legs	75,800 μT	Not specified

TABLE 5-3 ELECTRIC FIELD REFERENCE LEVELS AT 50HZ FOR IEEE AND ICNIRP

	IEEE 2002	ICNIRP 2010
GENERAL PUBLIC		
Exposure	5 kV/m 10kV /m (within right of way)	5 kV/m
OCCUPATIONAL		
Exposure	10 kV/m 20kV /m (within right of way)	10 kV/m

Figure 42. EMF Reference Levels from IEEE & ICNIRP (ENA [28, pp. 15–16])

Reference Levels—The basic restrictions in the ICNIRP and IEEE Guidelines are specified through quantities that are often difficult and, in many cases, impractical to measure. Therefore, reference levels of exposure to the external fields, which are simpler to measure, are provided as an alternative means of showing compliance with the basic restrictions. The reference levels have been conservatively formulated such that compliance with the levels will ensure compliance with the basic restrictions. If measured exposures are higher than reference levels, then a more detailed analysis would be necessary to demonstrate compliance with the basic restrictions. The ENA handbook specifies the reference levels for exposure to magnetic fields and electric fields respectively at 50Hz in Tables 5.2 and 5.3 and are shown in Figure 42.

7.4 Prudent Avoidance Principles

The prudent avoidance principle, also known as the precautionary principle, is a guiding principle used in the management and mitigation of EMF near power lines. It emphasises taking proactive measures to reduce exposure to EMF, even in the absence of conclusive scientific evidence of harm. The principle recognises the potential for health risks and aims to minimise exposure as a precautionary measure. The prudent avoidance policy adopted by TNSP's involves implementing no cost and very low-cost measures that reduce exposure while not unduly compromising other issues. In most cases the application of prudent avoidance can be implemented on a project or incorporated into network standards without the need for a specific assessment.

These general guidelines which follow assumes there will be compliance with the exposure limits (see above).

Potential locations of interest—from a practical perspective, the focus of public attention to EMF issues and therefore areas considered more relevant in a precautionary context would include schools, childcare centres, and other places where children congregate, homes and residential areas.

Exposure assessment—the focus of an exposure assessment in the context of prudent avoidance is on determining magnetic field exposure sufficient to be able to determine whether there are no cost and very low cost measures that reduce exposure while not unduly compromising other issues. This can often be achieved without the need for complex calculations and, in many cases, without calculations at all.

Loading conditions for prudent avoidance calculations—where specific calculations are required the following guidance is provided.

With prudent avoidance assessments, which address the ability to reduce fields with no cost or very low cost measures, the reduction in exposure arising from potential measures is more relevant than the highest predicted magnetic fields (as would be the case for exposure limit assessments).

While loads of substations and powerlines will generally increase over time after commissioning, a conservative approach which considers daily and seasonal variations would be to calculate the time-weighted-average (TWA) over a complete year using loads shortly after commissioning and also in the year representing the maximum foreseeable projected TWA.

Ground clearance for overhead lines—where specific calculations are required the following guidance is provided. A conservative estimate of ground clearance (or average conductor height) for prudent avoidance assessments would be to assume 2/3 of the calculated sag for a typical span under typical ambient conditions for the year representing the maximum foreseeable projected loads. There may be specific circumstances that justify alternative methods.

Prudent avoidance assessment reference points—when undertaking a prudent avoidance assessment, the primary reference points for calculations should be those areas where people, especially children, spend prolonged periods of time. As the epidemiological studies typically use exposure within the home (often a child's bedroom), and in the absence of data suggesting otherwise, a conservative approach for residential areas is to select the reference point as being the nearest part of any habitable room from the source. There may be specific circumstances that justify alternative methods.

The exception to this is noncompliance with exposure limits If the average exposure is less than or equal to typical background magnetic field levels, and no further assessment is required.

Possible ways to reduce exposure—exposure reduction can involve siting measures, which result in increased separation from sources and/or field reduction measures.

Consideration of other issues—Measures to reduce magnetic field exposure must be considered against numerous other objectives and constraints of the project including:

- worker safety,
- the location of the power source and the load to be supplied,
- availability of suitable sites,
- ease of construction and access,
- reliability,
- cost (prudent avoidance / precautionary measures should be no cost / very low cost),
- conductor heating,
- the nature of the terrain,
- maintenance requirements,
- visual amenity,
- provision for future development,
- legal requirements, and
- environmental impacts.

The goal of any project is to achieve the best balance of all the project's objectives, considering relevant social, technical, financial and environmental considerations.

Cost–benefit analysis

In Australia, there have also been some "benchmark" inquiries into the health impacts associated with EMF initiated by governments, most notably those lead by Sir Harry Gibbs[20] and Professor Hedley Peach[21].

Sir Harry Gibbs and Professor Peach recommended a policy of prudence or 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 WHO, in its document Extremely Low Frequency [ELF] Fields—Environmental Health Criteria Monograph No. 238 [30, p. 13], advise that:

> *"Provided that the health, social and economic benefits are not compromised, implementing very low cost precautionary procedures to reduce exposure is reasonable and warranted' [WHO 2007]."*

If the available mitigation measures cannot be implemented at no cost or very low cost then no further action is required.

Undergrounding is not consistent with prudent avoidance.

Because undergrounding is usually far more expensive than overhead construction, it is normally outside the scope of prudent avoidance / precaution in the context of an overhead powerline. On the issue of undergrounding, the Gibbs Report specifically stated that,

> *"…because of its additional cost, undergrounding solely for the purpose of avoiding a possible risk to health should not be adopted".*

[20] 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.

[21] 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

7.5 Measures to Mitigate EMF from Overhead and Underground Powerlines

Further to the prudent avoidance guidelines outlined above, the ENA's EMF Reference Management Handbook (2016) [28] recommends the following measures to mitigate EMF levels for designs and consideration of prudent avoidance.

1. Increasing the distance from source.
2. Modifying the physical arrangement of the source:
    - reducing the conductor spacing,
    - rearranging equipment layout and equipment orientation, and
    - for low voltage, bundling the neutral conductor with other phases.
3. Modifying the load:
    - optimally phasing and balancing circuits,
    - optimally configuring downstream loads,
    - applying demand management, and
    - for low voltage, balancing phases and minimise residual currents.

Additional measures which are less likely to satisfy the cost and convenience criteria which apply to precautionary measures but may be considered include:

4. incorporating a suitable shielding barrier between the source and the receiver;
5. active and passive compensation.

Examples of Mitigation of EMF on Overhead Lines by optimising phase conductor positions

The following diagrams in Figure 43 and Figure 44 below show the effect of re-arranging the phase conductors (A, B and C) on a 3 phase power line.

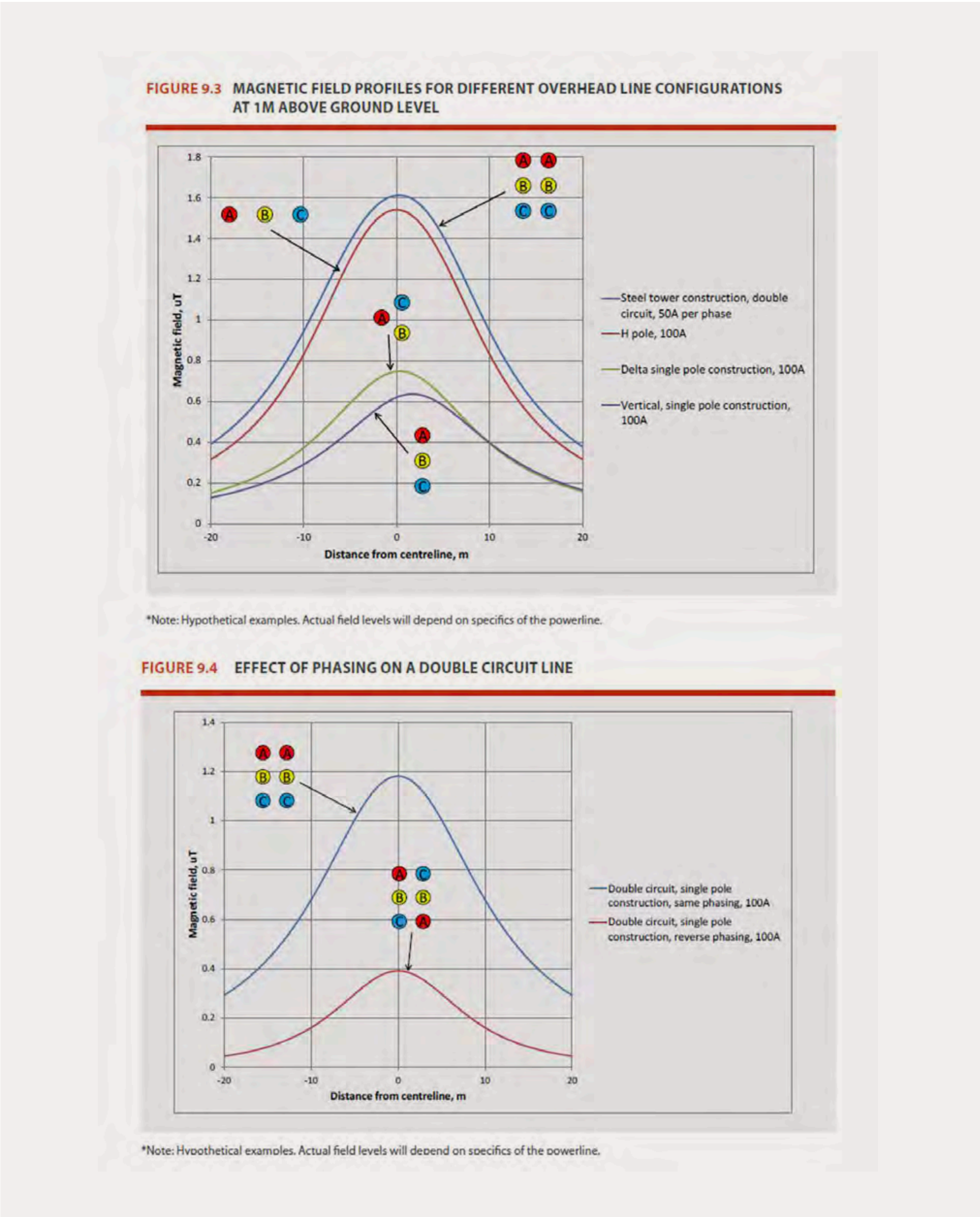


Figure 43. Effect of Phasing on EMF for Overhead Lines (ENA [28])

Examples of Mitigation of EMF on Underground Lines by Optimising Phase Positions (Flat Vs Tre-foil)

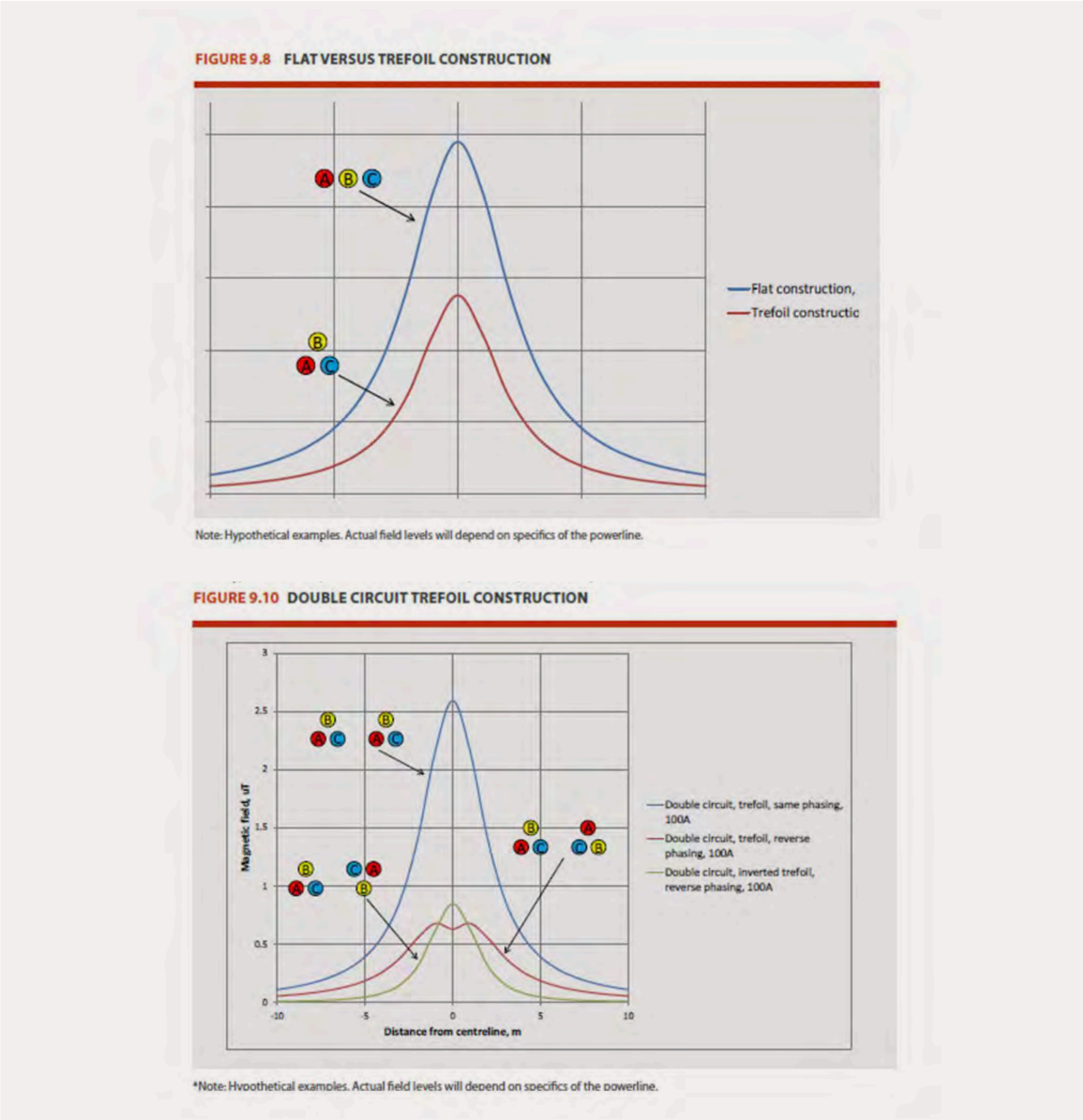


Figure 44. Effect of Laying Configuration and Phasing on EMF for Underground Cables (ENA [28])

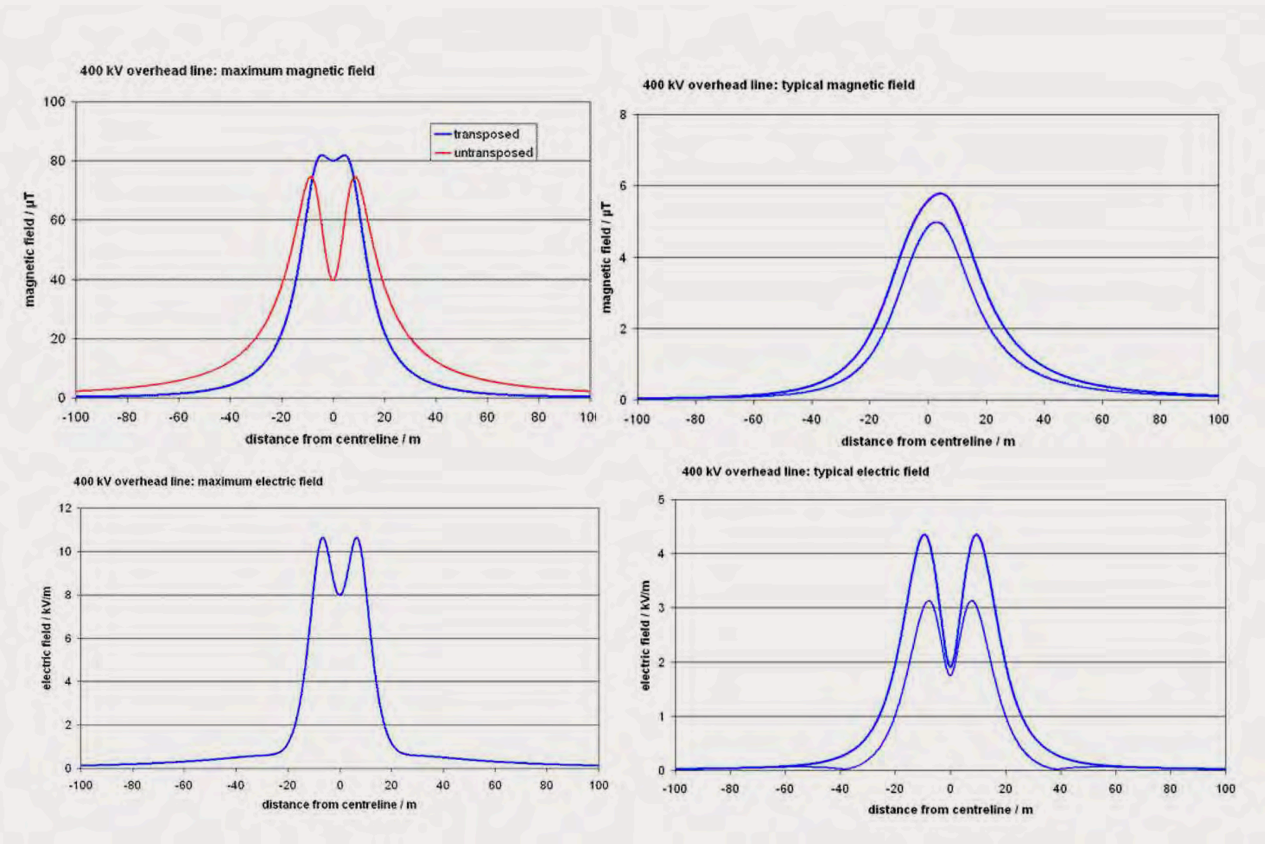
7.6 Typical EMF Profiles near Overhead and Underground Transmission Lines

7.6.1 EMF Profiles for 400KV Overhead and Underground Transmission Lines

The following EMF profiles for 400kV Overhead and Underground have been sourced from the UK's National Grid website emfs.info[22]. The website is operated by the UK company—National Grid which is responsible for transmission networks in England and Wales. The website also serves a purpose of providing information on EMF for the whole of the UK electricity industry. These profiles are likely to be similar on a comparative basis to 500kV Overhead and Underground.

[22] https://www.emfs.info/.

400kV Overhead Transmission Lines



Magnetic Field Graphs

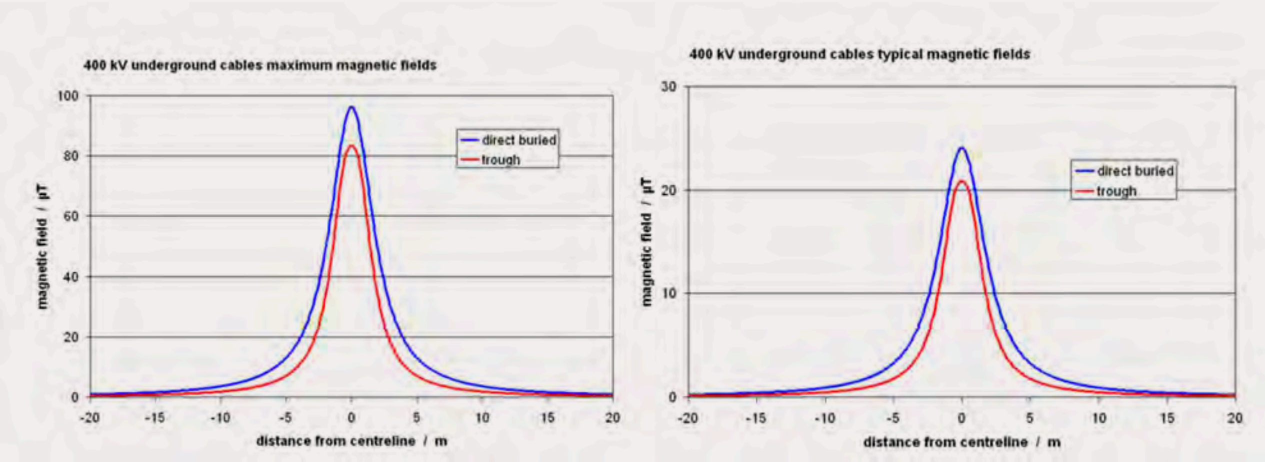
1. All fields calculated at 1 m above ground level.
2. All fields are given to the same resolution for simplicity of presentation (1 nT = 0.001 µT) but are not accurate to better than a few percent.
3. Calculations ignore zero-sequence current. This means values at larger distances are probably underestimates, but this is unlikely to amount to more than a few percent and less close to the line.
4. The “maximum field under the line” is the largest field, which is not necessarily on the route centreline; it is often under one of the conductor bundles.
5. Calculated fields agree well with measured fields.

Electric Field Graphs

1. All fields calculated at 1 m above ground level.
2. All electric fields are calculated for the nominal voltage. In practice, voltages (and hence fields) may rise by a few percent.
3. All electric fields calculated here are unperturbed values.
4 All fields are given to the same resolution for simplicity of presentation (1 V/m) but are not accurate to better than a few percent.
5. Calculations ignore zero-sequence voltages. This means values at larger distances are probably underestimates, but this is unlikely to amount to more than a few percent and less closer to the line.
6. The “maximum field under the line” is the largest field, which is not necessarily on the route centreline; it is often under one of the conductor bundles.
7. In efforts to reduce aerodynamic problems, a small number of 400 kV lines with quad bundles have had expanded bundles fitted, e.g. 500 mm horizontally. This produces slightly higher electric fields but is not included in these tables.”

Figure 45. Maximum and Typical EMF Profiles for 400kV Overhead Line (emfs.info)

400kV Underground Transmission Cables



1. All fields calculated at 1 m above ground level.
2. All fields are given to the same resolution for simplicity of presentation (0.01 µT = 10 nT) but are not accurate to better than a few percent.
3. Calculations ignore zero-sequence current. This means values at larger distances are probably underestimates, but this is unlikely to amount to more than a few percent.
4. Cable designs are not standardised to the same extent as overhead lines and the examples given here are representative.
5. The trough calculation is for a double circuit and the direct buried is for a single circuit, but in practice there may be other nearby circuits which affect the field.

There is no external electric field from metallic sheath underground cables.

Figure 46. Maximum and Typical EMF Profiles for 400kV Underground Line (emfs.info)

The typical and maximum magnetic field levels at 1 m above ground level at the centre of the line will be greater for an underground line compared to the equivalent overhead line.

However, the magnetic field levels for an underground cable drop off more rapidly compared to an overhead line, due the conductors being closely spaced. This results in corridor widths for underground transmission cables being less than overhead lines to meet reference levels.

7.6.2 Comparison of EMF from Power Lines and Typical Household appliances

ARPANSA provides a comparison of magnetic fields from typical household appliances and transmission and distribution lines. This information is presented in the Figure 47.

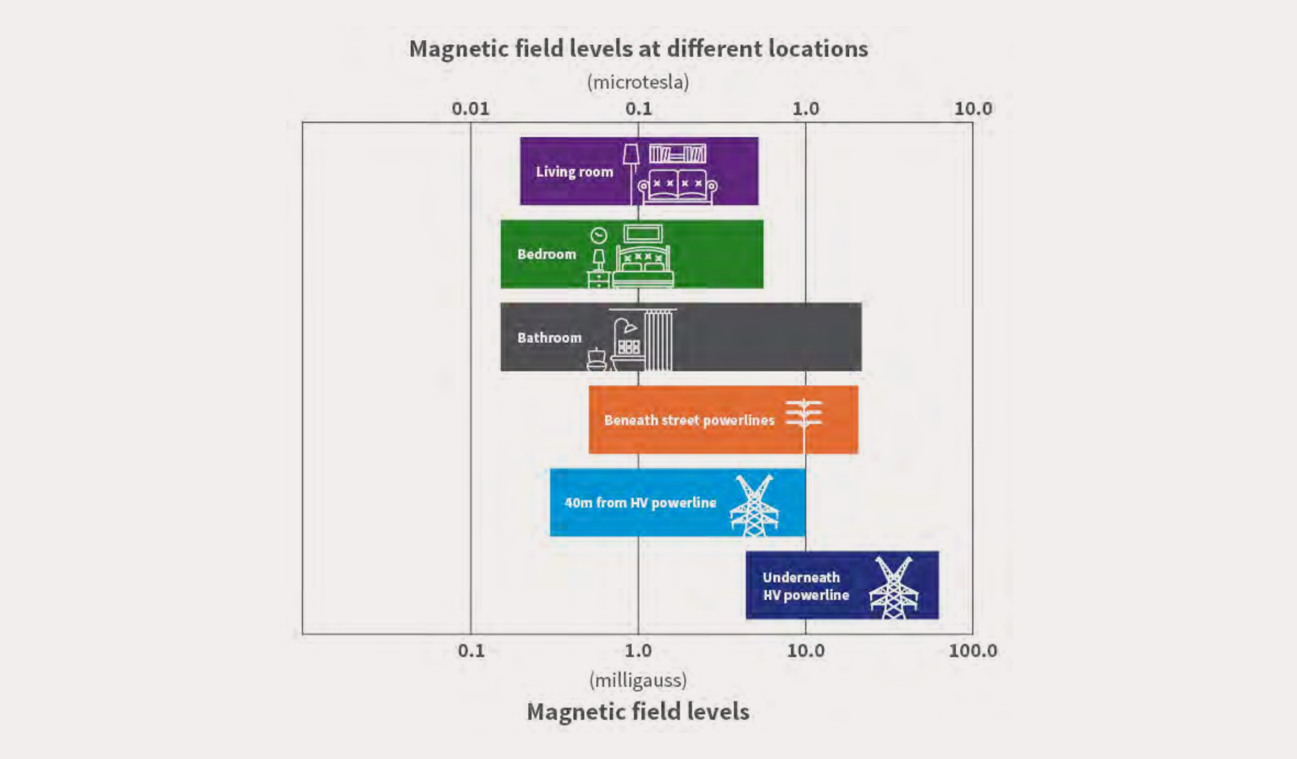


Figure 47. Comparison of Magnetic Fields from Household Appliances and Power Lines (ARPANSA[23])

7.7 HVDC Power Lines and EMF

Whilst AC transmission lines are characterised by low frequency (50Hz in Australia) electric and magnetic fields, HVDC is characterised by static electric and magnetic fields.

Characteristics and effects of static electric fields

On static electric fields, the INCIRP advises on its website[24]:

The strength of a static electric field is expressed in volts per meter (V/m). The strength of the natural electric field in the atmosphere varies from about 100 V/m in fair weather to several thousand V/m under thunderclouds. Other sources of static electric fields are charge separation because of friction or static electric currents from varied technologies.

Static electric fields do not penetrate the human body because of the body's high conductivity. The electric field induces a surface electric charge, which, if sufficiently large, may be perceived through its interaction with body hair and through other phenomena such as spark discharges (microshocks). The perception threshold in people depends on various factors and can range between 10–45 kV/ m. Furthermore, very high electric fields, such as from HVDC lines, can charge particles in the air, including polluted particles. There was a hypothesis that charged particles might be better absorbed by the lung than uncharged ones and so, raise people's exposure to air pollution. Current knowledge, however, suggests that an increased health risk from such charging of particles is very unlikely. Overall, the limited number of animal and human laboratory studies that have investigated the effects of exposure to static electric fields, have not provided evidence of adverse health effects.

[23] https://www.arpansa.gov.au/understanding-radiation/radiation-sources/more-radiation-sources/electricity
[24] https://www.icnirp.org/en/frequencies/static-electric-fields-0-hz/index.html

Effects of Static Magnetic Fields on the Body and Health Implications

On static magnetic fields the ICNIRP advises on its website[25]:

There are several known mechanisms by which magnetic fields can influence biological systems. Magnetic fields not only exert physical forces on metallic objects but also on moving electric charges. With respect to biological functioning, exposure to static magnetic fields will affect the electrically charged particles and cells in the blood, especially when moving through the magnetic field. The magnetic force can accelerate or reduce the movement of charged particles. An example is a reduction in the velocity of blood cells flowing through blood vessels. A further mechanism is via complex electronic interactions that may affect the rate of specific chemical reactions.

The ICNIRP in 2009 [31] reported a number of findings as follows. There is no evidence for adverse effects of exposure to fields up to 8 Teslas (T) except for limited information on minor effects such as on hand-eye coordination and visual contrast. Magnetic fields of 2-3T or higher (such as those generated by equipment in some industrial and medical settings or in some specialist research facilities—i.e., MRI) can evoke transient sensations such as vertigo and nausea. These occur as the result of the generation of small electrical currents in the ear's balance organ. The currents generate signals to the brain that provide different information to that obtained through vision, resulting in the sensations of vertigo and nausea. These effects are not adverse health effects in themselves, but they can be annoying, and they may impair normal functioning. Overall research has not shown to date that exposure to low-level static electric and magnetic fields have detrimental effects on health.

Sources of Exposure from HVDC Lines

The natural static magnetic field of the Earth is around 50µT, depending on the geographic location, and varies from between 30 to 70µT. Magnetic flux densities of the order of 20µT are produced under HVDC transmission lines.

ICNIRP Exposure Limits

The static electric field exposures according to ICNIRP are:

- occupational exposure: 10kV/m
- public exposure: 5kV/m.

The static magnetic field exposures according to ICNIRP are given in the table from ICNIRP presented in Figure 48.

Table 2. Limits of exposure[a] to static magnetic fields.

Exposure characteristics	Magnetic flux density
Occupational[b]	
Exposure of head and of trunk	2 T
Exposure of limbs[c]	8 T
General public[d]	
Exposure of any part of the body	400 mT

[a] ICNIRP recommends that these limits should be viewed operationally as spatial peak exposure limits.
[b] For specific work applications, exposure up to 8 T can be justified, if the environment is controlled and appropriate work practices are implemented to control movement-induced effects.
[c] Not enough information is available on which to base exposure limits beyond 8 T.
[d] Because of potential indirect adverse effects, ICNIRP recognizes that practical policies need to be implemented to prevent inadvertent harmful exposure of persons with implanted electronic medical devices and implants containing ferromagnetic material, and dangers from flying objects, which can lead to much lower restriction levels such as 0.5 mT.

Figure 48. ICNIRP Limits of Exposure to Static e.g. HVDC Magnetic Fields (ICNIRP [31, p. 511])

[25] https://www.icnirp.org/en/frequencies/static-magnetic-fields-0-hz/index.html

8.

Conclusions

8.1 Key findings

1.

High voltage alternating current (HVAC) overhead line technology, has been the dominant form of transmission infrastructure worldwide since the early twentieth century. This is because it has provided the most cost- effective and technically feasible system for constructing, operating, and maintaining a grid that meet high standards of safety and reliability. Overhead transmission lines have a service life of around 60 to 80 years with appropriate maintenance.

2.

HVAC underground cable transmission is feasible only for relatively short route lengths e.g around 50km for 500kV. This is due to the high electrical capacitance of transmission cables which requires expensive reactive power compensation plant (e.g. shunt reactors) to counteract the resulting transmission losses from this phenomenon.

3.

HVDC can be a feasible alternative to HVAC transmission for specific applications requiring high power transfer capacity over very long route lengths (i.e. several hundred kms depending on power transfer) that are point to point without intermediate connections. The economic feasibility for application of HVDC compared to HVAC, ultimately depends on project specific requirements, factors and constraints which determine whether HVDC should be considered. Regulatory investment test requirements also need to be satisfied.

8.2 Comparison Table – Technical Factors of HV Transmission Infrastructure

A summary comparing the technical factors of overhead and underground infrastructure is presented in Table 14 below.

Table 14. Comparison of HV Overhead and Underground Cable Transmission Lines

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
			Technical Factors - System Design, Installation and Performance		
1	**Power transfer capacity (typical):**	500kV: AC Single Circuit Quad Bundle ~3000 MW. 330kV: AC Single Circuit ~ 1000 MW. 275kV: AC Single Circuit Twin bundle – 800 to 1000 MW. 132kV: AC Single Circuit Single bundle ~ 200 MW.	500kV AC: 2000MW 330kV AC: 800MW 275kV AC: 800MW 132kV AC: 150MW	+/- 525kV: 2000MW +/1 320kV: 750MW	+/- 525kV: 2000MW +/1 320kV: 750MW
2	**Feasible maximum line route lengths**	Overhead transmission lines can traverse long routes up to 1000km. Overhead lines require less reactive compensation plant (per km) compared to underground cables.	40 to 60km based on critical length (length where cable capacitance equals the rating on cable, typically around 85km for 330 kV and 76km for 500 kV; practical lengths will be around half of these values). Reactive compensation plant such as shunt reactors or static var compensators at termination points are required for underground transmission to counteract the more significant capacitive effects of cables compared to an overhead line.	Feasible route length for comparable power transfers to HVAC lines is currently **up to around 750 to 1000km**. Route lengths greater than 1000km are feasible.	
3	**Conductors, Insulators and Cables**	Typically, aluminium and aluminium with steel core, with 2 conductor bundles at 275/330kV and quad bundles at 500kV. Insulator strings can be glass, porcelain or composite.	XLPE insulated cable is the most common technology. The first installation at 500kV was in 1988, so the technology is now mature.	Conductors similar to HVAC. Longer insulator strings generally required due to higher voltage across insulators compared to 3 phase AC.	XLPE cables similar to HVAC. However cable design provides for insulation subject to greater electrical stresses compared to HVAC.
4	**Reactive compensation equipment requirement**	Reactive compensation is required for longer line routes but is much less than the requirements for an equivalent rated UGTL.	Significant reactive compensation is required for circuit lengths at 50% to 100% of the critical length (around 50km to 70 km for EHV cables).	Not applicable.	Not applicable.
5	**Power conversion equipment requirement**	Not Applicable.	Not Applicable.	AC/DC power conversion equipment required at each end of the transmission line. This is a major cost factor for HVDC systems.	

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
	Technical Factors - System Design, Installation and Performance				
6	**Above ground impacts and construction requirements**	Typical lattice tower height and conductor span lengths for double circuit: 500kV : 60 to 80m high, spans 300 to 500 m 330kV : 50 to 60m high, spans 300 to 400 m 275kV : 40 to 50m high, spans 300 to 400 m 132kV : 30 to 40m high, spans 200 to 300 m Alternative pole or aesthetic designs may have lower heights. Aesthetic structures such as steel poles, T-pylons (UK) and lower height structures can be used in specific applications. However, there may be significant trade-offs such as cost, access and maintenance, additional structures and increased easement width.	Transition structures and fenced ground terminations required for connection to OHTL or at terminal substation.	Structure heights depend on DC voltage but will typically be less than the equivalent rated HVAC OHTL Structures will be more compact as less conductors will be needed. HVAC lines can be converted to HVDC application.	Transition structures required for connection to OHTL or at terminal substation.
7	**Below ground impacts and construction requirements**	Tower foundations and earthing conductors.	Depending upon design, voltage and power transfer rating: Cable trenching to lay conduits or cables - typically 1 to 2 m deep. Trench widths varying depending on number of cables and power transfer rating e.g. 500kV : 4 to 5m wide per circuit 330kV : 1.5 to 2m wide per circuit 275kV : 1.5 to 2m wide per circuit 132kV: 1 to 1.5m wide per circuit Horizontal direction drilling or micro-tunnelling required at some locations e.g., under waterway, rail corridors or busy roads. Cable tunnels will generally be required in high density urban areas for EHV cables.	Tower foundations and earthing conductors. Special earthing design required for ground electrodes.	Similar to HVAC UGTL, however trench widths will be less as a lesser number of cables will generally be required for same power transfer capacity.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
8	**Induced voltages**	OHTL's can induce voltages in nearby metallic objects such as fences, rail tracks and pipelines. Earthing and mitigation measures, such as phase conductor arrangements need to be considered in the design of an OHTL to ensure that the hazard is mitigated, and the design complies with standards.	UGTL's can induce voltages in nearby metallic objects such as fences, rail tracks and pipelines, however the earthed metallic screen significantly mitigates the induced voltages. Earthing arrangements of UGTL's that have metallic outer sheaths must also be considered as the induced voltages can cause current flows in the sheath that result in heat losses. Arrangements such as cross-bonding cancel the induced voltages in a 3-phase cable installation.	Induced voltages from HVDC lines into nearby metallic objects are static and tend to be lower than HVAC lines. Both steady state and fault currents in the HVDC line must be considered. Ground potential rise due to discharge currents via earth electrodes in HVDC systems must be considered in the design.	
9	**Vehicle access tracks**	Access tracks required for construction (heavy vehicle) and on-going maintenance (light vehicle). Primary requirement is access to structure location for construction lay down areas and where there is an ongoing requirement for vegetation management along the route.	Apart from where installation is under a formed public road, access tracks along the cable route are normally required for construction and on-going routine inspection and maintenance. The impact will vary depending upon the route, terrain, and installation methods.	Access tracks required for construction (heavy vehicle) and on-going maintenance (light vehicle). Primary requirement is access to structure location for construction lay down areas and where there is an ongoing requirement for vegetation management along the route.	Apart from where installation is under a formed public road, access tracks along the cable route are normally required for construction and on-going routine inspection and maintenance. The impact will vary depending upon the route, terrain, and installation methods.
10	**Future connection capability**	HVAC OHTL's provide the most economic and flexible capability for future connections to the line.	HVAC UGTL's provide economic and flexible capability for future connections to the line. Cost will be greater than OHTL's however with more expensive underground works to extend, joint and terminate cables.	HVDC lines provide the least economic and flexible capability for future connections due to the requirement for additional converter stations. HVDC is more suited to applications for direct power transfer between two distant locations.	
11	**Reliability**	Reliability of performance (typical forced outage rate of 0.5 to 1.0 per 100 km/year). Structural failures (for Australia, failure rate is around 1 in 150,000 per annum). Overhead lines are exposed to severe weather including lightning strikes. Repair time for faults is much shorter duration compared to underground.	For XLPE cables outage rates are typically less than 1 outage/100km/year and lower than equivalent overhead lines. Repair time for underground cable faults is a much longer duration than overhead lines due to excavation, cable jointing and electrical testing work required e.g., up to 4 weeks.	Limited data is available; however, outage rates are expected to be like HVAC OHTLs. The lesser number of conductors in a HVDC line would result is less exposure to faults compared to HVAC.	Limited data is available; however, outage rates are expected to be like HVAC UGTLs. The lesser number of conductors, joints and terminations in a HVDC line would result is less exposure to faults compared to HVAC.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
12	**IElectro Magnetic Fields (EMF)**	Magnetic field levels are maximum under the centreline of the transmission line and decrease less gradually with distance from the line compared to an underground line. Transmission lines are designed to meet industry compliance limits within the corridor. Electric fields are emitted from overhead lines, but lines are designed to be within compliance limits. Magnetic field levels at 40m from overhead transmission line are similar to levels from typical appliances found within a home. The electric fields from transmission lines rated at 330 kV and below will generally produce electric fields less than the reference levels or industry guidelines. Design measures need to address electric fields from 500 kV transmission lines.	Magnetic field levels are above the centreline of the underground transmission line and decrease more rapidly with distance from the line compared to an overhead line. Electric field are contained within a cable with outer earth bonded metallic sheath. EMF levels at 4m from underground transmission line are similar to levels from typical appliances found within a home.	DC magnetic fields are static and subject to higher reference limits (i.e., less onerous) compared to AC. DC electric fields are static and subject to higher reference limits (i.e., less onerous) compared to AC. Design measures to ensure compliance with standard limits are applied.	DC magnetic fields are static and subject to higher reference limits (i.e., less onerous) compared to AC. Design measures to ensure compliance with standard limits are applied. Electric fields are contained within the cable system.
13	**Audible Noise**	Audible noise can occur due to: • corona discharge on the transmission line conductors • dirt or pollution build-up on insulators • wind effects on structure and fittings These effects need to be considered in the design and maintenance measures employed to ensure noise is within compliance limits.	No audible noise from underground cables.	Audible noise – similar to HVAC OHTLs, but is dependent on voltage and size of conductors. Design measures are applied to ensure noise levels are within compliance limits. Audible noise from HVDC converter stations will occur. This needs to be considered in the design and location of converter stations in order to minimise impact.	No audible noise from underground cables. Audible noise from HVDC converter stations will occur. This needs to be considered in the design and location of converter stations in order to minimise impact.
14	**Corridor and easement requirements:**	For double circuit: 500kV AC – 70m wide 330kV AC – 60m wide 275kV AC – 60m wide 132kV AC – 20 to 40m wide Adjoining public roads may form part of a corridor.	For double circuit, rural: 500kV AC – 30 to 40m 330kV AC – 10m to 20m 275kV AC – 10m to 20m 132kV AC – 5m to 10m Urban installation corridor width depends on availability of suitable public road corridors or there is a requirement for a tunnel. Land is also required for underground to overhead transitions.	Corridor widths for HVDC OHTLs of equivalent power transfer ratings are similar to HVAC OHTLs. Buffer zones required for EMF reduction or prudent avoidance would be less.	Corridor widths for HVDC UGTLs of equivalent power transfer rating will be generally less than HVAC UGTLs. This is due to a lesser number of cables and reduced width trench widths required for an installation. Road corridors may be more readily used for cable routes. Land is also required for underground to overhead transitions.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
15	**Lifespan (Typical)**	60 to 80 years.	Greater than 40 years.	60 to 80 years (OHTL) Converters to be considered also.	Greater than 40 years (UGTL cable) Converters to be considered also.
16	**Project timeframes**	e.g. for a 500kV double circuit for 100km route length: Planning and approvals: 3-5 years. Construction: 2 years.	e.g. for a 500kV double circuit for 50km route length: Planning and approvals: 3 years. Construction: 4-6 years.	Construction: 2 years.	Construction: 4 – 6 years.
			Risk Management Aspects		
17	**WH&S – construction**	General construction industry risks. Working at heights risks for erection of towers and conductor stringing. May involve helicopter work. Electrical safety risks – HV switching, testing, live line works.	General construction industry risks. Excavation machinery risks Electrical safety risks – HV switching, testing. Overall risks considered lower for UGTLs compared to OHTLs.	General construction industry risks. Working at heights risks for erection of towers and conductor stringing. May involve helicopter work. Electrical safety risks – HV switching, testing, live line works also at converter stations.	General construction industry risks. Excavation machinery risks. Electrical safety risks – HV switching, testing including converter stations. Overall risks considered lower for UGTLs compared to OHTLs.
18	**Severe weather**	OHTL are exposed to severe weather damage from high winds, flooding, and lightning strikes.	UGTL have limited exposure risk to severe weather. Lightning strikes to the overhead network can cause damage to UGTL.	OHTL are exposed to severe weather damage from high winds, flooding and lightning strikes.	UGTL have limited exposure risk to severe weather. Lightning strikes to the overhead network can cause damage to UGTL lines.
19	**Bushfire risk and exposure**	OHTL can cause bushfires (releasing molten particles from conductor clashing or conductor contact with vegetation or ground). OHTL's may be exposed to bushfire damage risk (high bushfire risk areas).	UGTLs have limited exposure to bushfire damage risks. Above ground equipment including cable terminations at overhead to underground transitions would be exposed.	OHTLs can cause bushfires (releasing molten particles from conductor clashing or conductor contact with vegetation or ground). OHTL's may be exposed to bushfire damage risk (high bushfire risk areas).	UGTLs have limited exposure to bushfire damage risks. Above ground equipment including cable terminations at overhead to underground transitions would be exposed.
20	**Climate change**	Long term climate change effects could increase risks associated with severe weather, wind loads and bushfires on OHTL's. OHTL's line designs will need to consider these impacts which may result in increased project costs.	UGTL's will be less exposed to long term climate change risks. There is exposure to damage in flooding events where erosion of ground can expose cables.	Long term climate change effects could increase risk associated with severe weather, wind loads and bushfires on OHTL's. OHTL's line designs will need consider these impacts which may result in increased project costs.	UGTL's will be less exposed to long term climate change risks. There is exposure to damage in flooding events where erosion of ground can expose cables.
21	**Damage by other parties**	OHTL's may be exposed to malicious and accidental damage. Accidental damage can be by vehicles, construction machinery or aircraft.	UGTL's may be exposed to risk of third-party damage by other excavation machinery including drilling.	OHTL's may be exposed to malicious and accidental damage. Accidental damage can be by vehicles, construction machinery or aircraft.	UGTL's may be exposed to risk of third-party damage by other excavation machinery including drilling.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
22	**Earthquake**	Earthquakes have potential to cause damage to overhead infrastructure. However, repair times will be less than for underground cables.	Earthquakes have potential to cause damage to underground cables, joints, and terminations. Repair time in such situations would be considerably longer than for overhead infrastructure.	Earthquakes have potential to cause damage to overhead infrastructure. However, repair times will be less than for underground cables.	Earthquakes have potential to cause damage to underground cables, joints, and terminations. Repair time in such situations would be considerably longer than for overhead infrastructure.

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Appendix A

Literature Review Report on Technical and Economic Aspects of HV Overhead and Underground Cable Transmission Lines

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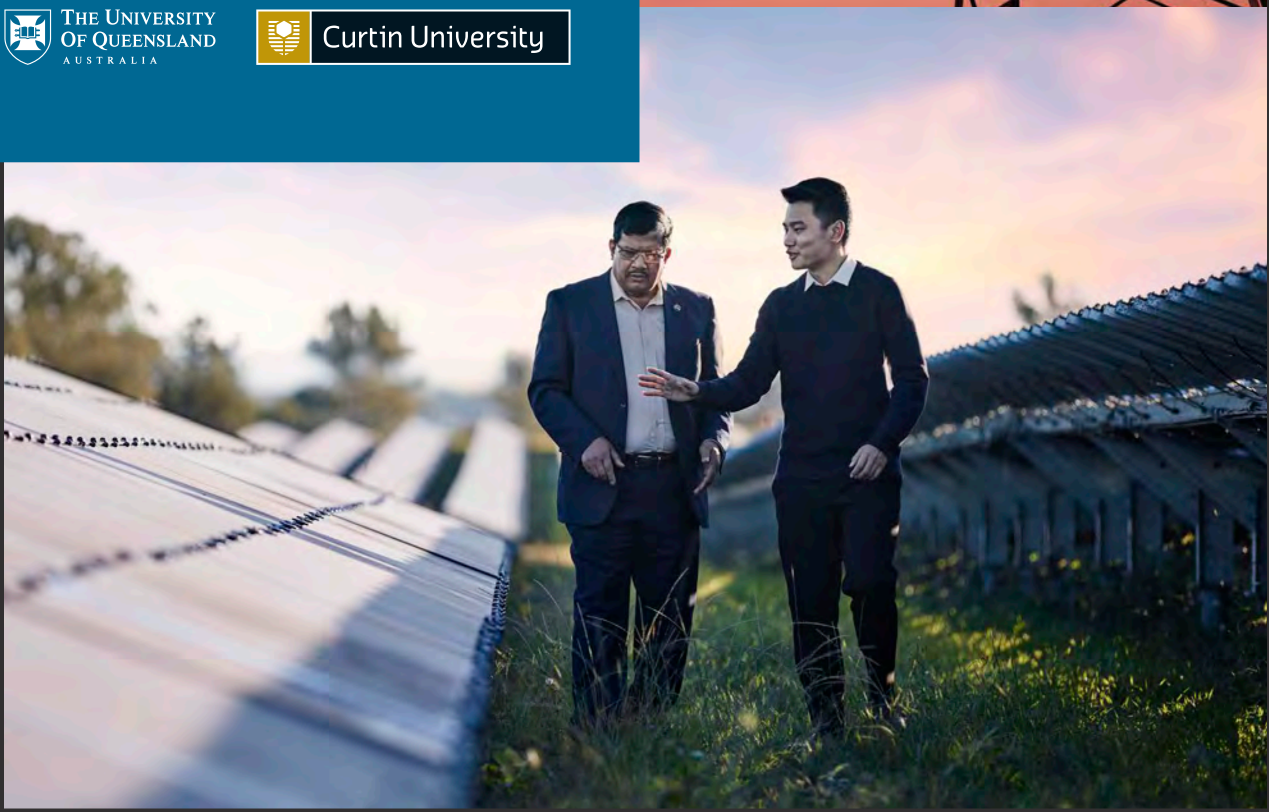

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Abstract

This report presents a systematic review of recent literature on the technical and economic aspects of overhead and underground cable electricity transmission lines. The study aimed to provide a comparison of overhead and underground cable lines on these aspects. The study reviewed literatures published since 2012 from academia including web of science, IEEE explore and Elsevier etc, and also some CIGRE and EPRI documents. Based on the literature review, it is found that the power transfer capability of overhead (OH) lines can be improved by using multi-circuits, multi-voltage lines, and High Temperature Low Sag (HTLS) conductors. For underground (UG) cables, two cables per phase may require to match the capacity of the OH line. However, number of cables can be reduced by employing DC system in place of AC system. Also, the burial depth of HV cables and the improved laying conditions using proper backfills may improve the thermal conditions of UG cable. UG cable system has less disruption to traffic, good protection from bad weather conditions and third-party disturbances. Therefore, UG cables appear to have higher reliability than OH line. However, the outage duration with UG cable can be much longer than the OH line due to difficulty in accessing the cable system. HVDC cables may show even better reliability than their AC counterpart due to their better performance at elevated temperatures. Also, UG cable has advantages of better aesthetics and less magnetic field on ground level (if buried at proper depth) than OH line.

The life of both OH line and UG cable may be affected by their design and operating conditions. In case UG cable, the external environmental factors and the location or route where the cables have been installed influence the cable end of life. While for OH lines weather and other external conditions significantly affects their life.

In terms of project planning and design, the UG cable projects may take much longer time than the OH line projects due to extensive construction requirements for UG cable projects. However, the approval of UG projects could be faster than the OH line projects due to increased public acceptance.

The initial capital cost of UG cable projects can be considerably higher than the OH line projects. However, the operation and maintenance cost of OH line projects may go higher than the UG cable project. The life cycle costs of UG cable are typically 2 to 6 times higher than the OH lines due to high capital costs of UG cable projects. However, the cost of UG cable can be minimized by using of multi-utility tunnels.

1.

Introduction

This literature review focuses on technical and economic aspects of overhead (OH) and underground (UG) transmission lines ranging from 110/132 kV to 500 kV. The outcome of this literature review will be used to provide a comparison of OH transmission line and underground (UG) transmission cable. The literature research scope is broken down in the various aspects of OH and UG transmission lines as follows:

1. Technical Aspects

a. Design Characteristics
b. Reliability Performance
c. Construction Requirements
d. Operating and Maintenance Requirements
e. End of Life Requirements
f. Electro Magnetic Field (EMF)

2. Economic Aspects

a. Project Planning and Pre-Design
b. Design, Approvals and Specification
c. Maintenance and Operation
d. Line Losses
e. De-commissioning Costs

To provide a systematic review, Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) methodology is adopted for guiding the literature review process, including data source selection, publication search, publication selection and summary [1].

The searches were primarily focused on the electrical engineering/ power system databases for a 10-year period between 2012 and 2023.

This report is broken up in the following sections:

1. Introduction
2. PRISMA methodology
3. Findings - a brief summary of all selected publications
4. Discussion (OH lines)
5. Discussion (UG cables)
6. Summary of Findings
7. References

It should be noted that Purposeful reference material and what is commonly referred to as “Grey Literature” were not included in the sources for this review. This material will be referenced separately in the main report that accompanies this Literature Review and largely comprises reference documents from industry, such as:

a. Reference books and major reports from the leading electrical engineering industry based research organisations of CIGRE and EPRI including
   - CIGRE Green Books Overhead Lines International Council on Large Electric Systems
   - (CIGRE) Study Committee B2: Overhead Lines. Springer Reference.
   - CIGRE TB 680 – Implementation of Long AC HV and EHV Cable System. CIGRE, 2017.
   - EPRI Underground Transmission Systems Reference Book. Electric Power Research
   - Institute, 2015.
   - EPRI AC Transmission Line Reference Book 200kV and Above, 2014 Edition

b. Standards, reports and reference material from the industry sources including Australian and international Transmission System Operators, AEMO, AEMC, Federal, State, and local Government bodies.

The “Grey Literature” have synthesized a number of research papers to the time of publication and will be covered separately.

This literature research focusses on other Significant or Relevant Research Material (SRM) which may be more recent than the reference book publication or can provide to contribution to the technical and economic aspects of OH transmission line.

2.

PRISMA Methodology

2.1 Eligibility Criteria (Inclusion & Exclusion):

2.1.1 Inclusion criteria:

- Studies which cover construction and structures used on overhead transmission line and underground cables, e.g., specialised structure designs to address visual amenity and/or ongoing land use
- Studies about economic aspect of overhead transmission line and underground cables, such as whole-of-life cost and operational factors (e.g., initial construction costs, social licence costs, ongoing maintenance and support of infrastructure, operational reliability and resilience, costs of end-of-life asset demolition)
- Voltage level in the range of 110/132 kV – 500 kV
- Published between 2012-2023

2.1.2 Exclusion criteria:

- Duplicated studies/publications
- Studies that are irrelevant to the scope of this review

2.2 Information Sources

Considering that this topic is in the field of electrical engineering/power system, the databases that contain the most relevant publications are selected, they are IEEE, Elsevier, MDPI, Springer Nature, IOP and Wiley.

2.3 Search Strategy

Critical terms are identified to be closely relevant to this topic, then they are combined in the search using "AND" and "OR" logic to reduce the number of search results. The terms, logic and scope used in the search are:

- "Overhead Transmission line (topic) and Construction (abstract)"
- Or "Overhead Transmission line (topic) and Condition assessment (topic)"
- Or "Overhead Transmission line (topic) and Lifecycle management (topic)"
- Or "Overhead Transmission line (topic) and HVAC (topic)"
- Or "Overhead Transmission line (topic) and HVDC (title)"
- Or "Overhead Transmission line (topic) and Investment (topic)"
- Or "Overhead Transmission line (topic) and Economic (abstract)"
- Or "Overhead Transmission line (topic) and Whole of life cost (topic)"
- Or "Overhead Transmission line (topic) and Loss (title)"
- Or "Underground Cable (topic) and 500kV (topic)"
- Or "Underground Cable (topic) and Construction (topic)"
- Or "Underground Cable (topic) and Condition assessment (topic)"
- Or "Underground Cable (topic) and Lifecycle (topic)"
- Or "Underground Cable (topic) and HVAC (topic)"
- Or "Underground Cable (topic) and HVDC (topic)"
- Or "Underground Cable (topic) and Investment (topic)"
- Or "Underground Cable (topic) and Economic (topic)"
- Or "Underground Cable (topic) and Whole of life cost (topic)"
- Or "Underground Cable (topic) and Loss (topic)"
- Or "Underground Cable (topic) and Case study (topic)"
- Or "Underground Cable (topic) and Project (topic)"

2.4 Data Collection Process

Based on the aforementioned eligibility criteria, information sources and search strategy, publications are identified as per the procedures presented in the flow chart in Figure 1. According to the search strategy, 511 publications about OH transmission line and 659 publications about UG cables are found through Web of Science, out of which 109 for OH and 116 for UG transmission lines are determined to be potentially contributing to the scope of this study after screening all publications' titles and abstracts. Then, these shortlisted publications are reviewed in detail and finally 24 publications for OH line and 28 publications for UG cable are selected for further discussions. Also, a CIGRE document [2], [3] on UG cable is included in the discussion because of its relevance to the scope of the project.

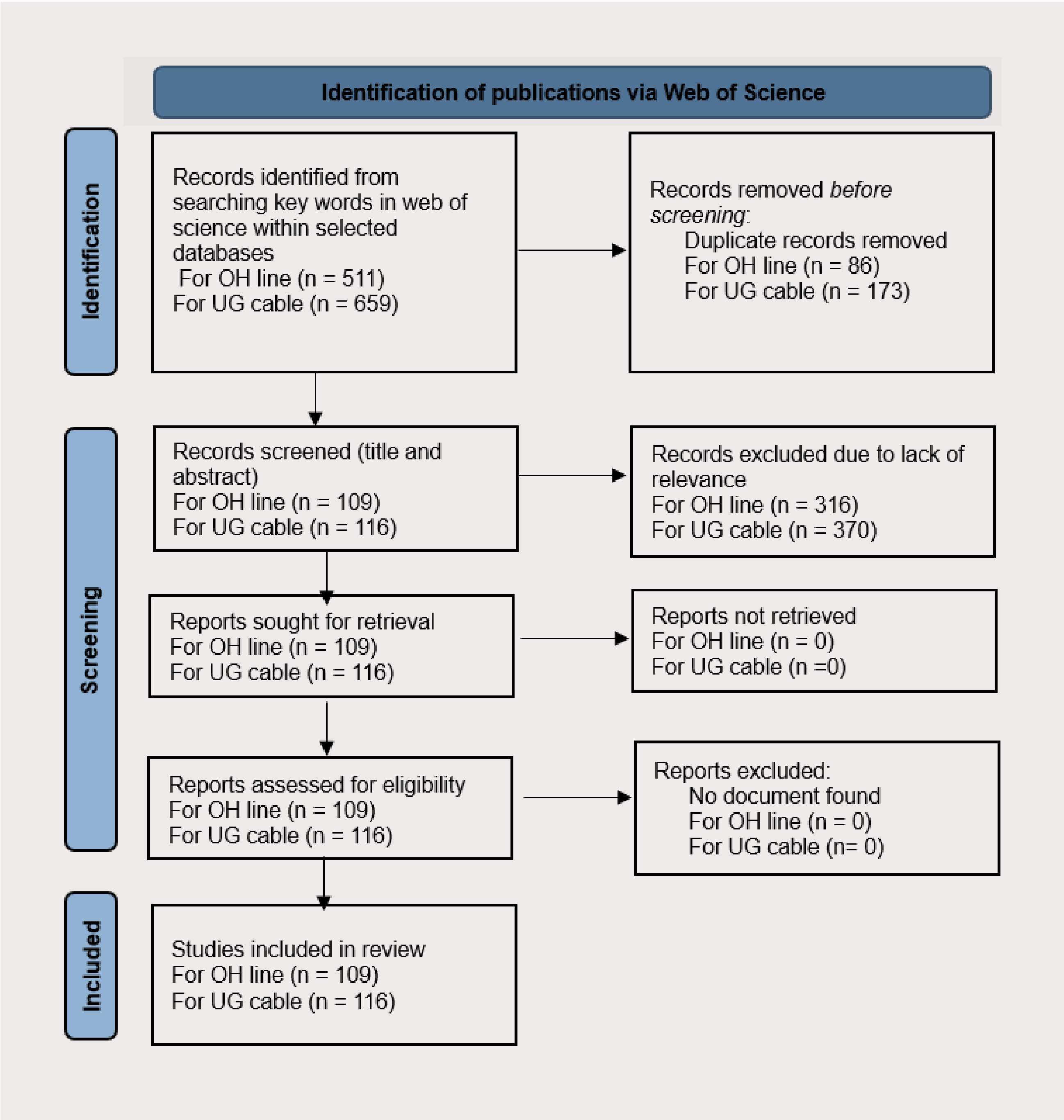

Figure 1 Prisma flow diagram of studies to be included in the systematic literature review

3.

Findings

As per the PRISMA approach, 109 papers have been screened and selected for detailed review for OH lines and 116 for UG cables. All these selected papers have been reviewed in detail to extract useful information, which covers various technical and economic aspects of OH and UG transmission lines. Table 1 and Table 2 gives a summary of the studies along with relevant aims and contributions to the scope of the review for OH lines and UG cables respectively from 24 publications for OH line and 28 publications for UG cable.

Table 1 – Study Summary with Voltage level, Aim of Publications and Contribution to the Scope of Review of OH lines.

Study	Voltage type & level	Aim of publication	Contribution
4	**HVAC/400 kV**	This paper presents a computing approach for determination of the magnetic flux density under OH line	Shows computed magnetic flux density of selected 220 kV and 400 kV OH lines
5	**HVAC** **110-330 kV**	This paper presents a holistic risk-based maintenance decision-making methodology for transmission overhead lines and its practical implementation. The methodology is implemented based on Estonian transmission system	Provides data about outage duration at different voltage levels.
6	**HVDC**	This paper presents an asymmetrical design of VSC-Based HVDC transmission lines	New design by adjust insulators to achieve higher power transfer capacity
7	**HVAC&HVDC** **420 kV**	This paper investigates the audible noise and corona losses of DC circuits on hybrid overhead lines, and conductor surface treatment to reduce audible noise	A real-case example of hybrid HVAC/HVDC 420kV ±400kV line in Austria
8	**HVAC&HVDC** **380 kV, 420 kV**	This paper presents benefit analysis of a hybrid HVAC/HVDC transmission line based on a Swiss case study. It is demonstrated that the hybrid conversion is beneficial since it can lead to reduction in the AC line loading, lower operating costs and increased utilization of the network infrastructure by enabling higher transit flows	A real-case study to demonstrate the benefits of hybrid HVAC/HVDC, drawback is efficiency decreases due to high converter losses
9	**HVAC 110, 220, 400kV**	This article presents an analysis of the use of multi-circuit, multi-voltage overhead lines as a compromise between ensuring the system's safe operation by increasing the transmission network capacity and managing the constraints related to its expansion.	1. It presents discussions on key factors in the design of HVAC multi-circuit, multi-voltage lines. 2. A list of real cases using multi-circuits, multi-voltage OH lines in Europe is presented.
10	**HVDC 800 kV**	Model of HVDC overhead transmission lines with covered conductors is presented. Results show that covered conductors can restrain ion flow field obviously.	Proves that covering conductor with a layer of insulation could restrain the ion flow significantly.
11	**HVAC 110 kV**	This paper presents a new tower design for OHAC 110 kV, called 110STJ tower that is of double circuits and access other lines with single π type, which is used in China for the first time.	Introduces a new tower design for 110 kV OHAC 110 kV

Study	Voltage type & level	Aim of publication	Contribution
12	**Hybrid HVAC/HVDC**	Hybrid HVAC/HVDC has various AC/DC interaction phenomena. The paper deals with the AC impact on the DC power circuits switched off for maintenance purposes.	transposition of the AC power circuits of the hybrid AC/DC transmission line is an efficient measure for the reduction of the induced currents in the de-energized DC conductors, but on the other hand the AC line transposition can cause the significant increase of the touch voltages on the de-energized DC conductors and can cause the violation of the safety requirements for the maintenance work.
13	**HVAC**	This paper presents the state of the art in monitoring technologies that can be used to identify thermal stress on OHL conductors, including the issues and challenges in monitoring.	Provides a comparison of conventional conductors and modified conductors.
14	**HVAC/HVDC** **400, 500 kV**	This paper seeks to propose a hybrid AC/DC power transmission network by the addition of superimposed HVDC lines overlaying existing European transmission corridors.	HVAC superposed with HVDC to save cost Cost details are illustrated with tables for comparison purpose.
15	**HVAC/HVDC, 500 kV**	this paper conducts a thorough Life-cycle cost analysis of HVDC in Turkey. A comparison of this cost between HVDC and HVAC is also presented.	Cost details of HVDC and HVAC are presented, which are valuable for economic analysis of HV lines.
16	**HV**	A project CALAJOULE, co-financed by the Italian Ministry of Economic Development in the framework of the “Ricerca di Sistema” programme, aims at proposing innovative solutions for overhead line conductors for the containment of Joule power losses. This paper presents the main characteristics of the innovative conductors along with the expected benefits deriving from their use in place of the traditional ones.	Introduce a new type of conductor that reduces Joule losses.
17	**HVAC**	This work presents cost evaluation of current uprating of overhead transmission lines by using Aluminium Conductor Steel Reinforced (ACSR) and High Temperature Low Sag (HTLS) conductors. The evaluation method is carried out based on twofold and fourfold ampacities, under both normal and stressed operating conditions. The test case is a 230-kV, double-circuit, transmission lines using 1272 MCM ACSR conductors.	This works details cost evaluation in five cost components, i.e., demolition cost, construction and installation costs, conductor cost, cost of energy losses, and land cost.
18	**NA**	In this paper, a D-distance risk factor was proposed to prioritize high-voltage transmission lines from high to low risk in transmission line maintenance and renovation management.	This paper presents a comprehensive condition assessment for OHTL. TBD
19	**HVTL/UGTL**	in this paper, economic analysis of power transmission lines using interval mathematics has been studied. Life cycle costing studies are performed using net present value analysis on a range transmission lines used in India and the results are analysed. A cost break even analysis considering right of way costs was carried out to determine the point of economy indifference.	This works provides a comparison of life-cycle cost analysis between HVTL and UGTL at 132kV, 220 kV and 400 kV.
20	**HVAC**	The paper presents some of the results of the CALAJOULE project co-financed by the Ministry of Economic Development in the framework of the “Ricerca di Sistema” programme.	This paper presents an innovative conductor that reduces Joule loss remarkably.
21	**HVTL**	Highly Efficient Overhead Line Innovative Conductors with Reduced Joule Power Losses.	Provides state-of-art presently adopted conductors for power lines, and introduced two innovative conductors.

Study	Voltage type & level	Aim of publication	Contribution
22	**HVDC**	HVDC System Solutions.	This paper introduces high-level basics of LCC and VSC HVDC solutions. TBD
23	**HVAC, 380 kV**	Innovative insulated cross-arm: requirements, testing and construction.	New compact tower design but there is a lack of more detailed information.
24	**HVAC/HVDC**	Integration Enhancement of Grid-Connected Wind Farms Using HVDC Systems: Egyptian Network Case Study.	To integrate a wind farm into Egyptian grid, three proposed plans for this 4000MW 75 km transmission line are proposed, and their economic analysis is compared.
25	**HV**	The paper deals with a comparative analysis of the technical (mechanical and heating limitations) and economic efficiency of using conductors of different types, which is based on two actual overhead line models.	The comparison results suggest that the use of HTLS conductors replacing the traditional type conductors can be more economically justified if the price of conductors with composite core is reduced, yet at the same time, it can be one of the possible solutions for increasing the limited capacity of the existing overhead lines
26	**HVAC**	Technical-economic comparison between three and four-conductor bundled 380 kV OHLs.	A very specific comparison, may be not very useful.

NA refers to no relevant information is found in the publication.

Table 2 – Study Summary with Voltage level, Aim of Publications and Contribution to the Scope of Review of UG cables.

Study	Voltage type & level	Aim of publication	Contribution
27	**Range of voltages**	Covers the technical aspects of Underground Transmission Systems.	Thoroughly presented the technical aspects of underground cable system.
2	**Range of HV and EHV**	The design, challenges, installation, maintenance, and monitoring of HV and EHV transmission cables are presented.	Protection system, harmonic resonance, magnetic field, testing, installation, transportation, quality assurance, and monitoring of cable system is presented. Also, experience of many cable projects from different countries are shared.
3	**150 kV**	Dynamic rating techniques are described.	Dynamic rating systems is discussed for 150 kV OH lines and UG cable.
28	**Range of voltages**	Technical aspects of HVDC cable system.	Fundamentals, main principles, design, space charge and life modelling of extruded HVDC cable system is presented.
29	**220 kV**	This paper discuss the specific challenges of power cable monitoring in a cable tunnel and the problems that are encountered due to design ignorance.	A case study is discussed.
30	**230 kV**	This paper highlights the use of UG power cables in conjunction with overhead lines, where the reactive power requirement of overhead line is compensated by UG power cables.	A case study is discussed.
31	**138 kV**	This paper summarizes the design choices and project challenges considered during implementation of six cable projects on the Delmarva peninsula in 2012 and 2013 that significantly expanded the reliability of the utility's power system.	Discussed cable design challenges. Sometimes only limited suppliers are available for a particular type of cable. Sometimes termination failures occur in cable system. In case of fault, the restoration time of cable can be much longer (days to weeks) than for overhead (hours to days). Two smaller power cables can be used to isolate the failed cable and maintain partial power transfer with other cable. However, two smaller cables require twice terminations. A system that has more accessories will inherently have lower reliability than a system with fewer accessories. Therefore, adding two cables per phase for shorter circuits does not always provide benefits in terms of reliability or shortened restoration time. Cables often have lower normal ratings than other transmission equipment, particularly overhead lines, but much higher emergency rating capabilities – particularly short-duration emergencies -- due to the long thermal time constant of cables and the mass of earth in which they are installed. The typical challenges of underground projects such as traffic control, pavement restoration, extensive permitting, easement procurement, etc.
32	**225 kV**	The paper presents the challenges of the construction of extra-long high power underground cable transmission lines. Advantages and disadvantages of different cable bondings are highlighted.	A novel direct cross bonding for 225 kV cable system is presented.

Study	Voltage type & level	Aim of publication	Contribution
33	**NA**	The paper presented the Lifecycle Cost (LCC) analysis of Multi-purpose Utility Tunnel (MUT) and buried utilities LCC by considering the influencing factors.	Life cycle cost of multi-purpose utility tunnel is estimated. Mainly discussed about Multi-purpose Utility Tunnel. Discussed about finance and cost sharing between multiple utilities in same tunnel. A case study of 250 m long tunnel is discussed. The cost of installation of 2 buried cables, which occupies space 1 meter wide in an area with population density of 27,078 persons per km^2 is mentioned to be $759,000. The operational (maintenance) yearly cost of buried cables is mentioned as $31,875 and tunnel maintenance cost is mentioned $ 6000/year. The lifecycle cost for buried cables are mentioned as $4,639,100. If Same cables are installed in multi-purpose utility tunnel, the lifecycle cost mentioned is $2,861,555.
34	**110 kV**	This paper developed an algorithm for decision-making mechanism for utility tunnel construction cost allocation by considering some cost allocation indexes.	Paper presented comparison between the cable laying costs in utility tunnel and direct laying. The service life of cables in utility tunnels are 15 years more than the cable directly layed.
35	**110 kV**	The paper presented a method to estimate the life time cost of different types of power lines. It considered the construction, maintenance and fault elimination costs depending on each power line type (OH, UG, high OH, and isolated wire OH).	Paper presented Latvian case studies to compare the construction and operating costs, and the customer cost of reliability for a 30 kms transmission line. Comparison is made between 30 Kms overhead line and 24 Kms overhead + 6 Kms underground cable options. The annual construction, maintenance, and failure cost for overhead line option is estimated as $ 29,568 while it is estimated as $28,776 for the overhead + underground cable option.
36	**NA**	This paper model the uncertainties of underground transmission cable for asset renewal projects considering the common risks and uncertainties associated with cable such as financial costs, project timing, real estate and environmental issues.	This paper discusses the common risks (related to the financial costs, project timing, real estate and environmental issues) and uncertainties associated with underground transmission cable asset renewal projects. Paper mentioned that there can be little to no control over the surrounding environment where underground cables get installed. "Not-In-My- Backyard" (NIMBY) objections from the public. The difficulty in obtaining new easements can result in drastically higher construction costs and can affect the financial viability of the asset sustainment project itself. The time frame required for the planning, construction and commissioning of a typical new underground cable circuit (including planning, route identification, engineering and construction) typically requires at least from 3 to 7 years, depending on the route location and the scope of the project. Many of the initial assumptions (budgetary, revenue sources, routing, technical, etc.) that were made originally at the time when the project was initiated often would often change throughout the project execution stage. This can result in cost overruns and affect the economic viability of the projects. The combination of normalized financial and non-financial possibility distributions into one resultant aggregate distribution represents the overall possibility distribution for the project, which in turn, can be compared to other developed projects to facilitate their ranking.

Study	Voltage type & level	Aim of publication	Contribution
37	**Reliability assessment tool for underground cable and overhead lines**	Reliability assessment tool for underground cable and overhead lines.	This paper presents a reliability assessment tool for underground cable and overhead lines considering attributes such as failure rates, repair times and intrinsic features under multiple circumstances and the seasonal variation of load and co-generation within them. The study is supported by the specific data collected from the regional utility companies and operators.
38	**Greenhouse gas emission comparison between HVAC and HVDC**	Greenhouse gas emission comparison between HVAC and HVDC.	The greenhouse gas emissions are compared between the HVAC and HVDC cables for per unit weight (1kg) of cable based on the amount of clean renewable energy carried over one year of operation in a Europe environment. The authors estimated 101,000 tons of greenhouse gasses emission saving per kg of HVDC cables, while it is 40,400 tons per kg of HVAC cables. The most frequent rated voltage of HVDC extruded cable projects in service in Europe is 320 kV. The highest voltage of HVDC extruded cable projects being installed at present is 525 kV DC and belongs to the huge German corridors. The voltage limit of applicability of Cigrè testing procedures for HVDC extruded cables has been recently pushed up from 500 kV of TB 496:2012 to 800 kV of TB 852:2021. The paper also discussed the future HVDC projects of German Corridors project.
39	**Paper discussed the issues and challenges of HVDC cables.**	Paper discussed the issues and challenges of HVDC cables.	The issues and challenges of HVDC cables are discussed considering accessories, higher voltage and power, laying environment (submarine and underground cables), modeling, multiterminal HVDC, operation and diagnostics, recyclable insulation, space charge behavior, testing, thermal stability, transient voltages.
40	**525 kV**	The paper described the development of 525 kV cable, its accessories and comparison with 320 kV extruded DC system.	Authors stated that 525 kV extruded DC cable system can transmit at least 50% more power over extreme distances than the 320 kV extruded DC system. As compared to 320 kV cable system, 525 kV cable system have lower cable weight per installed megawatt (MW) of transmission capacity and higher voltages provide reliable transmission and low energy losses.
41	NA	Paper discusses the extruded power cable technology for HVDC applications.	Techniques for measuring space charge and conduction are described for HVDC cable system.

Study	Voltage type & level	Aim of publication	Contribution
42	**150/400 kV**	Paper presents detailed information on life cycle stages of overhead line and underground cables.	Paper discusses how large are the impacts resulting from power losses in the equipment and how large is the share of impacts associated to each of the other life cycle stages of overhead line and underground cables: raw materials production, transportation, installation, maintenance, and dismantling. In addition to losses, processes included are for lines—production of materials for foundations, masts, conductors, and insulators and for cables— production of cable and cable trace. Installation (excavation, etc.) use/maintenance (replacement of parts, inspections) and end of life are also included for both overhead and cable systems. For overhead lines, among all impact categories, material for masts and conductor causes maximum CO2 emissions followed by foundations, installation activities, and at last maintenance operations. The end of life has a negative contribution in all impact categories, which means that the benefits of recycling of metal parts in the masts and conductors outweigh the sum of impacts generated by other end of life processes. For underground cable also, cable material production causes maximum CO2 emissions followed by cable traces which involves removal of old asphalt and building a new layer of sand, cement, and asphalt where the cable is to be installed. For land cables the impacts of end of life represent a cost (causes CO2 emissions) rather than a benefit.
43	**120/230/315 kV**	Underground cable management methodologies, managing and their renewal challenges and issues.	Paper states that due to inaccessibility, physical condition of cable is difficult to ascertain, taking cable sample for condition monitoring is difficult. There should be a systematic framework to evaluate and rank asset renewal investment projects based on modeling uncertainties (size of load lost, number of customers disconnected, critical loads, consequential damage, safety and environmental consequences) and on determining the relative importance (considering risks such as safety, financial, reliability, and environment) of a particular transmission line circuit in the power system as it affects the bulk power system reliability. Making such framework would be challenging because of lack of ability to accurately determine the condition of many underground cable, lack of knowledge in the failure probability for certain cables, difficulty in quantifying the financial consequence of asset failures, limitations in system reliability considerations, and lack of consideration of the time required for implementing the asset renewal / replacement plan.
44	**NA**	Comparison between superconducting cable and underground cable.	Comparison is made between superconducting cable and underground cable considering the factors such as investment cost, reliability, energy loss, capacity, environmental impact when connects two substations using these options.
45	**Na**	Presented a study to find the optimized maintenance and replacement cycle of underground cables.	This paper examined the actual failure rates of the underground cables, the costs of maintenance and repair of cables, and the costs caused by their failures.
46	Na	Total cost of production, installation, and operation of two types and sizes of cable is presented in this paper.	A detailed model for the calculation of the life-cycle cost of cable ownership is presented.

Study	Voltage type & level	Aim of publication	Contribution
47	**220/380 kV**	Techno-economic comparison is made between high temperature superconductor (HTS) transmission cables, overhead line, and XLPE underground cables.	In this paper techno-economic comparison is made between high temperature superconductor (HTS) transmission cables and other available alternatives such as overhead line and XLPE underground cables. As compared to other options, HTS cables are: economic, underground, higher power capacity, lower losses, reduced magnetic field emissions in (existing) OHL, compact: less occupation of land and less permits needed, a possibility to keep 380 kV voltage level in the grid for as long as needed. Different options of transmission are studied and compared based on number of conductors, power transfer capability and losses associated with each option.
48	**380 kV**	Capital cost, reactive power compensation cost, energy loss cost, burden on territory cost, end of life, operation and maintenance, and random failure costs are compared.	Power loss cost, operations and maintenance cost, commissioning and dismantling cost, repair cost, and overall cost is compared between OH line and UG cable.
49	**380 kV**	Comparison of superconducting 380-kV cables with existing overhead lines and underground cables.	Power loss is compared between OH line, UG cables, and superconducting transmission line.
50	**161 kV**	This paper analyses a junction tower, the interface between overhead lines and underground cables.	Electromagnetic analysis of junction tower with cable system is presented.
51	Up to 800 kV	Comparison of HVDC and HVAC. Many case studies presented and compared.	Paper stated that for overhead point-to-point transmission projects and connecting remote offshore wind farms that are more than 50-100 km away, HVDC is the preferred option for distances greater than 300-800 km. The paper covers the following aspects: technical and economic comparison of HVAC and HVDC systems; investigation of international HVDC market size and conditions. The contemporary operational challenges such as the ownership of Multi-Terminal DC (MTDC) networks are discussed. Subsequently, the required development factors, both technically and regulatory, for proper MTDC networks operation are highlighted, including a future outlook of different HVDC system components.
52	Range of voltages	This paper presents an update on superconducting transmission lines.	Technical and the socio-economic aspects of superconducting transmission lines are discussed in detail.

4.

Discussion (OH lines)

This discussion will be based on the 24 publications that are selected based on PRISMA approach. Note that is discussion will not cover a comprehensive basics of the technical and economic aspects, instead, this discussion intends to provide some potentially novel or new experiences that may benefit network operators.

4.1 Technical aspects

4.1.1 Design aspects

Power Transfer Capability

1. ***Multi-circuits, multi-voltage lines***

   A way to increase power transfer capability based on current transmission infrastructure is to expand current overhead transmission line into multi-circuits, multi-voltage lines. Practical examples could be found in Table 3 [9].

Table 3 – Selected examples of multi-voltage transmission lines in the world [9]

No.	Country	Number of Circuits	Rated Voltage	Actual Length of the Multi-Circuit Section	
			kV	km	%
1	Denmark	3	400 + 2 x 150	118	12.8/6.5
2	Denmark	2	400 + 150	215	23.3/11.9
3	Denmark	2	400 + 132	7	0.8/0.7
4	Germany	3	380 + 2x220	38.5	-
5	Germany	3	380 + 2 x 150	7.5	-
6	Germany	3	380 + 2 x 110	135.7	-
7	Germany	2	380 + 110	4.6	-
8	Germany	2	220 + 110	1.7	-
9	Montenegro	2	400 + 110	40	14/5.8
10	Netherlands	4	2 x 380 + 2 x 170	-	-
11	Lithuania	2	330 + 110	2.5	0.1/*
12	USA	2	345 + 230	-	-
13	USA	2	230 + 115	-	-
14	Switzerland	3	2 x 380 + 132	-	-
15	Poland	4	2 x 400 + 220+110	31.2	0.5/0.4/-
16	Poland	3	2 x 400 + 220	4.8	*/*
17	Poland	3	400 + 2 x 110	6.5	0.1/-
18	Poland	2	400 + 110	43	0.7/-
19	Poland	2	220 + 110	7.5	0.1/-
20•	Poland	3	2 x 400 + 220	~20	0.3/0.3
Note • = build scheduled for the years 2027-2030; * = less than 0.1 %					

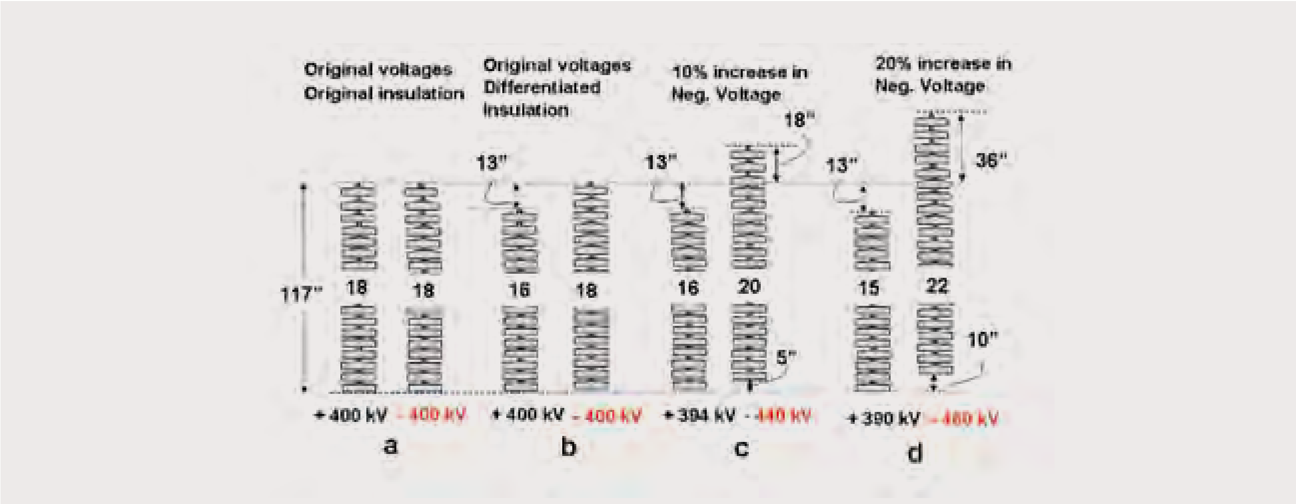

Figure 2 – 400kV example insulation and height adjustments [7]

2. ***Uprating existing HVAC line by replacing ACSR conductors with HTLS conductors***

   There have been various suggestions for improving existing power line networks with the purpose of increasing their throughput capacity as well as the reliability of power supply. This is an important problem that must be considered, especially if the transmission grid requires the prospective expansion of new electrical connections. Therefore, the use of High Temperature Low Sag conductors replacing the traditional type conductors can be one of the possible solutions for the posed problem. In [25], this paper deals with a comparative analysis of the technical (mechanical and heating limitations) and economic efficiency of using conductors of different types, which is based on two actual overhead line model. The results suggest that the use of HTLS conductors replacing the traditional type conductors can be more economically justified if the price of conductors with composite core is reduced, yet at the same time, it can be one of the possible solutions for increasing the limited capacity of the existing overhead lines.

3. ***Hybrid AC/DC***

   Hybrid overhead lines (OHL) are a promising concept to increase transmission capacity without building new lines. However, due to small distance between AC and DC line, an AC ripple would lead to increase in audible noise and corona losses. Conductor surface treatment can be used to reduce audible noise [8].

4. ***HVDC***

   The introduction of overhead DC transmission using VSC (Voltage Source Converter) technology enables the reversal of power direction by changing the current flow rather than altering the voltage polarity. This capability allows for independent design of the poles in HVDC lines, leveraging the differences in insulation strength, generation of radio and audible noise, and perception of electric fields at ground level based on polarity. By doing so, it becomes possible to achieve a negative voltage that is generally 10% to 20% higher than the positive voltage. Consequently, this results in an increase in the MW (megawatt) rating by approximately 5% and 10% respectively. Figure 2 is a picture showing adjustments in insulators to achieve higher negative voltage [7].

Conductors

Traditionally, conventional conductors were made up of strands composed entirely of aluminium alloy. However, in order to enhance their electrical and mechanical properties, the aluminium core of these strands has been replaced with alternative materials like steel or alloy (e.g., ACSR and AACSR). This substitution is necessary because aluminium wire exhibits a high thermal expansion coefficient, causing the core strand to expand rapidly when exposed to high temperatures. To improve power transmission through the line, the conventional conductor has undergone upgrades tailored to specific conditions. These enhancements include the use of different coatings to resist corrosion, altering the shape of the strands to prevent deformation, and modifying the geometric configuration of the conductor to optimize its performance. By making these adjustments, the electrical and mechanical properties of the transmission lines have been improved, strengthening the conductor's ability to withstand challenges such as strong winds (galloping), low wind speeds (aeolian vibration), ice loading, and high temperatures. [13] provides a comparison of conventional conductors and modified conductors in OHL as illustrated in Table 4 and Table 5.

Table 4 – Commonly available conventional conductors in OHL [13]

	Composite material	Function	Advantages	Disadvantages	References
AAC	**Outer: Al** **Core: Al (extra-hard-drawn 1350-1119)**	Most urban areas at short-span lengths.	Good corrosion resistance. Better conductivity than AAAC. Lighter than ACSR.	Poor strength.	[22], [28]
AAAC	**Outer: Al 1350-H19 Core: 6201-181 Al alloy**	Seacoast area More suitable than ACSR in overhead distribution.	Excellent corrosion resistance. Higher tensile strength than AAC. Lower resistance than equivalent ACSR.	Moderate conductivity. Moderate hardness against balding stress. Prone to fatigue failure problem. Present aluminium alloy makes it expensive.	[22], [28], [30]
ACAR	**Outer: Al 1350-H19** **Core: 6201 Al alloy**	Wide transmission line application.	Excellent corrosion resistance. Higher strength. May be consider as a replacement for conventional ACSR.	Lower corrosion resistance than AAAC.	[22], [31]
ACSR	**Outer: Al 1350-H19 Core: Galvanize steel**	Wide usage in long-span transmission lines and rural distribution area. Suitable across rivers. Ice and wind loading area.	Excellent strength and low Sag. Good conductivity. Higher durability compared with AAAC in bending stress.	Maximum operating temperature of 93 °C, limited to heavy load operation. Less conductivity compared with ACAR.	[22], [24]

Table 5 – Types of modified conductor [13]

Group	Type of conductor	Function	Advantages	Disadvantages	References
TW	**ACSR/TW,** **AAC/TW,** **AAAC/TW,** **ACSS/TW**	Application reduces wind and ice load problem.	Improves mechanical and electrical properties of conventional conductor. Lighter than equivalent diameter with conventional conductor. Geometric configuration increases current carrying capacity. Restricts creep over long term service.	Lines up to 16 kV, small conductors may be prone to the corona effect. Manufacturing the geometric configuration for stranding wire machine needs special equipment which may be prone to breaking.	[22], [37], [40]
TP	**ACSR/TP, AAC/TP, ACAR/TP**	Anti-galloping motion and aeolian vibration.	Configuration prevents ice formation. Low power lases.	Limited use for other applications. Lower operating conductor temperature. Costly installation and hardware.	[22], [34], [35]
HTLS	**ZTACIR (with INVAR), GZTACSR, TACSR, ACSS, ACCR, ACCC**	Use in high load operation. Wind area and aeolian wind. Crossing rivet or long distance.	Higher conductivity. Operates in high temperatures. Low potential sag. Lighter. Suitable in extreme weather. Minimum fatigue issues.	Higher installation cost. Higher energy losses.	[11], [22], [24],[32]

Ongoing efforts are being made to enhance the efficiency of overhead power transmission lines (OHTL) by incorporating novel materials into conductors, with the goal of reducing Joule losses. One such initiative is the CALAJOULE project, which is co-financed by the Italian Ministry of Economic Development as part of the "Ricerca di Sistema" program. This project aims to propose innovative solutions for overhead line conductors that effectively mitigate Joule power losses. Through this project, an innovative conductor, of which core is made of a carbon fibre composite material is proposed and proved to significantly reduce joule losses of OHTL [16], [20], [21], [53], as shown in Figure 3. This choice allows, with the same breaking load, to have a conductor core of reduced section, with a significant decrease in weight and thermal expansion compared to the traditional conductor (1/10 compared to steel).

By conducting an economic analysis, it was assumed that the conventional ACSR conductors in the current Italian high voltage (HV) and extra-high voltage (EHV) transmission grid would be replaced by the innovative conductors. The findings indicate that this substitution could lead to a significant reduction of 19% in Joule losses. As a result, it is estimated that such a change would generate annual savings of over 2 million Euros, with a total projected savings of more than 37 million Euros over the expected 40-year lifespan of the overhead lines (OHL).

Considering the environmental perspective, assuming an emission rate of 0.39 tons of CO_2 per megawatt-hour (t/MWh), replacing the traditional conductor with the innovative one would lead to a significant reduction in carbon dioxide emissions. Specifically, this replacement would result in an annual saving of 21.187 kilotons (kt) of CO_2. Over the expected 40-year lifespan of the overhead lines, the total savings would amount to 847.475 kilotons (kt) of CO_2.

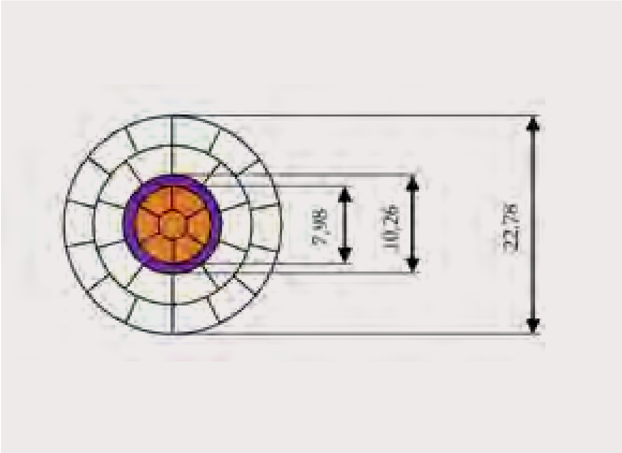

Figure 3 – Section of the ACCM/TW conductor with diameter 22.78 mm [16]

Figure 4 – General map of double circuits 110STJ tower [11]

Structure Heights and Widths

A new tower design for OHAC 110 kV, called 110STJ tower that is of Double circuits and access other lines with single π type, which is used in China for the first time, as presented in Figure 4 [11]. The Economic and Electrical Research Institute of Shanxi Electrical Power Company of SGCC has designed the double circuits of the 110STJ tower based on the principle of "reducing land area, minimizing obstructions, and preserving the environment" in line with general tower design concepts. The tower features a unique longitudinal arm located at the outer end of the cross arm. This design incorporates insulator strings at both ends of the special longitudinal arm to connect the transmission line leads and facilitate the connection of the new transmission line with a jumping string. The 110STJ tower effectively meets the requirements of practical engineering and serves as a valuable reference for the selection of 110kV tower transmission lines.

Cross-arm

In [23], an innovative insulated cross-arm is proposed, which could help to achieve a compact overhead line operating at 380 kV but having similar height of a 150 kV, Figure 5 and Figure 6 provide a comparison of these two overhead line tower and a detailed structure of the insulated cross-arm configuration. This new line allows for almost 10 times higher transfer capacity of energy. This may be an interesting example for other global utilities experiencing low public support of new overhead lines.

EMF

The assessment of risks of being exposed to electromagnetic field (EMF) under transmission line is important. The directive 2013/35/EC of European Parliament gives definition of the magnetic flux density limit from public health point of view. According to the defined limit, the RMS value of magnetic flux density for low action level, high action level and maximum safe value are 1.13 µT, 6.13 µT and 18.13 µT, respectively. This EMF could be either measured on site or calculated by certain methods.

[4] proposes a computing approach which could be used to determining the magnetic flux density under a transmission line. In this study, the magnetic flux density of a 400 kV OH transmission line is investigated. The 400 kV line parameters are:

- Steel-aluminium conductors with cross-section 500 mms
- Horizontal placement of conductors with a 5.5 m horizontal separation between phases
- Phase conductor suspension 24 m

Three curves are obtained from this computing approach, curve 1 – under tower (H=24 m). curve 2 – under the conductor at a point between them (H=12.75 m), curve 3 – under the conductor sag (H=9 m). As shown in Figure 7, all of them are below the high action level of 6.13 µT and also far less than the maximum safe limit value of 18.13 µT. This gives the confidence that with proper design the magnetic flux density could be reduced to a safe value that is not supposed to cause health issue to public based on relevant standard.

Other aspects

In contrast to HVAC (High Voltage Alternating Current) overhead transmission lines, HVDC overhead transmission lines experience ion flow and space charge, which can exacerbate issues related to contamination and corona. To mitigate these challenges, it is possible to utilize conductors that are coated with an insulation layer for HVDC overhead transmission lines. This approach helps to suppress corona discharge and reduce the effects of contamination. In [10], electric field of HVDC overhead transmission lines with covered conductors are calculated and analysed. A bipolar ±800kV HVDC overhead transmission line is used in the calculation. The height of bipolar ±800kV HVDC transmission lines is 18m. The distance of bipolar conductors is 25m. Four bundled conductors are used. The spacing between sub-conductors is 60cm. Radius of sub-conductors is 2.0975cm. The ion flow field of conductors covered with insulation layers at different thickness is calculated and presented in Figure 8.

Figure 5 – Example of the tower for the compact 380 kV overhead line equipped with insulated cross-arms based on composite insulators (left) in parallel with the existing 150 kV line (right) [23]

Figure 6 – Photo of the insulator set-up for pollution tests [23]

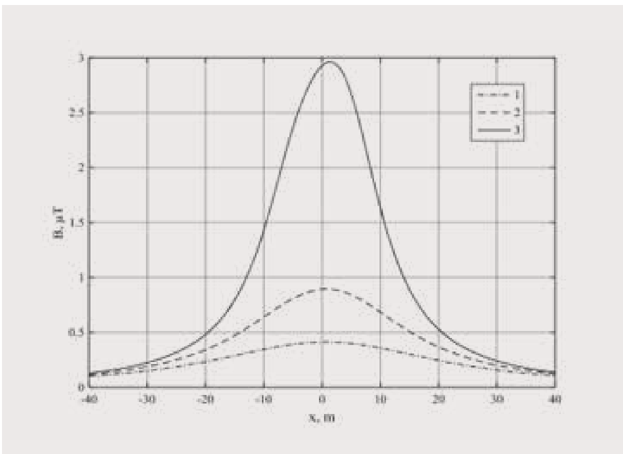

Figure 3 – Section of the ACCM/TW conductor with diameter 22.78 mm [16]

Table 6 – Estimated outage duration for OHLs according to tower type, voltage level and distance from roads [5]

Distance (m)	Estimated outage duration (h)			
	110 kV		330 kV	
	Steel	Concrete	Steel	Concrete
< 100	12	8	16	12
100 -1000	24	12	24	24
1001 -10000	36	24	48	36
> 10000	72	72	72	72

The results show that as the increase of the insulation thickness, the ion flow electric field reduces. It indicates that covered conductors can restrain ion flow field significantly.

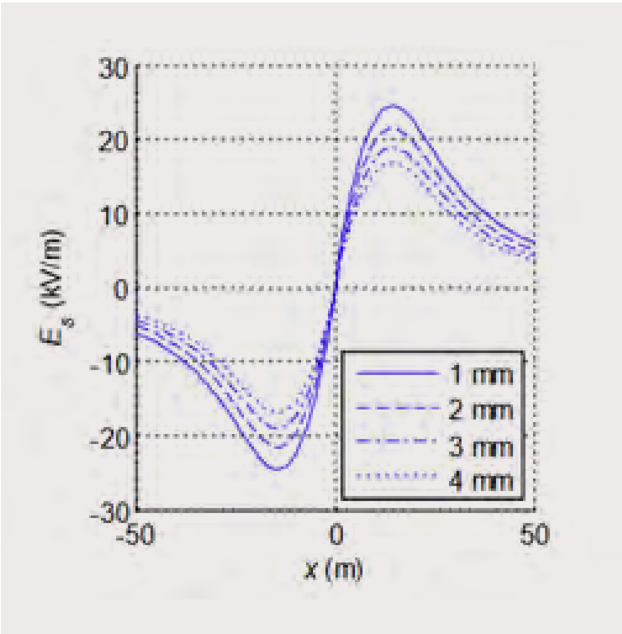

Figure 8 – Electric field at surface of the ground under HVDC overhead transmission lines based on ion flow field calculation with the thickness of insulation layer being 1, 2, 3 and 4 mm, respectively [10]

4.2.2 Reliability

Outage duration

Duration of the outage is usually determined by the type of failure, complexity and time of repair works of assets. A table illustrates the duration of outage at different voltage levels based on Estonian transmission system operators is presented in Table 6 [5]. The longer the distance from roads, the longer is the outage. Concrete tower tends to have less outage duration compared to steel tower type. Also, higher voltage level in many cases have longer outage duration.

4.2.4 Operating and Maintenance requirements

Hybrid HVAC/HVDC has various AC/DC interaction phenomena. In [12], the AC impact on the DC power circuits switched off for maintenance purposes was studied. The findings indicate that transposing the AC power circuits of the hybrid AC/DC transmission line is an effective approach to reduce induced currents in the de-energized DC conductors. However, it is important to note that AC line transposition can lead to a substantial increase in touch voltages on the de-energized DC conductors. This increase in touch voltages can potentially result in violations of safety regulations or standards.

4.2 Economic aspect

4.2.1 Project Planning and Pre-Design

Economic comparison of HVAC and HVDC – Egyptian case study

To achieve the government's objectives of reducing global warming by 2030, wind farms are being considered as a crucial solution. In Egypt, the planned target is to have more than 7000 MW of wind power capacity by 2022, with 4000 MW planned to be generated by wind farms in the Suez Gulf region.
In this context, HVDC (High Voltage Direct Current) technology, based on either VSC (Voltage Source Converter) or LCC (Line Commutated Converter), emerges as a viable alternative to HVAC (High Voltage Alternating Current) systems for integrating wind farms into the power grids. HVDC technology offers several advantages for the efficient transmission of power from wind farms to the grid. In [24], three transmission system configurations are considered to transmit the targeted power of 4000 MW 75 km from the wind farms in Suez Gulf to the national grid, they are:

- 500 kV new HVAC system with underground cable.
- ±320 kV new HVDC system with underground cable.
- ±160 kV HVDC system based on the existing 220 kV OHL.

A comparison of the estimated cost of these three alternatives could be seen from Table 7. The comparison reveals that HVAC (High Voltage Alternating Current) underground cables and HVDC (High Voltage Direct Current) underground cables are costlier compared to HVDC overhead lines (OHL). The primary reason for this cost difference is that the HVDC OHL alternative utilizes the existing 220 kV OHL infrastructure, resulting in significant savings by avoiding the construction of new transmission lines and towers, although infrastructure upgrades may still be required. The cost per kilometer data demonstrates that HVDC OHL is the most economical option at 12 million Euros per kilometer, followed by 500 kV HVAC underground cable at 19.76 million Euros per kilometer, while the most expensive option is the ±320 kV HVDC underground cable at 26.63 million Euros per kilometer.

Table 7 – Cost estimation for the proposed 74 km transmission systems between Ain Sokhna and Zafarana "cost in M$" [24]

No	Item	HVAC 500kV cable	HVDC ±320kV cable	HVDC ±160kV OHL
1	Substation 4000MW	282.87	800	800
2	4000MW TL	1118	1077	-
3	STATCOM		-	-
Invest. fixed cost		1400.87	1877	800
4	Variable cost	81	100	100
Total cost		1481.87	1977	900
5	cost/ km	19.76	26.63	12
PTC		4940 $/MW.km	6590 $/MW.km	3000 $/MW.km

Economic comparison of HVDC cable and HVDC OHTL

A global perspective for developed and developing countries in the HVDC projects by year, voltage, power, distance, type, and supplier is shown in Table 8 [15]. In a case study in Turkey, the cost input in the HVDC project is shown in these tables below. The total cost of HVDC-500 kV, underground cable/OHTL is illustrated in Table 9. It can be observed that the ratio of HVDC cable to HVDC OHTL is about 5.5.

Table 8 – The HVDC projects in several countries [15]

Name of the Project	Country	Year	Voltage (kV)	Power (MW)	Distance (km)	Type	Supplier
Three Gorges-Shanghai	China	2006	500	3000	1060	Thy	ABB
Estiink	Estonia-Finland	2006	150	350	105	IGB	ABB
NorNed	Netherland -Norway	2008	450	700	580	Thy	ABB
Yunnan-Guangdong	China	2010	800	5000	1418	Thy	Siemens
SAPEI	Italy	2011	500	1000	435	Thy	ABB
BorWin1	Germany	2012	150	400	200	IGB	ABB
Mundra-Haryana	India	2012	500	2500	960	Thy	Siemens
Zhoushan	China	2014	200	400	134	IGB	NA
AL-link	Aland-Finland	2015	80	10	158	IGB	ABB
Western Alberta TL	Canada	2015	500	1000	350	Thy	NA
Nord: Balt	Sweden Lithuania	2015	300	700	450	IGB	ABB
Skagerrak 4	Denmark Norway	2015	300	700	244	IGB	Nexans, ABB
Jinsha River II-East China	China	2016	800	6400	NA	Thy	NA
DolWin2	Germany	2016	320	900	135	IGB	ABB
SydVastlanken	Sweden	2016	300	720	260	IGB	Alstom
Western HVDC Link	UK	2017	600	2200	422	Thy	Prysmain Group, Siemens
Xinjiang-Anhui	China	2017	1100	10000	3333	Thy	NA

Table 9 – Overall investment costs for a case study [15]

	VSC-HVDC (M€)		HVAC-OHTL (M€)	LCC-HVDC- 500 kV (M€)	
	Cable	OHTL		Cable	OHTL
Station	153	153	39,7	120	120
Transmission	2400	340	700	2400	340
Compensation	-	-	40	-	-
Total Cost	2553	493	769,7	2520	460

Economic study of uprate OHTL by replacing ACSR conductor with HTLS conductor

One way to increase the power transfer capacity is to uprate the OHTL by replacing ACSR conductors with HTLS conductors. In [17], a study in cost evaluation of current uprating of overhead transmission lines using ACSR and HTLS conductors based on a 230-kV, double-circuit, single-bundle, overhead transmission line in Thailand is conducted. One ACSR and five HTLS with comparable sizes are selected for this study.

The total costs of current uprating are divided into five cost components:

- construction & installation costs
- conductor cost
- cost of energy losses
- land cost.
- demolition cost

Details of cost comparison in different uprating scenarios could be found the [17]. To conclude, it is suggested to consider the option of replacing ACSR conductor with HTLS conductor. It was found that cost of energy losses is the most important cost component, especially when the line is heavily loaded.

Economic comparison of three and four-conductor bundled 380 kV OHLs

An economic comparison between three and four-conductor bundled 380 kV OHLs was conducted in [26], the results show that the advantage offered by the four-conductor bundled solution depends strongly on the length of the line and on the load power factor. To be more specific, the addition of a fourth conductor per phase in transmission lines can theoretically enhance the transmission capacity by approximately 33%. However, this increase in capacity is applicable only for limited line lengths, typically ranging from around 50 to 100 kilometers. Beyond these distances, the benefits of adding a fourth conductor diminish, and alternative strategies may need to be considered to achieve higher transmission capacities.

The economic comparison, considering capitalized costs, emphasizes the advantage of utilizing a four-conductor bundled solution, particularly for heavily loaded transmission lines. This is primarily due to the significant impact of actual Joule losses on the overall costs. In such cases, the reduction in Joule losses achieved through the four-conductor bundled configuration outweighs the other associated costs, making it a more favourable and cost-effective option.

Maintenance cost

The factors which impact the O&M costs are age of the line, weather conditions and length of the line. In [19], the O&M costs are assumed as 1.5% and 0.15% of capital investment cost for OHTL and UGTL respectively.

In [18], a D-distance risk factor was proposed to prioritize high-voltage transmission lines from high to low risk in transmission line maintenance and renovation management in Thailand. Based on this study results, the maintenance cost at 115, 230 and 500 kV could be summarised as shown in the table below. As can be calculated from Table 10, the ratios of the total maintenance cost of 115kV, 230kV and 500kV are 1:1.24:2.52.

Table 10 – Maintenance cost of 115, 230 and 500 kV HVTL (KTHB/km) [18]

Group	115 kV		230 kV		500 kV	
	EQC	MC	EQC	MC	EQC	MC
conductor	508	43	900	50	1500	100
conductor accessory	66	35	67.5	40	120	70
insulator	50.18	130	72	150	100	200
steel structure	1600	100	1800	114	2600	2300
foundation	600	95	750	100	1000	200
lightning protection	130	35	150	40	300	100
tower accessory	4.8	4.8	5	5	10	10
right-of-way	15	15	18	18	25	25
sum	2973.48	457.8	3762.5	517	5655	3005
total maintenance cost (EQC + MC)	3431.28		4279.5		8660	
HVTL Information	115 kV		230 kV		500 kV	
investment of new line (THB/km)	3508.28		4285.06		10949.71	
ACSR conductor, double circuit	2 x 795 MCM		2 x 1272 MCM		4 x 1272 MCM	
inflation rate: IR (%)	3		3		3	
demand of sale: DS (MW)	100		100		100	
down time DT (hrs)	3		4		5	
electricity rate: ER (THB/kWh)	2.977		2.513		2.479	
loss of penalty fee: (LPF (THB/kW)	0.5		0.7		0.9	

Lifecycle cost

Transmission utilities in the recent years are drawing greater attention towards performing life cycle costing studies for cost management and decision making. Net present value is a way to perform life-cycle cost analysis.

Based on net present value method, in [19], life-cycle cost analysis is conducted for a range of transmission lines in India. Based on observations, it has been determined that the life cycle cost of a 220kV overhead transmission line (OHTL) is approximately 65% higher compared to a 132 kV OHTL, despite providing nearly 2.5 times more power carrying capacity. Similarly, the life cycle cost of a 400 kV OHTL is found to be 56% and 85% higher, respectively, in comparison to 220 kV and 132 kV OHTLs, while providing 3.5 and 8.5 times more power carrying capacity. These findings highlight that higher voltage OHTLs offer significantly increased power carrying capacity but also come with higher life cycle costs.

Furthermore, it has been observed that the life cycle costs of underground transmission lines (UGTL) are significantly higher compared to overhead lines, primarily due to the high capital costs associated with underground installations. Specifically, the life cycle cost of a 220 kV UGTL is approximately 19% higher than that of a 132 kV UGTL, despite being capable of carrying 2.5 times more power. Similarly, the life cycle cost of a 400 kV UGTL is found to be 14% and 31% higher, respectively, compared to 220 kV and 132 kV UGTLs, while providing 3 and 7 times more power carrying capacity. These observations highlight the considerable cost disparity between underground and overhead lines, with underground options incurring significantly higher life cycle costs. Overall, the life cycle costs of UGTL are two to six times more than OHTL [19].

In the breakeven analysis, the point at which the investment for overhead transmission lines (OHTL) and underground transmission lines (UGTL) becomes equal is determined. However, a forward breakeven analysis procedure cannot be straightforward applied to compare OHTL and UGTL due to the substantial and exponentially increasing difference in capital costs over the useful life of both types of lines. Instead, an alternative approach involves determining the breakeven point by considering the cost of land as a reference for the construction of these lines. This approach helps in understanding the point at which the costs of OHTL and UGTL converge and become comparable. Figure 9 presents a comparison of OHTL and UGTL overall cost per km as a function of cost of land for 400 kV. Table 11 summarises the breakeven for different voltage levels.

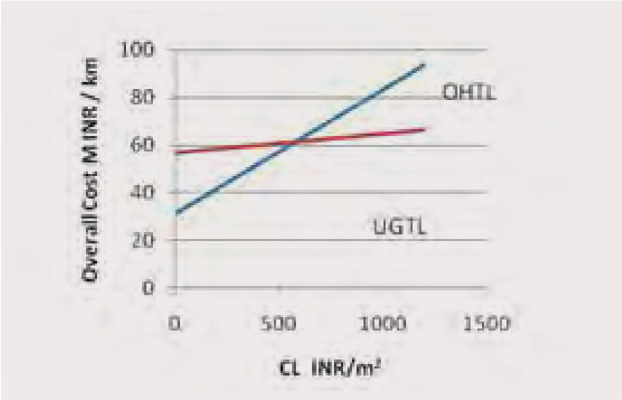

Figure 9 – Overall cost per km as function of CL for 400 kV lines [19]

Table 11 – Results of breakeven analysis [19]

Voltage Level (kV)	Breakeven Cost (INR/m²)		
		Uncertainties case	
	Base Cable	Lower Bound	Upper Bound
132	1200	1250	1450
220	900	820	1070
400	550	450	650

4.3 Hybrid AC/DC

Given the time, investment, and public acceptance required for the construction of new overhead lines, the conversion or modification of existing AC corridors into hybrid AC/DC lines presents an intriguing solution. This approach allows for the transmission of bulk power from renewable energy sources (RES) and addresses local bottlenecks while minimizing the need for significant new investments. Additionally, it helps mitigate risks associated with objections and delays that often accompany the construction of entirely new transmission infrastructure. By leveraging existing AC corridors and integrating DC transmission, this hybrid solution offers a more efficient and cost-effective means of expanding transmission capacity and supporting the integration of renewable energy into the grid [14]. Research focused on the feasibility of integrating AC and DC technologies within the same infrastructure has been undertaken with the aim of converting AC circuits into DC circuits. The objective is to explore the potential for combining both AC and DC transmission systems in a coordinated manner, leveraging existing infrastructure while reaping the benefits of DC technology. This research aims to assess the technical and economic viability of such hybrid systems, considering factors such as compatibility, efficiency, grid stability, and the overall cost-effectiveness of the proposed integration. By sharing the same infrastructure, this approach has the potential to optimize resource utilization and enhance the flexibility of the power grid.

In [14], one proposal is presented to take advantage of selected existing AC transmission corridors and increase their power transfer capacity by its transformation onto AC/DC corridors. Figure 10 shows the superimposed-line strategy for European network, which consists OF interconnecting the most distant regions by adjusting selected existing HVAC lines to add new HVDC corridors. The idea is to benefit from the existing right-of-way of lines by adding new conductors to existing transmission towers, as illustrated in Figure 11.

Economical estimates could be conducted to identify the cost range of upgrading existing AC to hybrid AC/DC. Table 12 presents the derived for different transmission capacity upgrading alternatives. The cost categories suggested are: a) converter costs; b) land use; c) line costs and d) right of way.

The estimated converter costs in this analysis assume the use of LCC (Line Commutated Converter) technology, which results in a cost that is 50% higher for VSC (Voltage Source Converter) cases. Both the AC/DC conversion and the proposed hybrid design with an additional DC circuit would have similar cost requirements. In terms of line costs, the reference is based on estimations for a new 2000 MW HVDC bipolar overhead line (OHL). The equivalent AC/DC conversion option would not necessitate new tower installations but would involve the replacement costs of the conversion equipment and tower modifications. On the other hand, the proposed hybrid design does not require new tower installations either but will require more extensive tower modifications compared to a regular AC/DC conversion of a circuit.

The major factors influencing costs in this context are land acquisition and preparation, including the necessary permits. These costs are significantly reduced in the case of the proposed hybrid design compared to a completely new installation. Another significant cost factor is tower design and modifications. In the case of the hybrid design, these costs are expected to be slightly higher than the estimates for AC/DC conversion due to the additional circuit requirements. However, it is important to note that the overall impact of these costs will depend on the specific project and its unique circumstances.

Based on this comparison, the proposed hybrid design would achieve to cost between 0.3 and 0.8 M€/km. Also, a comparison of the proposal with the installation of new HVDC OHL, following similar routes and excluding land acquisition costs, results in almost 20 percent of savings as shown in Table 13.

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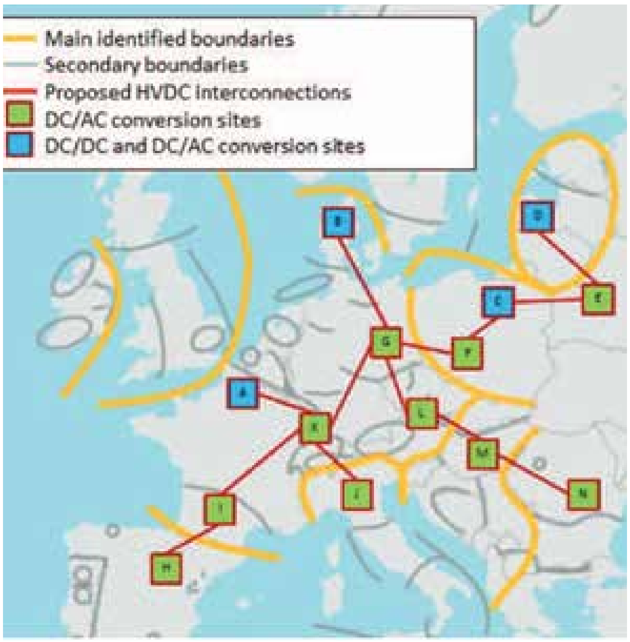

Figure 10 – A possible hybrid AC/DC transmission network proposal [14]

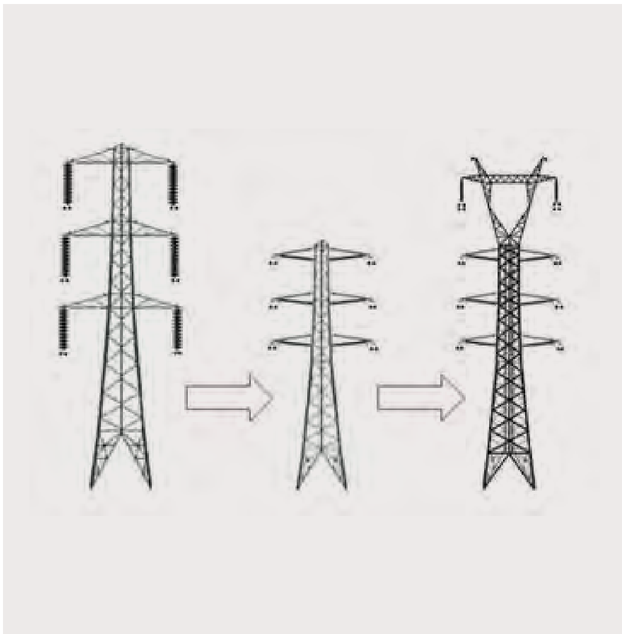

Figure 11 – A possible upgrading proposal of a typical transmission line design to a compact tower with composite arms and additional module (not to be considered as a final design) [14]

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Table 12 – Related costs comparison for upgrading transmission capacities technologies for OHL [14]

Category	Upgrade Technology		
	New line	AC/DC conversion	Proposal
a (USD/unity)	300000 [a]	same	same
b	yes	moderate	moderate
c (USD/km)	250000	less + AC removal	less
d	yes	N/A	N/A
a 50% higher for VSC			

Table 13 – Comparison of total line costs of the proposal vs. new corridor installation [14]

Scenario	New HVDC OHL (M€)	Proposal (M€)	Savings (%)
1	35915	29000	19
2	57670	46485	19

4.4 HVDC

HVDC technology has been in mainstream use in power systems for over 50 years and is now well matured, with over 100 schemes in service worldwide, and this number continues to grow. The thyristor has been the exclusive semiconductor in use for most of this period, with an LCC HVDC link rating of ±500kV, 3000MW as the common industry maximum [22]. In recent years there have been significant advances in 2 directions:

- Extending the LCC rating up through ±600kV, ±660kV and ±800kV, with planned development up to ±1100kVdc for China.
- Introducing VSC HVDC on a large scale, with ratings up to ±320kV, 1000MW, and increasing still further as investment in development continues to take advantage of new semiconductors.

Indeed, the new Voltage Source Converter (VSC) technology has brought about a more robust solution to the complexity of multi-terminal High Voltage Direct Current (HVDC) systems. This technology has become the focal point of national, regional, and even continental scale grid developments worldwide, where HVDC is being extensively deployed. The advantages of VSC-based HVDC systems include improved control capabilities, enhanced grid stability, better utilization of renewable energy sources, and the ability to connect multiple terminals or grids together. This technology has opened up new possibilities for large-scale grid integration, enabling the transmission of power over long distances with reduced losses and improved efficiency. As a result, VSC-based HVDC systems are being increasingly adopted in grid expansion projects globally, as they provide a reliable and flexible solution to meet the growing demands of modern power systems.

Presently available LCC and VSC technology mainly consists of:

- HVDC circuit configurations
- Main circuit components and equipment
- Station Layouts

For HVDC circuit configurations, HVDC interconnections may be configured in a number of different forms, namely:

- Back to Back
- Cable Transmission
- Line Transmission
- Multi-terminal

For line commutated converters, the main power circuit of an LCC HVDC converter station consists of the following major areas and equipment:

- Thyristor Valves
- Converter Transformers
- AC Harmonic Filters
- AC Switchyard
- DC Smoothing Reactor
- DC Harmonic Filters
- DC Switchyard

Figure 12 shows typical layouts for LCC converter stations, noting that the dominant area of the footprint is the AC switchyard and the AC Harmonic Filters.

For voltage source converters, the main components in the power circuit of a VSC HVDC system are as follows:

- IGBT Converters
- Converter Transformers
- Arm/Limb Reactors

Figure 13 presents the layouts for VSC converter stations. In VSC layouts, the main difference between these and LCC is the absence of AC harmonic filters.

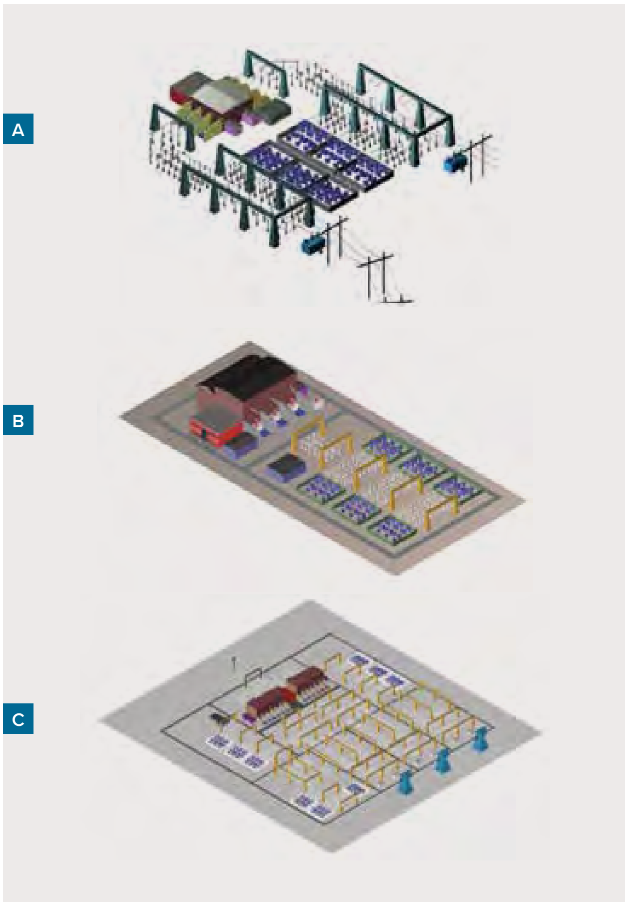


Figure 12 – Typical layouts for LCC converter stations: (a) back to back monopole HVDC converter station; (b) HVDC monopole cable converter station; (c) HVDC bipole overhead line converter station [22]

Figure 13 - Typical layouts for VSC converter stations: (a) back to back VSC HVDC converter station; (b) VSC cable converter station; (c) Overhead line VSC HVDC converter station (courtesy ABB) [22]

5.

Discussion (UG cables)

5.1 Technical aspects

It should be noted that the literature research on underground cable mainly focussed on recent research papers which are Significant or Relevant Research Material (SRM) including following three Key research materials from grey literature:

- EPRI Underground Transmission Systems Reference Book 2015 “Green Book” [27]
- CIGRE report “Implementation of long AC HV and EHV cable system” Working group B1.47 dated March 2017 [2]
- CIGRE 2006 paper B1-305 “A dynamic rating system for an existing 150 kV power connection consisting of an overhead line and undergroundpower cable” [3].

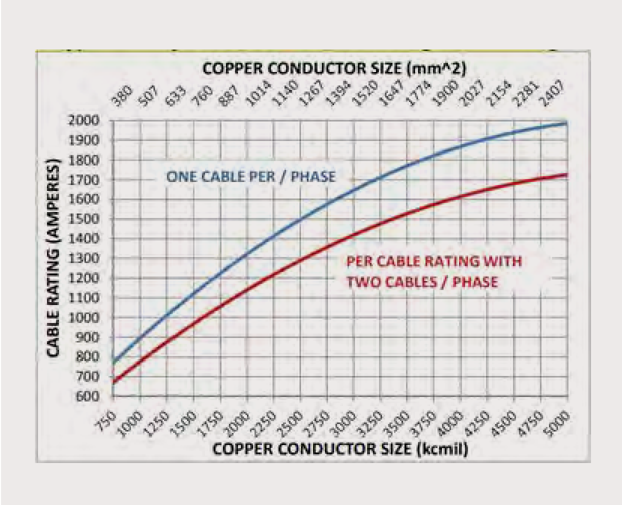


Figure 14 - Variation of cable current rating with cable size [31]

5.1.1 Design aspects

Power Transfer Capability

The OHL current rating is based on conductor properties and static environmental conditions (temperature, wind speed and sun radiation). If the same conductor is used for an underground cable, it will have a lower current rating because heat from buried cables must pass through the earth before reaching the air which is the ultimate heat sink [2], [27]. Also, the cable’s coaxial electrodes and outer shielding create a capacitance that affects power transfer. Moreover, the dielectric losses in cable insulation are present any time the cable is energized and reduces the amount of power transfer [27]. Therefore, the cable might require two cables per phase (essentially two cable systems) to match the capacity of the overhead line [3], [27]. The current rating can be increased by the conductor size and conductivity (copper instead of aluminium) [2]. Figure 14 shows the variation in rating versus conductor size. It is worth to note that with two cables per phase, the per-cable rating with two cables/phase is approximately 88% (not 100%) of the single-cable rating [31]. However, larger cross sections or numbers of cables per phase for UG cables can be economically unattractive [3], [28].

In many circumstances the thermal inertia of underground cables should be considered when matching a cable to an OHL. This can result in smaller conductor sizes, cheaper conductor materials, less cables per phase and hence a reduced installation trench width. A reduced installation swath not only reduces civil costs but may ease right of way requirements and allow the cable system to be installed in narrow installation corridors. Reducing the number of cables per phase also give less maintenance and especially for high voltage cables it produces less reactive power.

The selection of circuit types used in UG cable is shown in Figure 15. Figure shows duct-manhole and pipe system which have advantages in cities of fast installation and less disruption to traffic [27]. Direct buried systems have higher ampacities. Tunnel systems have more direct routes and good protection from third party disturbance. Figure 15 also shows DC transmission circuits require two parallel cables while AC transmission circuits require three cables. For comparison purpose the cables in Figure 15 are shown installed at a common minimum depth. It is usual to specify a minimum depth of burial to the top of the cable for rural and urban sections of the route. Depth provides increased protection from dig-in and plow damage. Increased depth also decreases the magnetic field at the surface [27].

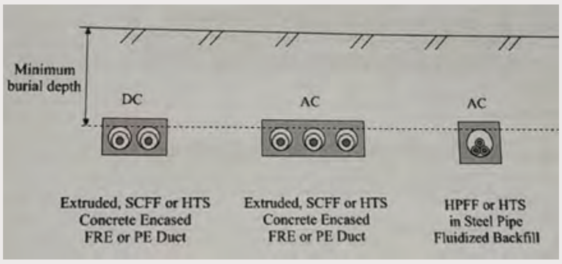


Figure 15 Underground cable circuit cross section for ac and dc transmission[27]

Four cable systems that can be considered for underground installations are following [27]:

- Extruded dielectric with XLPE or EPR insulation
- Self-contained fluid filled (SCFF) or gas filled (SCGF) cable
- Pipe type, either fluid filled, or gas filled
- Special (Gas insulated lines)

This report mainly discusses the Extruded with XLPE cable and pipe type cables. Gas insulated lines are not discussed in this report because that is out of scope of the literature review.

Pipe type cables have been the most commonly used cable system at higher voltages. Now, with the advances in purity of extruded dielectric cables, they are becoming more common at increasingly higher voltage levels and longer circuit lengths [27].

XLPE insulated cables are being designed and installed at voltages up to 230 kV and 345 kV in long lengths.

Over the past 20 years, there has been significant and swift progress in the advancement of high-voltage (HV) and extra-high-voltage (EHV) cables that utilize Cross-linked polyethylene (XLPE) as the insulating material. For instance, contemporary XLPE cables possess improved characteristics such as a reduced dielectric constant and the ability to operate at higher temperatures, making them significantly more effective compared to the older paper-insulated cables that were impregnated with oil [2]. Also, the simplified manufacturing process of XLPE cables has resulted in a remarkable surge in the availability and utilization of HV AC cables. For example, in China, more than 1100km of 220 kV and 100km of 500 kV cable were produced in China in year 2014 and during the past 10-15 years more than 100,000km of HV & EHV cables have been installed in the country [2]. Currently worldwide more than ten fully qualified manufacturers of XLPE insulated AC cable rated at 500 kV are present [2].

SCFF cables are generally only used in specialized extra high voltage applications.

In urban environments, extruded dielectric cables installed in duct banks and pipe types of cables are frequently used because of their ruggedness and the ability to install short lengths of pipe or ducts at one time in city streets with trench openings of only 300-600 ft. The cable is installed in a separate operation, with minimum traffic disruption [27].

In suburban places, extruded dielectric, pipe type and SCFF cables can be used, depending upon the specific application [27].

In rural areas, any cable system can be suited. Low traffic volume and long trench openings allow flexibility for the designer to consider all different types of cable systems [27].

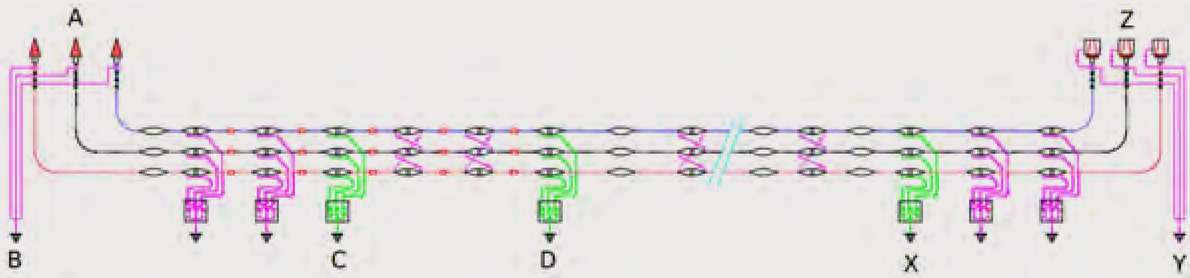


Figure 16 Schematic diagram of extra-long 225kV cable line with direct cross-bonding sections [32]

For special applications such as long underwater crossings, usually SCFF or extruded dielectric cables are used primarily because it is difficult to make pipe type splices underwater. SCFF or extruded dielectric cables are preferred for bridge crossings because the weight and expansion characteristics of pipe type cable requires resolution of bending forces which complicates the design. Also, pipe type cable systems are not economical for short length applications [27].

A practical experience with the newest bonding system called “direct cross bonding” implemented on an extra-long cable system of 2000mm^2 and 2500 mm^2 Cu XLPE 225kV cables, as shown in Figure 16, is presented in [32]. Three different types of joints and their associated hardware are incorporated in this [32].

- Joints with earthing in C, D and X.
- Joints with classical cross-bonding connections between B and C and between X and Y: the screen interruption is protected with SVL’s.
- Joints with direct cross-bonding connections on a major part of the line between C and D and up to X: no SVL are provided for the protection of screen interruption against overvoltage.
- Joints without earthing: on some sections, normal straight joint without earthing has been implanted in order to optimize the earthing scheme.

HVDC

High voltage DC (HVDC) transmission cable systems have the potential to transform major electrical grids; they can deliver very high powers over long distances with high efficiency and reliability [41]. As compared to HVAC cables, in HVDC cables the skin effect and the proximity effect in the conductor are absent (so that the section of the conductor is fully exploited). Also, dielectric losses are also absent in practice if leakage currents can be neglected, as is mostly the case. The average higher electric field stress of HVDC cables leads also to a higher utilization of the cable [41]. Moreover, the lower line costs with the same transmitted power. HVDC cable lengths are not limited by charging currents and no reactive compensation (for the cable itself) is required at the end stations and/or at intermediate points as in the case of AC transmission systems [32]. The advantages of HVDC cable over HVAC cable are shown through Figure 17 [28]. A very thorough comparison between the HVAC and HVDC system is presented in [51].

Conductors

The UG cable are typically single-core cable or three core cable with each core consisting of either copper or aluminium conductors. The new underground long length AC cable links are being supplied with single core XLPE cables while the three-core cable is typically used in submarine cables [2]. Although copper conductors are more expensive, they offer lower electrical resistance, allowing for a reduced cross-section and less material for the outer layers. Therefore, wherever there is very high current carrying capacity is required, copper conductors are specified. Additionally, copper was often favoured due to its superior corrosion resistance properties, particularly in submarine cables. However, this consideration is not highly relevant since well-designed cable conductors are designed to avoid contact with seawater. Therefore, aluminium conductors

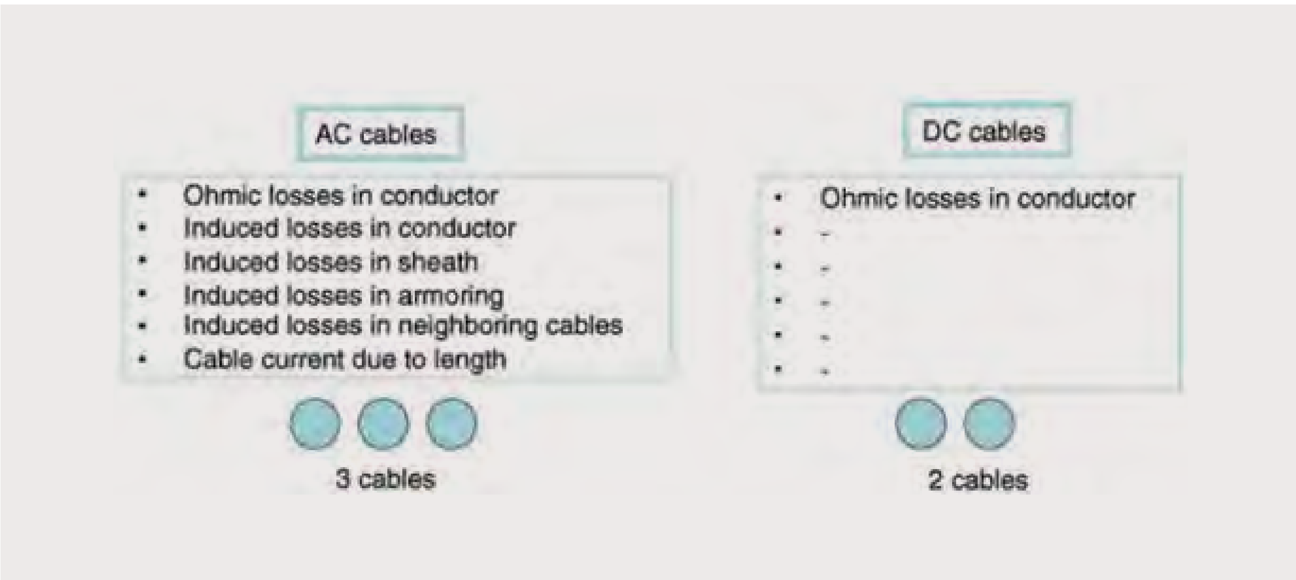


Figure 17 Comparison of HVDC and HVDC cable [28]

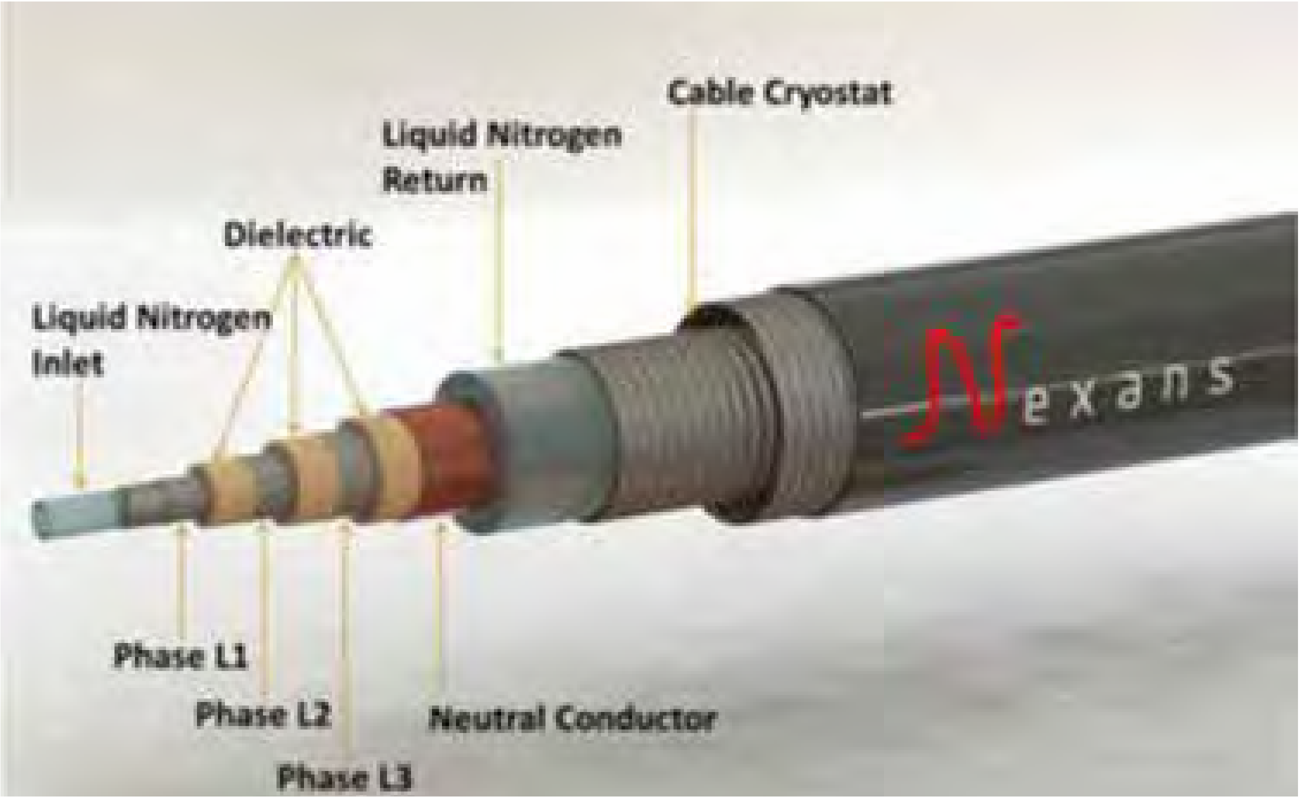


Figure 18 Design of a high temperature superconducting (HTS) cable for AC operation [52]

are now gaining broader acceptance due to their lower cost, lighter weight, and better strength-to-weight ratio in mechanical properties. This is particularly notable in deep installation and dynamic situations [2].

Another option with high power transfer capability over long distances are the superconducting cables [49], [52]. The high temperature superconductor (HTS) transmission cables can play a role in strengthening the grid. The advantages as compared to the OH lines and UG cables are: economic, underground, higher power capacity, lower losses, reduced magnetic field emissions in (existing) OHL, compact: less occupation of land and less permits needed, a possibility to keep 380 kV voltage level in the grid for as long as needed [47]. However, a cryogenic envelope is needed to keep the superconductor cooled below its critical temperature to maintain its non-resistivity. The easy availability and use of liquid nitrogen as a coolant allows the superconducting behavior even at higher temperature (T = 77 K) and also simplifies the design of cryogenic envelope. The design of a high temperature superconducting cable is shown in Figure 18 [52].

The design of the superconducting cable itself also requires substantial engineering for optimum performance (especially for AC operation due to the fast-switching magnetic field). However, these challenges have been already addressed and solutions only need to be adapted to the specific transmission line project [52].

A list of global superconducting projects is presented in Table 14 [52].

Table 14 Global superconducting cable projects [52]

Project	location	Length (m)	Capacity [MVA]	Schedule	Operator
LIPA	long Island/USA	600	574 (138 kV AC, 2.4 kA)	In operation since 2008	LIPA
Ampacity	Essen/Germany	1000	40(10 kV AC, 2.3 kA)	Start of operation 01/2014	RWE
	Amsterdam/NL	6000	250 (50 kV AC)	Proposed	Alliander
St Petersburg Project	St Petersburg/ Russia	2500	50(20 kV D, 2.5 kA)	Start of operation 2015	FGC UES[a]
Ishikari	Ishikari/ Japan	2000	100 (± 10 kV DC, 5 kA)	Start of construction spring 2014	City of Ishikari
	Icheon/ Korea	100	154 (154 kV AC 3.75 kA)	Operating since 11/2013	KEPCO[b]
	Jeju Island/ Korea	1000	154 (154 kV AC 3.75 kA)	Operation 2015	KEPCO
	Jeju Island/ Korea	500	500 (80 kV DC)	Operation 2014	KEPCO
HYDRA	Westchester county/ USA	170	96(13.8 kV AC/4 kA)	Start of construction early 2014	ConEdison
	Yokohama/Japan	250	200 (66 kV AC, 5kA)	Operation stopped December 2013, continuation planned with new high-performance refrigerator 2015	TEPCO[c]
	China	360	13 (1.3 kV DC, 10 kA)	Operating since 2011	IEE CAS[d]
REGf	Chicago/US	5 km	to be specified	Planning since 2014	ComEd[e]
Tres Amigas	New Mexico/US		750/5000	Postponed	Tres Amigas LLC

[a] Federal Grid Company United Energy System
[b] Korea Electric Power Corporation.
[c] Tokyo Electric Power Company.
[d] Institute of Electrical Engineering. Chinese Academy of Sciences.
[e] Commonwealth Edistion.
[f] Resilient Electric Grid

The advantages of superconducting power lines compared to the most modern underground standard HVDC cables (7320 kV XLPE HVDC) are [52]:

1. One of the advantages is the compact size of superconducting cables, requiring only a width of a few 10 cm. This is in stark contrast to a standard HVDC ±320 kV cable installation, which necessitates a 17 m wide trench containing 24 cables to achieve a 10 GW capacity. This width measurement does not include the additional 2.5 m safety area on both sides.
2. There is a potential for significantly reduced land usage, possibly as low as 10% compared to standard HVDC cable installations. The extent of land use reduction depends on factors such as capacity, geographical area (urban or rural), and applicable regulations.
3. Superconducting cable provide an attractive solution for long-distance and high-capacity electric energy transportation. This is particularly relevant because standard conductor cables suffer from significant losses (> 6% per 1000 km at full load for ±320 kV XLPE HVDC cables).
4. By adjusting the nominal current to align with the desired or existing operating voltage, particularly in medium and low voltage grids, it becomes possible to eliminate the need for transformers. This has the advantage of reducing the space occupied and the number of components within the grid system, thereby minimizing the likelihood of technical failures.

5. In hot climates, superconducting cable offer a superior solution due to their vacuum-isolated cryogenic envelope. This envelope acts as a barrier, preventing heat from entering the system and effectively stabilizing the temperature of the superconducting conductor. In contrast, the capacity of standard HVDC cables is diminished by higher soil temperatures.
6. Do not heat the surrounding soil.
7. Much easier use of existing right-of-ways (ROW) to transfer GWs of power.
8. The cryogenic system can store energy by cooling to lower operating temperatures at times of high renewable energy input.

Figure 19 shows the right-of-ways and power transfer capacity comparison between ± 800 kV HVDC OH line, ± 320 kV HVDC XLPE cable, and ± 125 kV HVDC superconducting cable [52].

The primary concern raised by communities opposing the construction of new transmission lines is the visual impact they would have. A single pylon of a ±800 kV 6.4 GW HVDC power line has a height of 50–90 m and the width of the corridor would be estimated around 125 m [52]. Two HVDC lines with a maximum capacity of 10 GW (maximum of 12.8 W) span a width of 245 m. Similarly, towers supporting ±500 kV HVDC transmission lines share comparable dimensions but require wider rights-of-ways due to the lower capacity, which scales with the square of the voltage. The visual impact of such infrastructure is substantial: A structure that is 50 m tall can be visible from a distance of ~ 25 km when observed from sea level. This implies that the construction of an overhead HVDC transmission line has the potential to significantly alter the landscape, impacting an area of 50 km^2 for every kilometer of its length [52].

As per authors of [49], for 380 kV and 6.6 GVA, overhead transmission lines require corridors of 70 m in width, in contrast to less than 7.7 m corridor width necessary for superconducting 380 kV cables.

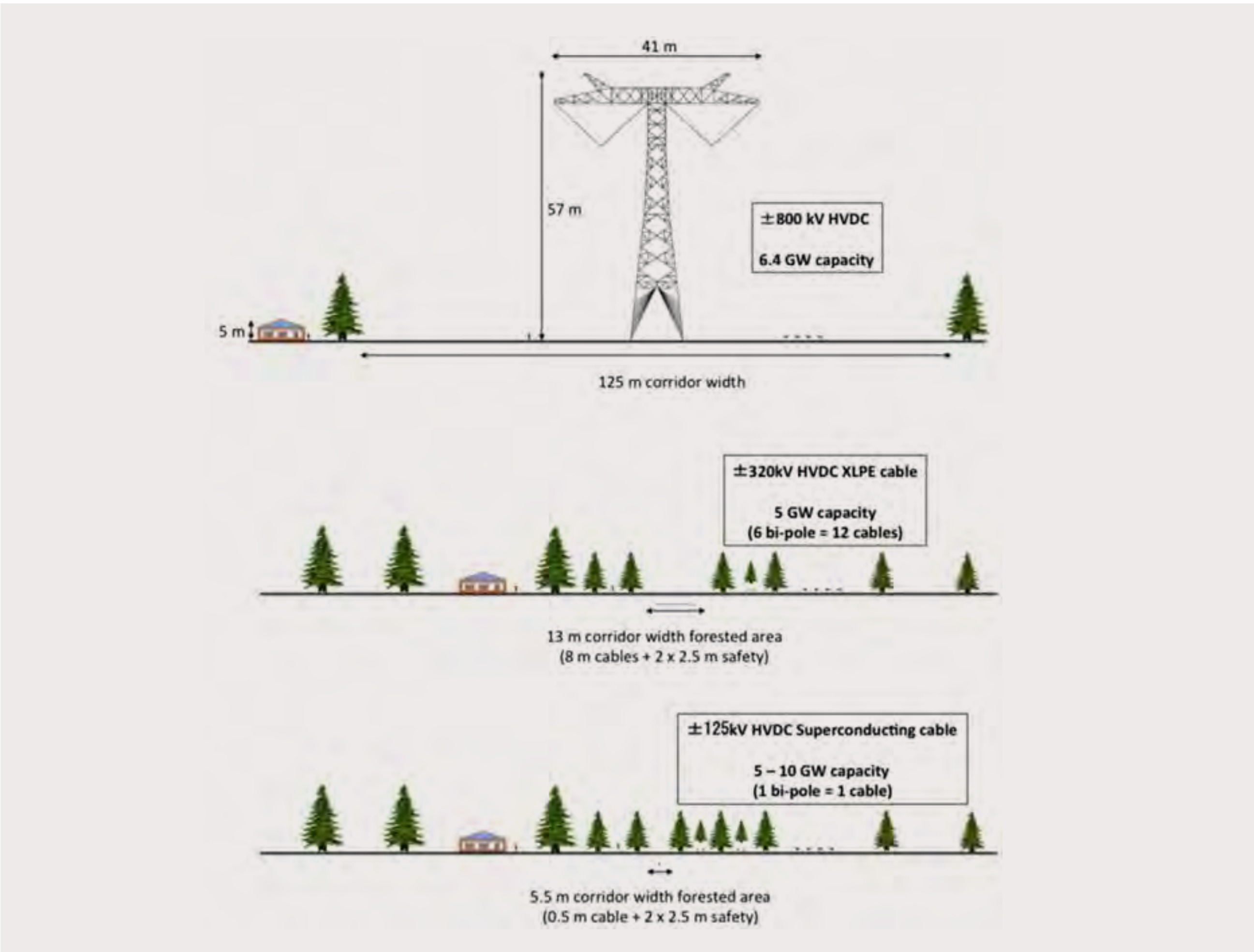


Figure 19 ROW and power transfer capacity comparison between different power transmission lines. [52]

Insulators

XLPE - cross-linked polyethylene which is now one of the most common and well-established insulation materials in modern extruded high voltage cable design. A major reason for the XLPE success is the excellent electrical, mechanical, and thermal properties of the material. The most advantageous features are the low dielectric losses, the low dissipation factor, the high electrical breakdown strength, the high modulus of elasticity and the high tensile strength. Low operating and low maintenance costs, combined with good system availability, results in a low lifetime cost for the XLPE cable system. XLPE is a suitable insulating material for conductor temperatures up to 90 °C which is the normal operating temperature for XLPE cables. The cables can however withstand up to 250 °C under short circuit conditions. Consequently, there is both a high overload potential and a high safety margin in the cables [2].

A HV XLPE Cable with corrugated Aluminium sheath is shown in Figure 20. The cable insulation system is protected from the water by a metallic layer such as lead alloy or a welded metallic sheath which is also used as electrical screen and a PE layer is extruded to protect this metal sheath. The 3 phases are laid up together and optical fibre elements are often laid in the interstices between the cores as well as some other materials e.g. PP ropes or PE profiles. The bundle is then protected against mechanical damage by metallic armour made of steel wires. An outer protective covering is often made of PP yarns applied outside the armouring [2].

The insulation thickness of XLPE cables primarily depends on the required withstand voltage. However, for long-length extra-high-voltage (EHV) cables, the insulation thickness also affects the generation of reactive power by the cable. The below equation indicates that reactive power is primarily influenced by voltage, but also by capacitance and frequency [2].

$$Q\_cable=2\pi fCV^{\wedge 2}$$

where *Q cable* is the reactive power in Var, f is the power frequency in Hz, C is the cable capacitance in farads, and V is the line voltage in volts.

To compensate for reactive power in a system, shunt reactors are commonly installed. However, this solution introduces complexity due to electrical and spatial constraints, increased losses, and the need for redundancy. Therefore, reducing the amount of reactive power produced becomes desirable. This can be achieved by either increasing the insulation thickness or decreasing the conductor size, although the latter is often impractical [2].

Increasing the insulation thickness results in reduced capacitance, leading to lower reactive power compensation, as well as decreased dielectric loss and charging current. However, there are drawbacks to increasing the insulation thickness of XLPE cables. One significant challenge is maintaining the quality of the extrusion process when dealing with very long runs of HV cable. While a small increase in insulation thickness could be beneficial for lengthy EHV cables, it is important to consider the potential negative consequences [2].

Despite these challenges, opting for more insulation in a cable system can yield certain advantages. Some of the additional costs associated with increased insulation can be offset by reduced investments in reactive compensation and lower system losses throughout its lifespan [2].

The HVDC cable insulation system is categorized into two groups: 1) Oil-paper insulation, and 2) Extruded insulation.

Oil-paper insulation: The oil–paper insulation is achieved by wrapping strips of pure cellulose paper onto the conductor, applied in helical layers to reach the total design thickness of the insulation. Then the insulation is impregnated with mixtures or mineral base fluids to impart and improve the dielectric properties. In the polypropylene paper laminated insulation, the traditional paper insulation is replaced with a laminate consisting of alternating layers of paper and polypropylene, thereby improving the characteristics of the dielectric [28].

Extruded insulation: Polymers investigated and tested so far for the construction of extruded insulation HVDC cables can be grouped into two categories: pure materials and materials with proper additives. Cable manufacturers seem to have abandoned the pure

Figure 20 HV XLPE cable [2]

polymeric insulation in favour of insulation with properly selected additives to improve the accumulation of space charges. Extrusion is a technique to deposit a uniform and compact layer of polymer around the conductor, in between the two layers of semiconductive screens [28].

Depending on the type of insulation, different types of cables are designed. The most common typologies of HVDC cables are shown in Figure 21 [28].

Mass-impregnated nondraining (MIND) cables are available for voltages up to 500 kV and a transmission capacity of up to 800 MW in one cable. Oil-filled cables are suitable for DC voltages up to 600 kV DC. Due to the required oil flow along the cable, the transmission line lengths are, however, limited to < 100 Kms. For PPL insulated cables some manufacturers have developed HVDC cable systems with a voltage rating of 600 kV. In extruded HVDC cable, the extruded insulation is polymeric and mostly based on polyethylene compounds, among which the preferred ones are low-density polyethylene (LDPE) and particularly cross-linked polyethylene (XLPE) which is a special kind for best performance under HVDC condition. This special kind of XLPE is commonly referred to as DC-XLPE [28].

5.1.2 Reliability

While overhead lines are generally more susceptible to failures caused by weather conditions, cables tend to have fewer failures. However, in the event of a failure, the time required for restoration can be significantly longer for cables, ranging from days to weeks, whereas overhead lines can be restored within hours to days [31]. If a failure occurs and is limited to a specific set of cables, it is possible to employ certain measures to isolate the failed cable and partially restore power transfer through the remaining circuit. This typically involves using two smaller cables instead of a single cable per phase, which necessitates double the number of terminations and, if needed, splices [31]. An alternative cable system can improve the reliability of system and also addresses the needs of higher capacity cable alternatives [31].

However, the situation becomes more complex because the accessories, rather than the cable itself, are typically more susceptible to failures. This is due to issues related to their installation, such as workmanship and environmental factors, as well as a higher vulnerability to mechanical damage caused by thermal-mechanical movement. As a result, if all other factors remain constant, a system that incorporates a greater number of accessories will naturally have lower reliability compared to a system with fewer accessories [31]. Even with redundancy measures in place, the presence of splices in shared manholes or terminations in close proximity on common structures can lead to failures affecting the accessories of both adjacent circuits. In such cases, introducing two cables per phase for shorter circuits does not always result in improved reliability or shorter restoration times [31]. Therefore, it is advisable to consider using a single cable per phase in designs for shorter circuits, as the probability of a cable circuit failure directly impacting the cable is considerably lower compared to longer circuits [31]. The faults occurred due to the ancillary facilities of a tunnel of four 220 kV cable system within the initial two service years is shown in Figure 22 [29].

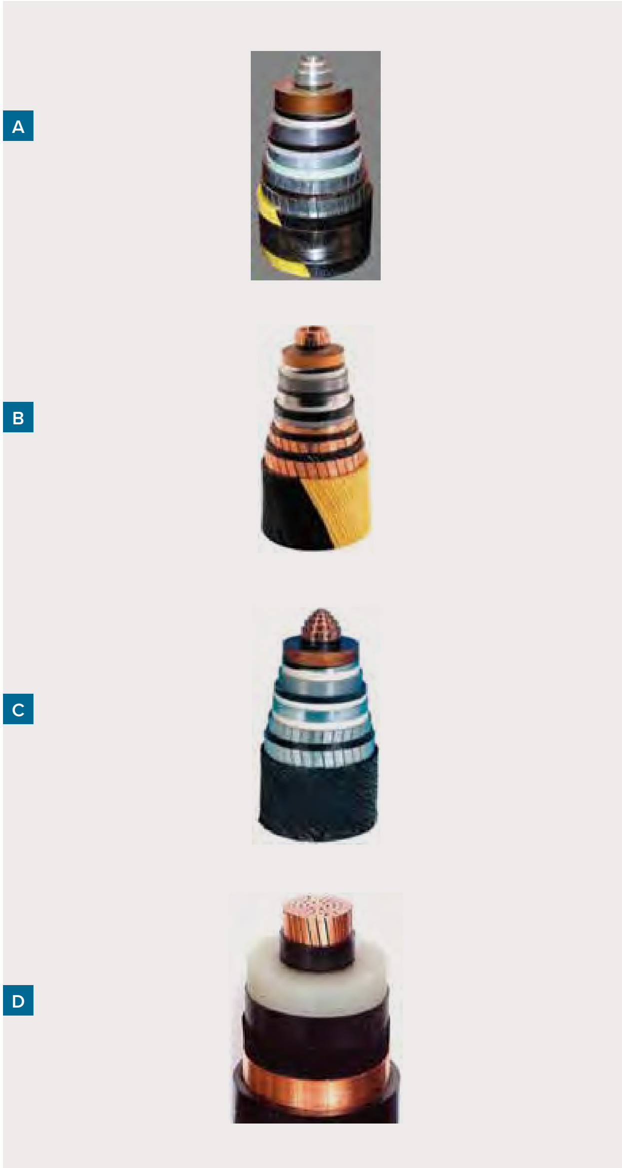


Figure 21 Main typologies of HVDC cables used in transmission systems: (a) mass-impregnated nondraining (MIND) cables, (b) self-contained oil-filled (SCOF) cables, (c) polypropylene paper laminated insulated cables, (d) polymer-insulated or extruded-insulation cable [28]

Table 15 Share of fault duration in UGCs and OHLs for the tested networks [37]

Equipment	Normal			Adverse		
	Mom. %	Temp. %	Sust. %	Mom. %	Temp. %	Sust. %
132 & 110-kV OHL (km)	82	14	4	75	15	10
132 & 110-kV UGC (km)	0	0	100	0	0	100
33-kV OHL (km)	51	20	29	62	24	14
33-kV UGC (km)	0	0	100	0	0	100

Table 15 shows the share of momentary (Mom.), temporary (Temp.) and sustained (Sust.) faults for UG cable and OH line under normal and adverse weather conditions for an IEEE-30 bus network [37]. Failure times for momentary, temporary and sustained faults were considered to be, respectively, 0.5 s, 10 min and repair time [37]. The authors of [37] did the reliability analysis of IEEE 30-bus network, as underground and as overhead networks, and in a typical Nordic 25-bus sub-transmission network and concluded that the underground parts of the network exhibit more homogeneous outage time throughout the year than the overhead parts.

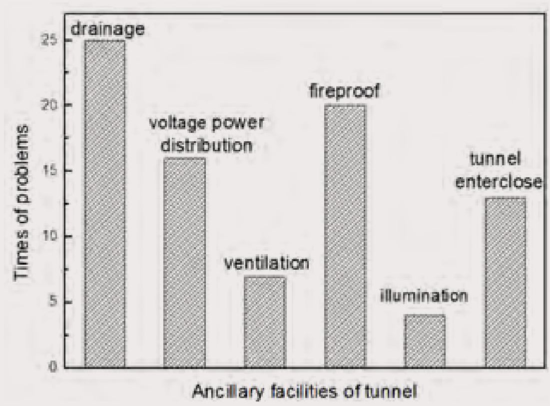


Figure 22 Failure frequency of ancillary facilities of 220 kV cables system [29]

To ensure high reliability throughout their anticipated lifespan at higher voltages and powers, HVDC cables require a comprehensive assessment and improvement of extruded insulation performance [38]. In this regard, several key features contribute to the longevity, dependability, and environmental friendliness of HVDC extruded cable systems. These include low electrical conductivity at elevated temperatures and fields, minimal space charge retention, favourable material compatibility, efficient and streamlined manufacturing processes, reliable and robust accessories, straightforward and eco-friendly installation techniques, and consistent performance under operational conditions [38].

Figure 23 shows the system reliability in three selected years 2010, 2020, and 2050 for underground cable and high temperature superconducting (HTS) cable [44].

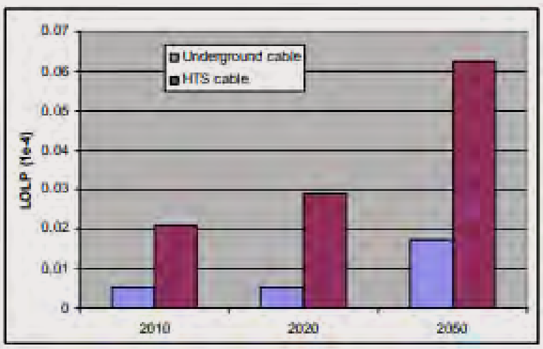


Figure 23 Comparison of loss of load probability (LOLP) [44]

An example of high reliability of superconducting cable is the HTS cable within the Asahi substation operated by Tokyo Electric Power Company (TEPCO) in Yokohama, as shown in Figure 24. During two years of operation of an HTS cable, no faults were reported. The installation, including the refrigeration system, was remotely monitored from TEPCO in Tokyo with no service man at the station [52].

5.1.3 Construction requirements

The typical method for cable systems construction involves creating open trenches from the surface to accommodate conduit bundles, which are then filled with high-strength concrete, as shown in Figure 25. It is recommended that the horizontal bending radii for duct runs be maintained at a minimum of 6-10 meters (20-30 feet) to minimize pressure on the sidewalls and reduce tension forces during cable installation [31].

The construction of cables is such that they often have lower normal ratings than other transmission equipment, particularly overhead lines, but much higher emergency rating capabilities – particularly short-duration emergencies. The higher emergency rating of cable is due to the long thermal time constant of cables and the mass of earth in which they are installed [31].

Figure 26 shows a 2x4 duct bank configuration with 168mm (6.625in) conduits, and Figure 27 shows an example cable duct bank with a 2x2 configuration with 220mm (8.625in) conduits [31].

Near riser structures, 90° vertical sweeps are possible, however, to avoid increases in pulling tensions and sidewall bearing pressure forces it is wiser to install cables with direct buried sections near riser structures and transition poles, as shown in Figure 28 [31].

Figure 24 TEPCO AC HTS cable with a joint at Asahi substation in Yokohama/Japan [52]

Figure 25 open cut excavation for cable system [31]

Figure 26 2x4 duct bank, with 6-in conduits and 9-5/8in centre-line separation [31]

Figure 27 2x2 duct bank (left) and concrete backfill installation (right) [31]

Figure 28 Direct buried section near a compact transition pole with one cable per phase (left) and conventional risers with two cable per phase (right) [31]

For crossing the cable under a structure such as railway tracks, pipe-jacking method can be employed, as shown in Figure 29 [31].

Figure 29 Pipe-jacking operation under rail sidings [31]

For underground-overhead hybrid system, a junction tower is used which is the interface between overhead lines and underground cables. Many times when underground cables have to cross the rivers, underground cables are converter to overhead lines to cross rivers by junction towers [50]. An improper arrangement of cables may lead to losses in the junction tower and the magnetic field around it [50]. Figure 30 shows the L-type structural steels which are used in junction towers to provide a high degree of mechanical construction for the cable route. These steels are magnetic and are excellent conductors. Therefore, three-phase cables that run parallel to the steels produce a transverse magnetic field that induces eddy currents and losses inside the steels [50].

One of the advantages of underground-overhead hybrid system could be reactive power compensation by the UG cable itself. The reactive power requirement of the OH line could be compensated by the UG cable [31]. An appropriate length of cable with OH line can assist in the reactive power requirement along with improving overall system stability [31].

For HVDC cables, the extruded insulation cables are less well established, not only as regards the design and construction but also in terms of experience in the installation, operation, and maintenance, but the research and innovation efforts are enabling their production for use with increasing voltage and power ratings up to 300 kV and 1000 MW at present [40][4].

The main peculiar challenges for UG HVDC cables are perhaps the huge number of remolded (field) joints to be installed in long lines like the German Corridor, as well as the risk of interactive thermal instability with the soil in case that voltage, current and temperature gradient ratings are very high, and the heat exchange properties of the soil are not excellent [39]. The burial depth of HV cables should rescue them from most problems, but in some cases— particularly in hot climates and in the presence of long drought periods— the possibility of partial drying out of the soil has to be carefully evaluated, and the laying conditions might need to be improved by the use of proper backfills [39].

Figure 30 Junction tower with structural steel (left) and lateral view of flat arrangement of cables (right) [50]

5.1.4 Operation and Maintenance requirements

The authors of paper [29] presented their experience of operation, maintenance, and condition monitoring of 220 kV cable system. Water vapor within the cable tunnel (which may not be considered during the design process) may cause significant damage due to their very erosive nature. The presence of erosion and moisture may cause faults in tunnel ancillary facilities such as drainage, fireproofing, power distribution, and tunnel facilities [29]. The drainage system may be affected by the short circuit faults and erosion that may affect the submergible drainage pump. For such scenario, use of an anti-wound stainless steel submersible pump can be the solution [29].

The short circuiting of the temperature-sensing fire detectors and the short circuiting of manual alarm (caused by water drenching) may trigger false alarms which can bother the residents sometimes. For such issues, a waterproof block can be added to the manual alarm and temperature-sensing fire detectors can be replaced annually [29].

Paper [29] suggests the following maintenance conduct: increase the period of patrolling, which needs to be finished for every tunnel within each week; increase the usage efficiency of the monitoring system; strengthen the inspection of the accessories within the tunnel during the flood season; strengthen communication with the civil engineering department; and hold annual drills for emergencies. Also, condition monitoring systems for a 220 kV four cable system is presented in Table 16 [29].

Asset management is a crucial part of operations and maintenance of UG cable system. In numerous instances, it is challenging to assess the physical conditions of underground cable assets due to their installation locations that are either hard to reach or inaccessible [43]. Also, existing tests used to determine the remaining lifespan of an underground cable circuit necessitate obtaining an actual cable sample from the field and conducting laboratory testing. However, acquiring samples from an existing underground cable circuit is typically difficult and usually only possible after a cable fault has taken place [43].

Table 16 Monitoring items in 220 kV cable tunnel system [29]

Monitoring system	Subsystem	Items
Vision and environmental monitoring system	Vision monitoring system	Entrance, exit
	Environmental monitoring system	Gas, water level, intrusion, IP phone
Cable on-line monitoring system	Circulating current monitoring system	Circulating current, load
	DTS	Surface temperature of the power cable
	Bi-end fault location finder	Fault current
Fireproof monitoring system		Fire, smoke

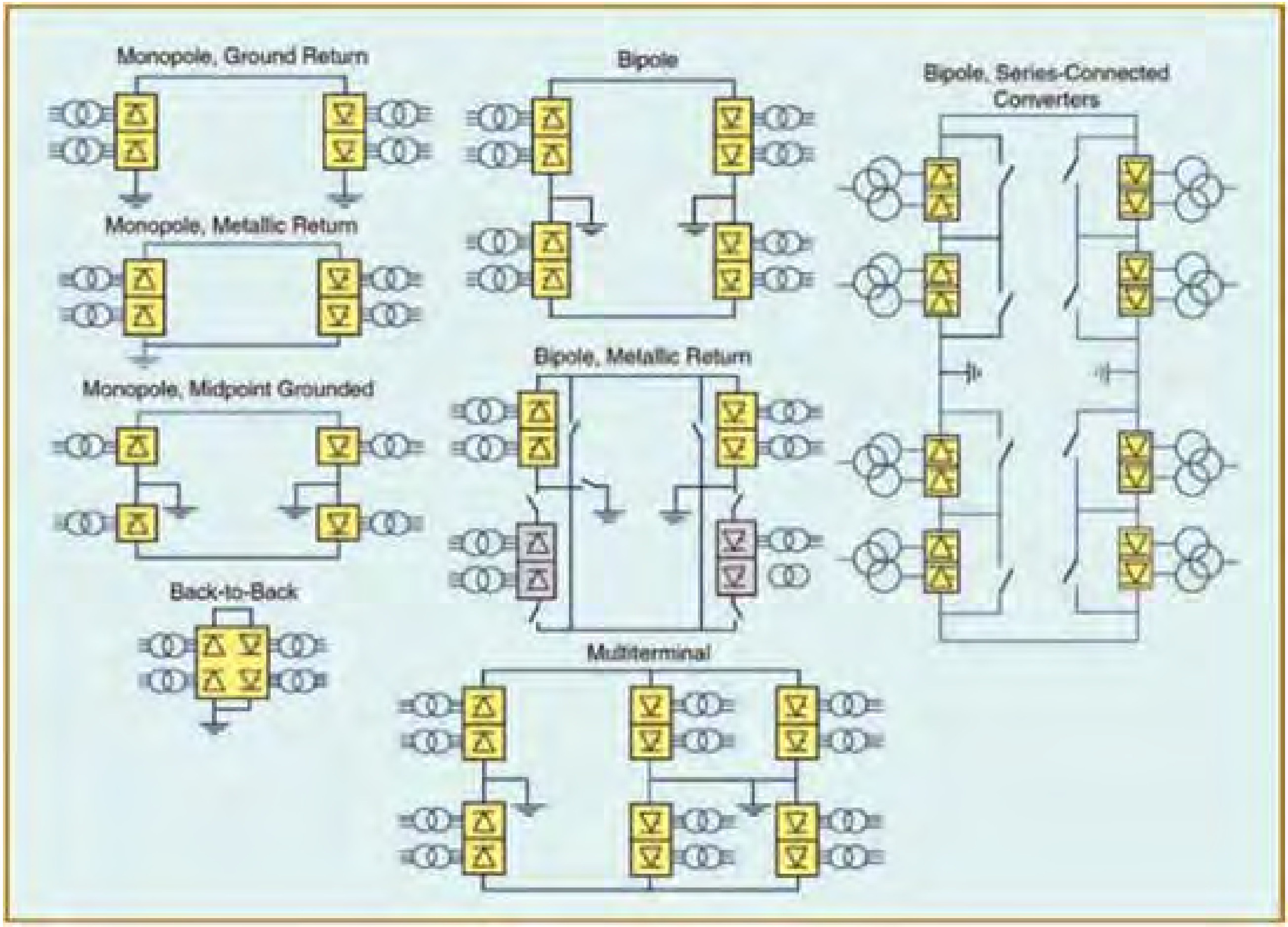


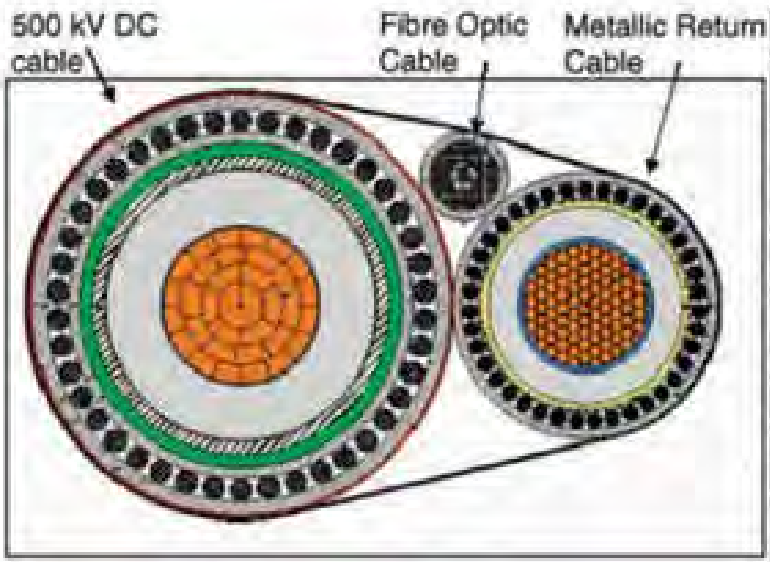
Figure 31 HVDC configurations and operating modes [29]

Figure 31 shows the various common system configurations and operating modes used for Current Source Converter HVDC transmission. Monopolar systems are the simplest and least expensive systems for moderate power transfers since only two converters (one per each terminal) and one high voltage insulated cable or line conductor are required. For current return such systems can be used with electrodes (land acts as an electrode) or with dedicated medium-voltage insulated conductors (also referred to as ‘metallic return’) [28]. Bipolar configuration can have a third path for the current return to be used in emergency conditions via electrodes or metallic return.

For monopolar transmission systems, the return path is either the ground or a second cable. Ground as a return path is environmentally friendly electrode systems, whereas the metallic return has severe impact on the costs of the overall transmission scheme [28]. Therefore, cables are sometimes developed with an integrated return conductor. As to the return conductor (often XLPE insulated), it can be wound outside the lead sheath as an a “second screen,” thereby also forming part of the armour, together with the flat steel wire layer on the outside of the return conductor insulation. Alternatively, the XLPE insulated metallic return cable can be simultaneously laid (and buried, if needed) in ground in close bundle together with the HVDC cable and a single fiber-optic cable, as shown in Figure 32. Such solution is selected for the Neptune Regional Transmission System, a 105-km-long HVDC interconnection between Sayreville, New Jersey, and Nassau County on Long Island, New York, via undersea and underground cables with a monopolar HVDC—metallic return scheme—rated terminal voltage is 500 kV DC [28]. The main details of the HVDC cable used in the Neptune Intertie are listed in Figure 32.

For the land portion on Long Island, the metallic return cable was split into two cables in parallel, laid on the two sides of the HVDC cable. This configuration was chosen in order to minimize the magnetic field due to the direct current flowing in the cables to a value less than 20 mT [28].

Nowadays, the most frequent rated voltage of HVDC extruded cable projects in service in Europe is ±320 kV (with a capacity of ≈1000 MW per bipole) [38]. The highest voltage of HVDC extruded cable projects being



CONSTRUCTIONAL DETAILS OF 500 kV HVDC CABLE			
1- Copper Conductor: Diameter of circular conductor		mm² mm	2100 51.9
2- Conductor Screen			
3- Insulation: mass impregnated, paper Thickness		mm	19.5
4- Insulation Screen			
5- Lead Alloy Sheath:			
6- PE Sheath			
7- Reinforcement: Galvanized steel tapes			
8- Bedding: Polyester Tapes			
9- Armour: Galvanized steel wires			
10- Serving: Polypropylene strings			
Overall diameter of the cable		mm	131
Weight of cable	In air	kg/m	53.5
	In water		44

Figure 32 Bundle of three cables—a 500-kV HVDC cable, a medium-voltage metallic return cable, and a fiber-optic cable—for the HVDC Neptune Regional Transmission System[28]

installed at present is ±525 kV- DC and belongs to the huge German corridors. The voltage limit of applicability of CIGRE testing procedures for HVDC extruded cables has been recently pushed up from the 500 kV of TB 496:2012 to the 800 kV of TB 852:2021. Therefore, the cable manufacturers are targeting ±800 kV- DC [38].

5.1.5 End of life requirements

There are several factors which lead the cable system towards the end of their life. For example, ground pollution, the thermal resistivity of the native soil, proximity to other heat generating buried facilities that create hot spots in the ground, etc., can have adverse effects on the life of the underground transmission cable assets. Consequently, the point at which power transmission underground cables will reach the physical end-of-life would depend in many cases on the external environmental factors and the location or route where the cables have been installed, rather than on the cable design or operating parameters itself [36].

5.2 Economic aspect (UG Cables)

The factors that influence the lifecycle economy of the buried utilities, such as UG cable, can be categorized into three groups: (a) UG cable project specifications (b) location conditions (c) the method of construction and maintenance. These categories can be further divided into factors such as the location of UG cable project, type of cable used, length of cable, rural or urban area, number of excavation and reinstatement, concurrent development projects, type of soil, hydrological conditions, traffic density, depth of cable, and tunnel building method etc. [33].

The standard shipping length for UG HV and EHV cable was in the range of 500m. On the economical approach, by having longer lengths per shipping drum, the hardware cost, the labour cost and the civil work cost are reduced [32]. In addition, the cost of UG cable power line can be minimized by reducing the amount of protections put on the different joints along the route, irrespective of the section length between them [32].

For HVDC cable system, the lower-cost cable installations made possible by the HVDC extruded cables and prefabricated joints makes long-distance underground transmission economically feasible for use in areas with rights-of-way constraints or subject to authorization problems and delays with overhead lines [28].

5.2.1 Project Planning and Pre-Design

The process of planning, constructing, and commissioning a typical new underground cable system takes a considerable amount of time, ranging from 3 to 7 years, depending on the location of the route and the project's scope. This timeframe includes activities such as planning, identifying the route, engineering, and construction. Because transmission circuit projects have lengthy planning and construction timelines, many of the initial assumptions made during project initiation, including budget, revenue sources, routing, and technical aspects, often undergo changes during the project execution phase. Consequently, these changes can lead to cost overruns and have an impact on the project's economic feasibility [36].

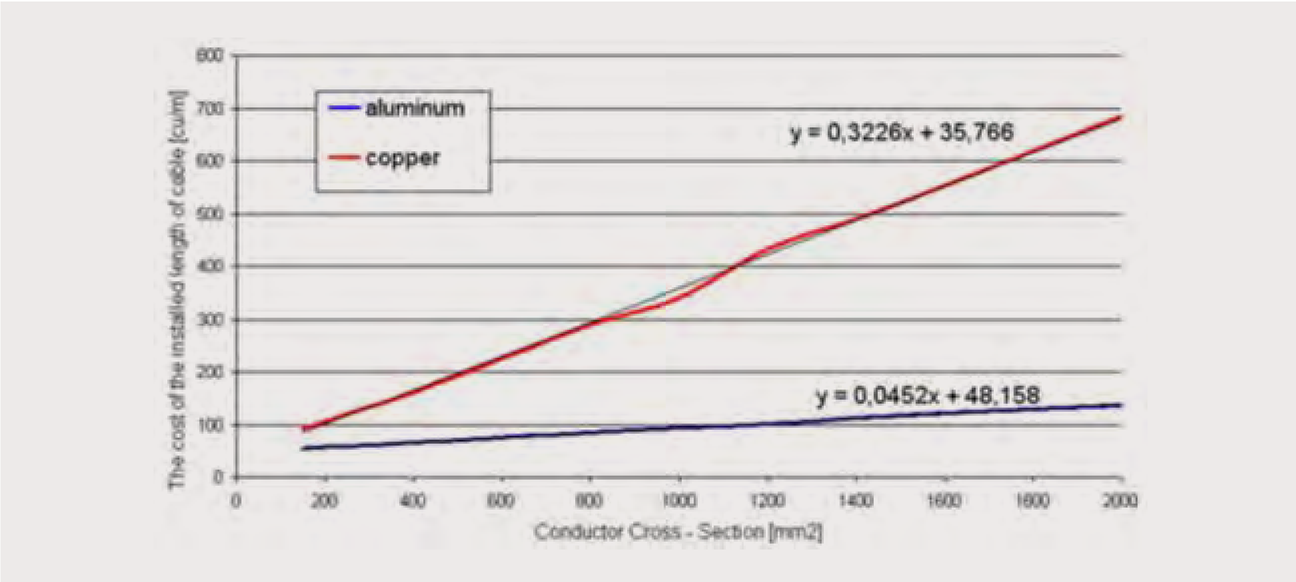


Figure 33 Cost of one meter of cable (cable and losses) as a function of the cross [46]

Underground transmission cable project planning involves selection of cable, locations planning, routes planning, environment and construction planning. Utility's rating standards for summer and winter ambient temperatures is often considered to calculate the ampacity of cable. Also, tests are done on soil to estimate the soil thermal resistivity [31]. Moreover, under selection of cable planning, the type of cable can be defined by specifications, such as diameter, material, and lifespan. Larger diameters are costlier and need larger volume of excavation, resulting in higher cost. The cost of cable is also directly related to the material. Selecting the cable material depends on many factors, such as the needed protection, technical requirements, needed capacity, availability of material etc. [33]. The cost of one meter of cable as a function of its cross-section is presented in Figure 33 [46].

The cost of installation components and the cost of production, installation, and operation of 2000 mm^2 size cable is presented in Table 17 and Table 18 respectively [46].

Under location planning, it is essential to have information about the whereabouts of current utility systems or upcoming underground utility projects to calculate the expenses involved in digging, setting up, and restoring [33]. In addition, the type of soil influences directly the cost. For example, excavation of hard rocks can be more expensive than clay. Furthermore, underground water or the existence of rivers and lakes in the route of cable can add extra costs. Examples of extra cost can be for dewatering of construction site, water proofing of trenches, and deviation of cable route to avoid water [33]. Therefore, water table within the location need to be assessed to predict if water may

Table 17 Cost of cable installation components [46]

Cost item	Unit	Unit cost [$]
Labor (earth work including the cost of concrete slabs)	m^3	50
Cost of laying the cables	m	125
Backfill material	m^3	28.75

Table 18 Cost of production, installation, and operation of cable system [46]

Costs ($ x 1000)		
Conductor	43	33
Other layers	17	16.5
Operation	8.25	7
Other costs*	9.25	10
Total cable cost	77.5	66.5
Backfill material	34.25	50.75
Installation	148.75	178.5
Total installation cost	183	229.25
TOTAL COST	260.5	295.75

*Other costs include items such as profit (counted as 10% of the cost). Wasted material and labour for making the cable.

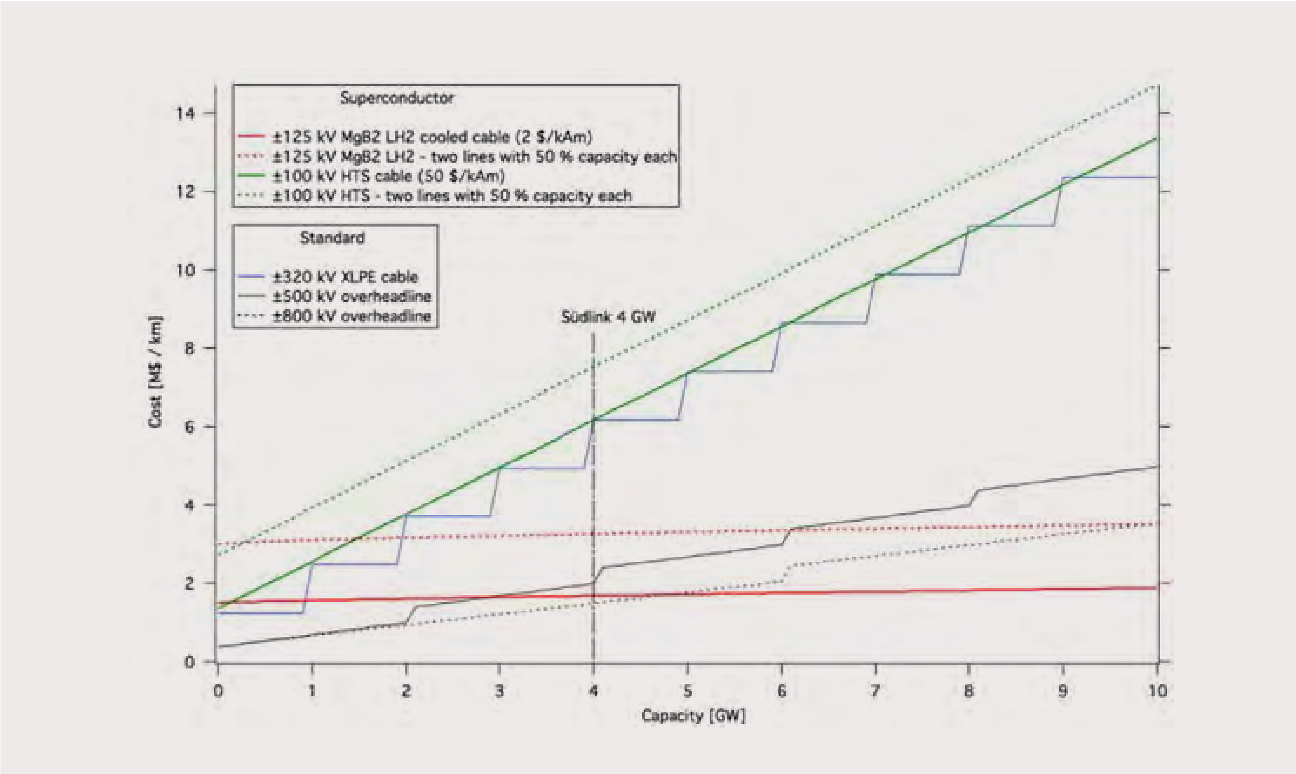


Figure 34 Comparison of capital cost per capacity and length for HVDC options [52]

intrude into the trenches, accordingly well point systems and submersible pumps can be planned to use [31].

Route planning involves collecting information on development level, concurrent projects, soil type, hydrological condition, population density, traffic, and slope etc. The expenses associated with cable systems rise from rural regions to suburban and urban areas due to additional costs imposed by urban environments. These costs include decommissioning and bypass expenses for existing utilities, traffic control measures, acquisition of underground space, social costs, and more [33]. Synchronizing the construction of cable system with other planned underground concurrent projects at the same location (such as metro, shopping centres, pedestrian corridors) can save the costs by sharing the resources.

Many of the typical challenges of underground projects such as traffic control, scheduling station outages, pavement restoration, extensive permitting, easement procurement, etc. need to be planned in the construction of underground cable system.

The indicative capital cost per capacity and length for HVDC OH lines, UG cables, and superconducting cables are shown in Figure 34 [52]. The cost of two redundant superconducting cable systems is shown with respect to the (n-1) criterion and possible redundancy requirements. The step like appearance of standard transmission lines stems from fixed costs like towers, trenching, installation or cables systems (±320 kV XLPE) needed to accommodate increased capacity [52]. For superconducting cable, increased capacity is accommodated for by adding more superconducting material without changing the design and thus only small further additional costs in case of Magnesium diboride (MgB2) appear [52].

5.2.2 Design, Approvals and Specification

For several years, the expansion of the grid has faced significant opposition to the construction of new transmission lines, particularly overhead lines. A notable instance is the Wahle-Mecklar overhead power line in Lower Saxony and Hesse in Germany, which received approximately 21,000 objections. Protesters and residents affected by these projects are advocating for the use of underground cables, despite the considerably higher costs involved [52]. In such scenarios it is utmost important to explore less expensive options for underground cable considering their design, specification, and approval time.

As per the data in [33], the design and construction cost of cable system is almost 23 times the yearly operations and maintenance cost of cable. The cost of design, construction, and maintenance of UG cable system can be reduced by using the multi-utility tunnels [33], [34].

The start of a new UG cable project or replacing an existing underground transmission line (which is close to end of its life) often necessitates acquiring new land easements and right-of-ways to establish a new route for the cable circuit. This task becomes particularly challenging in certain areas, such as city locations, where obtaining new easements for transmission lines is highly problematic due to the presence of numerous utility plants, environmental concerns, and objections from the public known as "Not-In-My-Backyard" opposition. The difficulty in obtaining these new easements can lead to significantly increased construction expenses and may impact the overall financial feasibility of the asset sustainment project [36]. Moreover, typical underground transmission lines are constructed across extensive geographical areas and are commonly installed within public corridors. The installation process necessitates coordination and approval from numerous utility companies, environmental agencies, and government bodies [43]. Given the involvement of multiple stakeholders and the intricate nature of renewing underground transmission lines, the completion of an UG cable project, from the initial planning phase to the final commissioning, often spans several years [43].

For HVDC cable system, the HVDC extruded cables with prefabricated joints used with Voltage Source Converter-based transmission are lighter, more flexible, and easier to joint than the mass-impregnated oil–paper cables used for conventional HVDC transmission, thereby making them prone to land cable applications where transport limitations and extra jointing costs can raise installation costs [28].

With superconducting cable, there is a benefit of low visual impact, which can lead to increased public acceptance and subsequently reduce the time required for approval [52]. For example, in Long Island Power Authority (LIPA) project, LIPA made substantial investments in system upgrades and improvements by employing a 600 m superconducting power cable operating in the grid at 138 kV and 2400 Ampere. LIPA recognized superconducting power lines as a possible solution to various needs and related problems such as [52]:

1) Right-of-way (ROW) congestion: superconducting cables provide increased power transfer capability within existing ROWs.

2) Public acceptance: permission problems for overhead lines.

3) Potential cost savings: cheaper than upgrading to 345 kV overhead transmission systems.

5.2.3 Maintenance and Operation

In order to access buried cables for maintenance and repair, excavation and reinstatements are needed during the lifecycle, which will increase the lifecycle cost of buried cable [33]. The cost of maintenance can be reduced by synchronizing the maintenance of cable system with other planned underground development projects at the same location [33].

Table 19 shows the laying cost and maintenance cost (in Chinese Yuan) of 110 kV cable project of Shanghai Taopu Science and Technology Intelligence City in China. Another case study comparing the construction and maintenance cost and fault elimination cost (in Euros) for two options for 110 kV network: 1) Network is fully formed by OH line 2) Network is formed partially by OH line and partially by UG cable (1/5th length of whole network length) is presented in Table 20 [35].

The authors of [45] conducted a study to find the optimized maintenance and replacement cycle of underground cables with added economic perspective, minimize power outages, and increase the power supply reliability. The study examined the actual failure rates of the underground cables, the costs of maintenance and repair of cables, and the costs caused by their failures. The paper compared the maintenance and repair cost for two scenarios using Monte Carlo simulation. In the first scenario cable is used without maintenance for 30 years and in second scenario the first maintenance is carried out in the fifth year of use, and the subsequent

Table 19 Laying and maintenance cost of 110 kV cable project in China [34]

	110 kV Cable
Laying cost (104 CNY/km*pipe)	40
Service life (years)	50
Maintenance cost (104 CNY/km)	0.1

Table 20 Cost comparison between full OH line and OH line with partial cable option [35]

Costs	OHL	OHL+ cable
Construction	17620	19131
Maintenance	11156	8928
Fault elimination	793	717
Total costs:	29568	28776

Table 21 Total cost (in USD) for maintenance and repair for each Scenario [45]

Simulation counts	Scenario 1	Scenario 2
2000	6,678,843	1,025,589
4000	13,399,634	2,146,605
6000	20,005,285	3,153,821
8000	26,705,307	4,247,150
10000	33,318,380	5,198,425
12000	39,767,563	6,496,467
14000	46,704,445	7,385,933
16000	52,957,207	8,659,146
18000	59,913,721	9,653,424
20000	66,556,140	10,553,002

maintenance would be carried out every three years after that. The simulation was conducted ten times, starting with 2000 samples and adding 2000 samples up to 20,000. Table 21 presents the maintenance and repair cost comparison between the two scenarios [45]. The result shows lower maintenance and repair cost for scenario 2.

5.2.4 Line Losses

Figure 35 shows the comparison of the energy loss along the interconnectors with the two different interconnecting technologies i.e. underground cable and HTS cable [44].

For HVDC systems, for a given cable conductor cross section, the line losses with HVDC cables can be about half those of AC cables [28]. This is due to AC cables requiring more conductors (three phases), carrying the reactive component of current, skin, and proximity effect, and induced currents in the cable sheath and armour.

Superconducting cables have inherent advantages in transferring large amounts of electrical energy, primarily due to their negligible losses apart from cooling losses. As the capacity increases, superconducting cables becomes even more attractive in terms of energy efficiency [49], [52]. This is because the design and size of superconducting cables undergo minimal changes when scaling up the capacity, thanks to the high current density of superconductors. Higher capacities result in a smaller cost-to-capacity ratio, particularly for more affordable superconductors like MgB2, as the expenses for the cryogenic envelope and trenching remain relatively fixed, with the additional cost incurred only for the superconducting material itself [52]. However, even low-capacity superconducting cables can still be economically competitive and serve to address the drawbacks of existing power grids [52]. For example, low-voltage superconducting cables can be employed to replace high-voltage lines and transformers.

Superconducting cables offer significant advantages in terms of size and reduced electrical losses for transmitting high capacities, surpassing the capabilities of standard conductors. This not only minimizes the environmental impact but also promotes a more sustainable way of transmitting electric energy [52]. For example, in the case of Ampacity (superconductor project in Germany), the responsible utility company RWE was convinced by an economic study that showed that a SC cable is one of the two cheapest options to upgrade the existing grid. In particular, by employing a

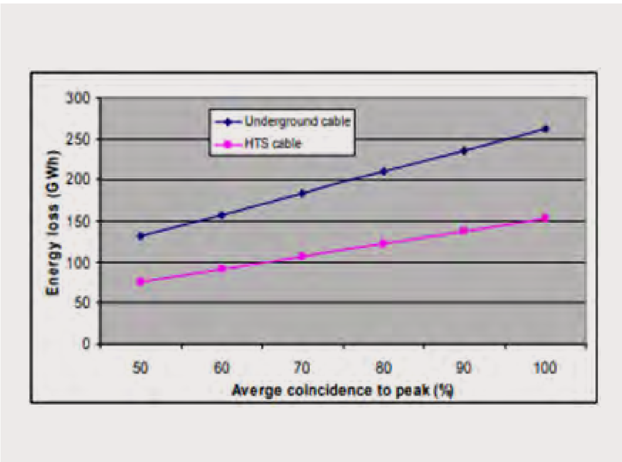


Figure 35 Comparison of energy loss [44]

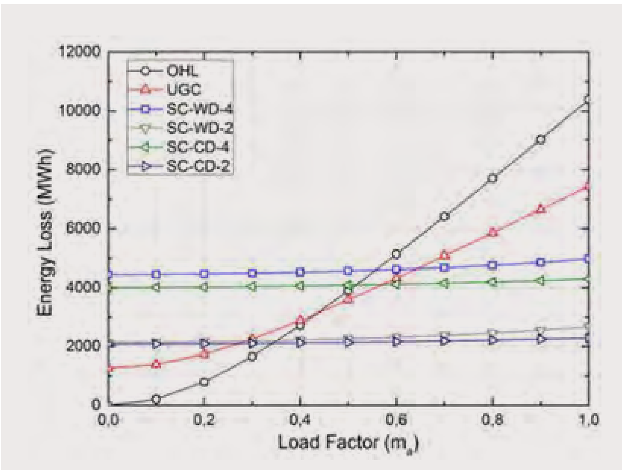


Figure 36 Energy loss vs load factor [49]

Table 22 Power losses (kW/km) of OH line and double circuit UG cable for 25 Km at 380 kV voltage [48]

Sr = 1800 MW + j 360 Mvar			
OHL	Power losses kW/km	UGC εsh=0.53	Power losses kW/km
P_j Joule losses	515	P_j Joule losses	140.2
Pg_1 Insulator and corona losses (fair weather)	1.56	$P_{Reactor}$ Reactor losses	12.3
Pg_2 Insulator and corona losses (rainy weather)	12.5	$P_{Reactor}$ Reactor losses	12.3
$Pj + Pg_1$	516.56		168.8
$Pj + Pg_2$	527.5	$P_j + P_g + P_{Reactor}$	

SC cable, one can take advantage of its high current density to operate at a lower voltage (10 kV) and one can thus eliminate the aging 110-10 kV AC transformers [52].

A comparison for energy loss as a function of load factor between OH line, UG cable, and superconducting cables are shown in Figure 36. At a load factor lager than 0.65 all superconducting cable are more efficient than conventional transmission lines [49].

The impact of transmission line losses on different aspects such as climate change, fossil depletion, human toxicity, and ozone depletion etc. are presented in [42]. The impact of line losses on mentioned aspects are highlighted for OH lines and UG cables. Also, the impact of different processes in the lifecycle of OH line (production of materials for foundations, masts, conductors, and insulators, installation, maintenance, and end of life) and UG cables (production of cable and cable trace, installation, maintenance, and end of life) on above mentioned aspects are presented [42].

A comparison for power losses between the OH line and UG cable for a 25 km length of transmission line project in Italy is presented in Table 22 [48].

5.2.5 De-commissioning Costs

A comprehensive analysis of a transmission line cannot disregard its end of life: the decommission and dismantling stage. The corresponding costs (mainly for circuit dismantling, disposal of waste materials, restoration of the corridor) can be roughly estimated as a percentage of the global investment cost. It is usually assumed that all end-of-life costs add up to about 5% of the initial investment. For the OH line example, the amount of these costs discounted to the present time (n = 40) is 0.0043 (M Euros/km), while it is 0.0265 (M Euros/km) for UG cables [48].

A comparison of overall cost for OH line and UG cable is presented in Table 23 [48].

Table 23 Overall cost comparison between OH line and UG cable system rated 380 kV [48]

	OHL (M€/km)	Double-circuit UGC (M€/km)
(I) Capital cost	0.6	3.5
(ΔI)sh Shunt compensation costs	0	0.24
((E)) Loss energy costs	1.554	0.594
(T) Burden on territory	0.1.wx	0.018.wx
((D)) Dismantling costs	0.0043	0.0265
((OM)) Oper. & Maint. costs	0.052	0.035
((R)) Random failure exp. rep. costs	0.0121	0.03

6.

Summary of Findings

	AC Overhead Transmission Lines	DC Overhead Transmission Lines	AC Underground Cable Transmission Lines	HVDC Underground Transmission Lines
1. Technical Aspects				
1.1 Design	Power transfer capability could be improved based on current infrastructure through the following ways: (a) expand current overhead transmission line into multi-circuits, multi-voltage lines; (b) replacing ACSR conductors with HTLS conductors. (c) convert existing AC line into hybrid AC/DC line.	NA	Power transfer may reduce in UG cables due to lower heat dissipation inside the soil and more dielectric losses. Therefore, cable system might require two cables per phase to match the capacity of the overhead line. UG cable system design has advantages of less disruption to traffic, good protection from bad weather conditions and third-party disturbances, better aesthetics, and less magnetic field over the ground surface if buried at good depth. Cables are being designed and installed at voltages up to 230 kV and 345 kV in long lengths. XLPE - cross-linked polyethylene is the most common and well-established insulation materials in modern extruded high voltage cable design. This insulation demonstrate good electrical, mechanical, and thermal properties with low dielectric losses, low dissipation factor, high electrical breakdown strength, high modulus of elasticity and high tensile strength. It is suitable for conductor temperatures up to 90 °C and can withstand up to 250 °C.	More power transfer due to less losses in the HVDC cable than the HVAC cable. HVDC cable lengths are not limited by charging currents and no reactive compensation is required like in AC transmission systems. As compared to AC transmission circuits, which typically require three cables, DC transmission circuits require two parallel cables only.
1.2 Reliability	The longer the distance from roads, the longer outage. Concrete tower tends to have less outage duration compared to steel tower type. Also, higher voltage level in many cases have longer outage duration.	NA	Cables tend to have fewer failures. However, in the event of a failure, the time required for restoration can be significantly longer for cables, ranging from days to weeks. If failure occurs in a specific set of cables, faulty section can be isolated and partial power transfer through the remaining circuit can be maintained. The cable accessories, rather than the cable itself, are typically more susceptible to failures. A greater number of accessories will naturally have lower reliability compared to a system with fewer accessories. Introducing two cables per phase may not necessarily improve the reliability as the presence of splices in shared manholes in close proximity on common structures can lead to failures affecting the accessories of both adjacent circuits.	HVDC cables may show better reliability than their AC counterpart due to their better performance at elevated temperatures and fields, minimal space charge retention, favourable material compatibility, and reliable and robust accessories.

	AC Overhead Transmission Lines	DC Overhead Transmission Lines	AC Underground Cable Transmission Lines	HVDC Underground Transmission Lines
1.3 Construction requirement	NA	NA	For cable systems construction usually, open trenches are made in which conduit bundles are placed. Trenches are then filled with high-strength concrete. The horizontal bending radii is recommended at a minimum of 6-10 meters to minimize pressure on the sidewalls and reduce tension forces during cable installation.	The main challenge with UG HVDC cables are large number of remoulded (field) joints which needs to be installed in long lines and also the thermal instability with the soil, especially when voltage, current and temperature gradient ratings are very high, and the heat exchange properties of the soil are not excellent. The burial depth of HV cables and the improved laying conditions using proper backfills may improve the thermal conditions.
1.4 Operations & maintenance	NA	NA	Water vapor within the cable tunnel may cause faults in tunnel facilities because water vapours are very erosive in nature. Therefore, it is recommended to drain the water from the tunnel using an anti-wound stainless steel submersible pump. The short circuiting of the temperature-sensing fire detectors and the short circuiting of manual alarm may trigger false alarms. Therefore, waterproof block can be added to the manual alarm and temperature-sensing fire detectors should be replaced annually. Increased period of patrolling, strengthen the inspection of the accessories, annual drills, and increase the usage efficiency of the monitoring systems, such as cable online monitoring system, fireproof monitoring system, and vision and environment monitoring system, can improve the cable system maintenance. However, it is challenging to assess the physical conditions of underground cable assets due to their installation locations that are either hard to reach or inaccessible.	Among the different HVDC system configurations, operation of monopolar system is the simplest. For monopolar transmission systems, the return path can be ground which is economic and environment friendly.
1.5 End of life	NA	NA	- The point at which power transmission underground cables will reach the physical end-of-life may be affected by the cable design or operating parameters. However, cable end of life significantly depends on the external environmental factors and the location or route where the cables have been installed.	NA

	AC Overhead Transmission Lines	DC Overhead Transmission Lines	AC Underground Cable Transmission Lines	HVDC Underground Transmission Lines
2. Economic Aspects				
2.1 Project planning & pre-design	In a study, it shows that the ratio of the total cost of HVDC cable to HVDC OHTL is about 5.5. The option of replacing ACSR conductor with HTLS conductor could be economically beneficial. It is found that cost of energy losses is the most important cost component, especially when the line is heavily loaded. Compared with three-conductor bundled 300kV OHTL, four-conductor bundled lines has the advantage in case of heavily loaded lines.	In a study, a comparison of three alternatives shows that based on the cost per km, the HVDC OHL is the most economical alternative (12 M/km), followed by 500 kV HVAC underground cable (19.76 M/km) and the most expensive one is ±320 kV HVDC underground cable (26.63 M/km).	Planning, construction, and commissioning of a typical new underground cable system may take time, ranging from 3 to 7 years. Change in budget, revenue sources, routing, and technical aspects may lead to cost overruns and can impact the project's economic feasibility. Underground transmission cable project planning involves selection of cable, locations planning, routes planning, environment and construction planning. Many of the typical challenges of underground projects are traffic control, scheduling station outages, pavement restoration, extensive permitting, and easement procurement.	NA
2.2 Design, approvals, & specifications	NA	NA	Construction of new OH transmission lines face significant opposition. Protesters and residents supports underground cables, despite the considerably higher costs of UG cables. However, the cost of design, construction, and maintenance of UG cable system can be reduced by using the multi-utility tunnels. Replacing OH line with UG cable requires acquiring new land easements and right-of-ways which can significantly increase the construction expenses and may impact the overall financial feasibility of the project.	For HVDC cable system, use of HVDC extruded cables with prefabricated joints can reduce the installation costs. With superconducting cable, there is a benefit of low visual impact, which can lead to increased public acceptance and subsequently reduce the time required for approval.
2.3 Operations & maintenance	In a study, the O&M costs are assumed as 1.5% and 0.15% of capital investment cost for OHTL and UGTL respectively. In a study, the ratios of the total maintenance cost of 115kV, 230kV and 500kV are 1:1.24:2.52.	NA	For maintenance and repair of buried cables, excavation and reinstatements are needed, which will increase the lifecycle cost of buried cable. However, the cost can be reduced by synchronizing the maintenance of cable system with other planned underground development projects at the same location.	NA

	AC Overhead Transmission Lines	DC Overhead Transmission Lines	AC Underground Cable Transmission Lines	HVDC Underground Transmission Lines
2.5 Decommiss-ioning costs	For the OH line, the amount of decommissioning costs discounted to the present time (n = 40) is calculated 0.0043 (M Euros/km) for a European project.	NA	Typically end-of-life costs add up to about 5% of the initial investment. For the UG cable, the amount of decommissioning costs discounted to the present time (n = 40) is calculated 0.0265 (M Euros/km) for a European project.	NA
2.6 Lifecycle cost	The life cycle cost of 220 kV OHTL is approximately 65% higher than a 132 kV OHTL providing nearly 2.5 times more power carrying capacity and the life cycle cost of a 400 kV OHTL is 56% and 85% higher, providing 3.5 and 8.5 times more power carrying capacity as compared to 220 kV and 132 kV OHTL respectively.	NA	The life cycle costs of underground lines are much higher compared to overhead lines and this is mainly due to high capital costs in case of underground lines. Overall, the life cycle costs of UGTL are two to six times more than OHTL.	NA

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4.

Cost and Economic Aspects

Comparing high voltage overhead and underground transmission infrastructure (up to 500 kV)

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Abbreviations and Acronyms

Abbreviation	Description
AC	Alternating Current
ACSR	Aluminium conductor steel-reinforced cable (or conductor)
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AVP	AEMO Victorian Planning
CBA	Cost Benefit Analysis
CIGRE	International Council on Large Energy Systems
DC	Direct Current
EHV	Extra High Voltage—consensus for AC Transmission lines is 345kV and above
EIS	Environmental Impact Assessment
EIR	Environmental Impact Review
EIS	Environmental Impact Statement
ELF	Extremely low frequency
EMF	Electromagnetic Fields
ENA	Electricity Networks Australia
EPR	Ethylene propylene cable
EPRI	Electrical Power Research Institute
GIL	Gas Insulated Line
GC	Gas cable
HDD	Horizontal Directional Drilling
HPOF	High-pressure oil-filled cable
HTLS	High Temperature Low Sag Conductors
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ISP	AEMO's Integrated System Plan
NEM	National Electricity Market
OH	Overhead
OHTL	Overhead transmission line
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
REZ	Renewable Energy Zone
RIT-T	Regulatory Investment Test—Transmission
ROW	Right of Way (e.g. easement)
SCOF	Self-contained oil-filled cable
SLO	Social Licence to Operate
UG	Underground
UGC	Underground cable
UGTL	Underground transmission line
XLPE	Cross-linked polyethylene

1.

Introduction

This study aims to investigate the benefits and trade-offs between overhead and underground transmission line infrastructure, specifically focusing on issues associated with under-grounding new transmission infrastructure. It seeks to establish a clear and consistent approach to the evaluation of overhead lines and underground cable transmission, including the consideration of community concerns around the need for new transmission infrastructure to connect large renewable energy generation projects. It does this through systematic reviews of the literature as well as incorporating experiences of Transmission Network Service Providers (TNSPs) in Australia and overseas. The study has a particular focus on 500kV infrastructure which is expected to be the system voltage for high-capacity transmission lines in Australia going forward.

Historically, transmission networks in Australia developed from the need to transfer large amounts of power from large coal fired power stations, typically co-located near coal reserves, over long distances to major cities and industrial load centres. In contrast, the proposed large scale renewable generation facilities, mainly solar and wind farms, require greater land areas and are largely being located in greenfield areas with little or no existing transmission network infrastructure. These new developments are naturally creating community interest and concerns around a range of potential impacts, including but not limited to: visual amenity; environment; Traditional Owner lands; agricultural land use; and social licence to operate concerns. This has led to questions surrounding when it is appropriate to underground transmission infrastructure and the likely implications of doing so.

There have been many studies by government bodies, TNSP's, industry organisations and stakeholders comparing the cost of overhead and underground cable transmission either generally or for a specific project. Based on published literature including Parsons Brinkerhoff [1] and AEMO [2], the ratios are generally in the range of 3 to 20 depending upon type of construction, route length and other project specific factors.

To ensure the most up to date and objective information was used to form the basis of any comparisons, the research included both systematic literature reviews of published papers using the PRISMA methodology. The literature review focused on the technical and economic aspects of HV transmission infrastructure. The technical and economic literature review is contained in Appendix A of *Chapter 3 - Technical Aspects*. A purposeful search of additional published materials included: i) reference books and major reports from the leading electrical engineering research organisations of CIGRE and EPRI[1]; and ii) standards, reports, and reference material from electrical industry sources; Australian and international Transmission System Operators; the Australian Energy Market Operator (AEMO); the Australian Energy Market Commission (AEMC); and other federal, state, and local government reports.

A detailed review of HVDC transmission costing and economics is not within the scope of this study, however information from the literature reviews will be presented and discussed.

[1] CIGRE Green Books Overhead Lines International Council on Large Electric Systems (CIGRE) Study Committee B2: Overhead Lines. Springer Reference.
CIGRE TB 680—Implementation of Long AC HV and EHV Cable System. CIGRE, 2017. EPRI Underground Transmission Systems Reference Book. Electric Power Research Institute, 2015.
EPRI AC Transmission Line Reference Book 200kV and above, 2014 Edition.
EPRI Underground Transmission Systems Reference Book: 2015.

2.

Transmission Lines in Australia

Traditionally, electricity transmission network planning has involved evaluation of options to address forecast needs and limitations on the network including power demand, connection of new customer loads, new energy generation and storage developments, replacement of ageing infrastructure and decommissioning of redundant network. Options are typically evaluated on an economic basis over an expected lifetime using net present value calculations based on underlying assumptions of capital, operating and maintenance costs, demand growth, inflation rates and other factors. The costs that are broadly considered across the lifetime of an overhead or underground transmission line project are summarised in Table 1.

Table 1. Transmission Line Whole of Life Cost Elements

Lifecycle Phase	Cost Components
Planning, Design and Approvals	Planning and preparatory activities including consultation and engagement. Design and survey Environmental offsets Social licence Property—easements, right of way, landholder payments
Construction	Procurement of plant and materials Construction (civil, structural, electrical) Commissioning
Operating and Maintenance	Ongoing compliance costs Transmission line energy losses Preventative—Inspection, condition monitoring, testing, component replacement Corrective—defect repairs, component replacement or refurbishment Emergency—repairs after faults, severe weather damage
End of Life	Decommissioning Recovery of assets Land remediation

HVAC transmission line development options considered will be either be (1) overhead, (2) underground or (3) hybrid overhead/underground. HVDC technologies may also be considered, typically for projects involving long land or submarine routes not requiring future connections to the line along the route.

There have been many studies by government bodies, TNSPs, industry organisations and stakeholders comparing the cost of overhead and underground cable transmission lines either generally or for a specific project. The cost ratio of underground to overhead transmission in these studies are generally in the range of 3 to 20 depending upon project specific factors. Some of these studies are referenced in section 4 - Transmission Line Cost Estimating Methodologies.

An independent UK industry report by Parsons Brinkerhoff and endorsed by the Institution of Engineering and Technology (UK) "Electricity Transmission Costing Study An Independent Report" [1] stated in its conclusions: *"Cost ratios are volatile, and no single cost ratio comparing overhead line costs with those of another technology adequately conveys the costs of the different technologies on a given project. Use of financial cost comparisons, rather than cost ratios, are thus recommended when making investment decisions."*

3.

Australian NEM Regulatory Framework for Economic Assessment of Projects

In Australia, under the National Electricity Law, TNSPs must undertake the Australian Energy Regulator's (AER) Regulatory Investment Test for Transmission (RIT-T) when potential solutions to reinvest in network assets or increase the capacity of high voltage transmission network are over a $7 million threshold, as defined in the National Electricity Rules. The Australian Energy Regulator (AER) is responsible for ensuring that RIT-T provisions are complied with, while the Australian Energy Market Operator (AEMO) is responsible for coordinating the overall planning of the national grid in conjunction with the state and regional TNSPs.

Regulatory Framework—the National Electricity Rules and prescribed supporting documents such as the AER's Cost benefit analysis guidelines[2] outline what costs and market benefits are included and excluded from economic assessment of projects. Costs include:

- costs incurred in constructing or providing the projects;
- operating and maintenance costs in respect of the projects;
- the cost of complying with laws, regulations, and applicable administrative requirements in relation to the construction and operation of the projects;
- any other class of costs specified in the CBA guidelines;
- or that AEMO determines to be relevant, and the AER agrees in writing before AEMO publishes the draft ISP.

A Market Benefit can currently only be considered in the assessment if it can be measured as a benefit to generators, DNSPs, TNSPs and consumers of electricity.

Non-Market Benefits—AEMO's 2023 Transmission Expansion Options Report August 2023 [2] states: *"Where an impact, or cost, is not included as a relevant consideration in the regulations, the regulations do not permit these matters to be considered, which includes matters like broader social and environmental impacts . Similarly, the regulations do not allow consideration of wider benefits of building or maintaining transmission infrastructure such as increased regional jobs, local manufacturing, utilisation of local contractors, training and apprenticeships, or economic opportunities unlocked or facilitated by the projects."*

This excludes, for example, considering the improved visual amenity of an underground transmission line compared to an overhead line as a social benefit in a RIT-T or ISP assessment.

In response to the increasing community and stakeholder concerns over significant transmission infrastructure programs to facilitate connection of renewable generation, many TNSPs —internationally and in Australia are now introducing incentive payments to landholders for hosting overhead transmission line infrastructure in addition to legal compensation required for easements or access rights[3]. In the case of Queensland's framework, adjoining landholders within 1 km radius of the transmission line are also entitled to payments based on property size.

The new landholder incentive payments are an initiative to improve social licence. However, the costs should be included in the RIT-T economic assessment of project options as initial costs or on-going operational costs depending on the specific arrangements for a project and land holders.

[2] https://www.aer.gov.au/taxonomy/term/1364.
[3] https://www.energyco.nsw.gov.au/sites/default/files/2023-01/overview-strategic-benefit-payments-scheme.pdf. https://www.powerlink.com.au/sites/default/files/2023-05/SuperGrid-Landholder-Payment-Framework.pdf.

4.

Transmission Line Cost Estimating Methodologies

Project cost estimation is complex, and methodologies vary between organisations. Cost estimates transition from a low level of accuracy to higher accuracy as a project progresses through its life from concept to construction. This section provides an overview of transmission project cost estimating in the planning phase with reference to the approaches used by 1) AEMO for the Integrated System Plan; and 2) Parsons Brinkerhoff's Transmission Costing Study Report for the UK Industry.

4.1 AEMO's Transmission Cost Database

AEMO's approach to transmission project costing for the ISP is described in documents published on its website [3] [2]. The AER RIT-T Application Guidelines[4] provide guidance for AEMO and TNSPs on the types of options and costs to be considered for application in RIT-T.

AEMO has adopted the Association for Advancement of Cost Engineering (AACE) International classification system for estimates. This is used in many industries for defining the level of accuracy of a cost estimate, based on the amount of design work that has been done. This system defines a series of 'classes' of estimates, ranging from Class 5 (least accurate) to Class 1 (most accurate). Cost estimates progress from a very early development stage with little design or information known (least accurate) to a fully costed and engineered estimate built up over years (most accurate)

AEMO's has defined 2 stages of class 5 accuracy estimates for its application:

- Class 5b—concept level scoping with no site-specific review or TNSP input
- Class 5a—Screening level scoping including high level site-specific review and TNSP input.

TNSPs are responsible for the higher accuracy estimate as risks and uncertainties are resolved, and the project progresses through its development stages.

AEMO has produced cost estimates for future ISP projects using a Transmission Cost Database (TCD)[5] tool, which is designed to produce Class 5a estimates. The TCD produces Class 5a estimates (concept type) and a manual adjustment is made to produce Class 5b estimates. Cost estimates are broken down into several components with adjustment factors for project specific requirements and addition of risks and indirect costs as outlined in Table 2.

The TCD includes cost estimates for overhead transmission lines and underground cables, both of which vary significantly with voltage level and capacity. Figure 1 shows a comparison of these cost estimates for given voltage levels and power transfer capacities [2, p. 34]. The HVAC option is included as a reference point. The costs of underground cables are approximately four to 20 times higher than overhead lines depending on the type of installation. Direct buried cables are at the lower end of this range, while tunnel installed cables are at the upper end.

[4] https://www.aer.gov.au/networks-pipelines/guidelines-schemes-models-reviews/rit-t-and-rit-d-application-guidelines-2018.
[5] https://aemo.com.au/en/consultations/current-and-closed-consultations/transmission-costs-for-the-2022-integrated-system-plan.

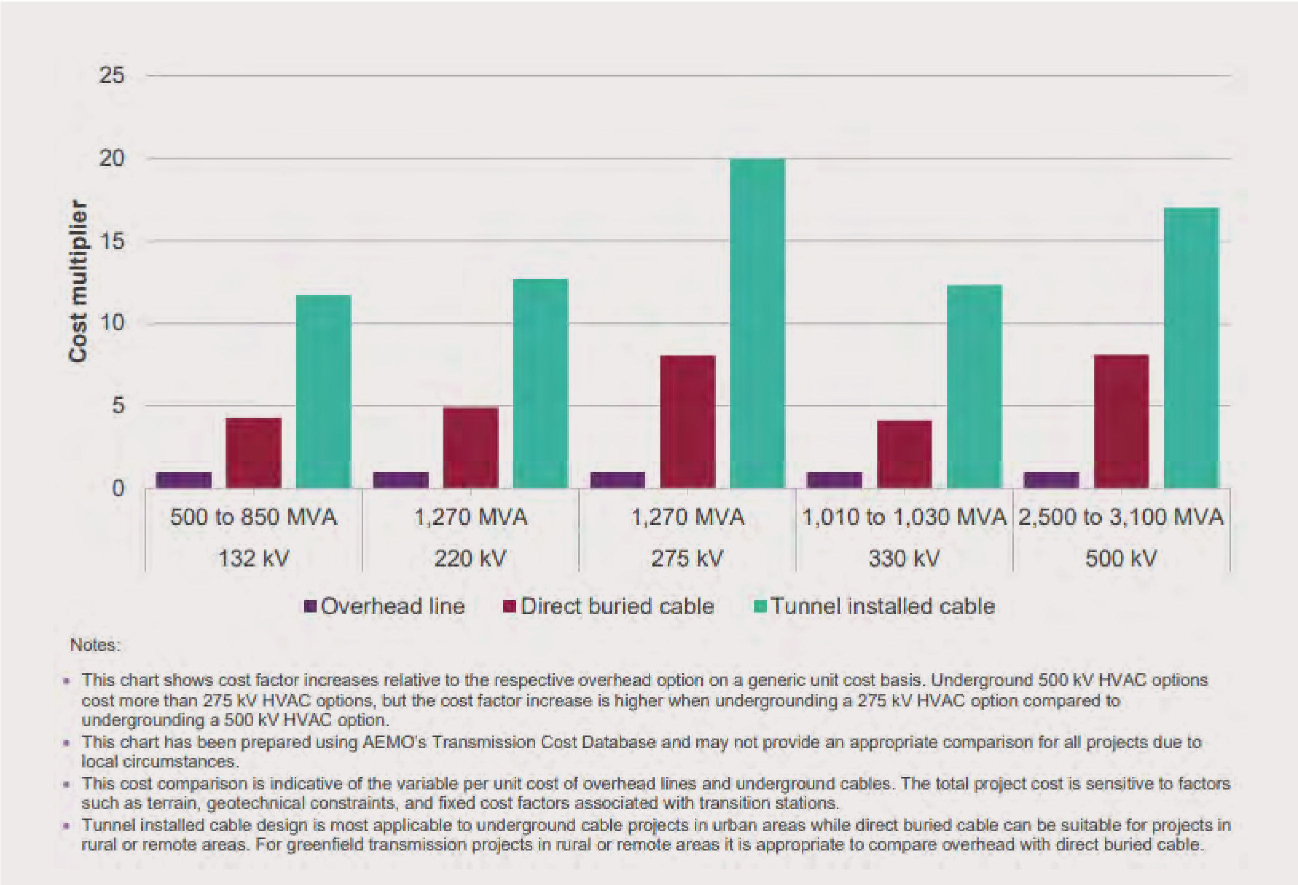

Figure 1. Indicative Unit Cost Multiplier from HVAC Overhead Lines to HVAC Underground Cables (AEMO 2023 Transmission Expansion Options Report [2, p. 34])

Table 2. Cost Breakdown Structure adapted from—AEMO 2021 Transmission Cost Report[6]

Phase Cost Categories	Cost Components / Factors	
Capital Costs - Planning, Design, Approvals and Construction	Building Blocks	Plant and materials Civil and structural works Testing and commissioning Secondary systems Contractor project management and overheads Environmental offsets Design and survey Easement / property Electrical works
	Adjustment Factors	Location (Regional / distance factor) Location wind loadings Terrain Delivery timetable Greenfield / brownfield Project network element size Jurisdiction Proportion of environmentally sensitive area Contract delivery model
	Known Risks	Compulsory acquisition Environmental offsets Macroeconomic influence Market activity Cultural heritage Geotechnical findings Outage restrictions Project complexity Weather days
	Unknown Risks	Plant procurement Productivity / labour Project overhead Scope and technology
	Indirect Costs	Project development Works delivery Land and environment Procurement Stakeholder and community engagement Insurance
Operating and Maintenance Costs	1% of the total capital cost per annum is assumed as operation and maintenance cost for each transmission project. If more detailed information is provided from a TNSP, and AEMO is satisfied with the evidence provided, this may take precedence over the 1% assumption.	

6 https://aemo.com.au/-/media/files/major-publications/isp/2021/transmission-cost-report.pdf?la=en.

The TCD has gone through a calibration process through a comparison with a selection of large-scale transmission projects and following calibration, the TCD was found to be within +/- 15% of the benchmark reference cost estimates. However, AEMO acknowledged there were several limitations identified with the use of the TCD as follows:

- The property and environmental offsets reference costs were found to have errors for overhead projects of +/- 15% and should not be relied on.
- The output is Class 5a estimate (which can be adjusted for Class 5b) and therefore suitable only for estimating the costs of network options which are in the very early stages of development for use in the ISP modelling.
- The TCD is not suitable for Class 4 or better estimates—these should be produced by the TNSPs.
- The accuracy bands have been derived statistically, such that 80% of project estimates should fall within these limits.
- The output represents Australian construction environment, asset and design standards, industry and business practices, regulatory framework, commercial rules, labour laws, and safety regulations in 2021.
- The output represents stable macroeconomic (forex, commodity, labour and wage price indices, social and political) conditions that Australia has experience in recent years up to 2021.
- The output represents efficient preliminary investigation, project development, project management, competitive tendering, site management and contractual arrangements.

4.2 Parsons Brinkerhoff's Transmission Costing Study Report (UK)

This report was completed in 2012 and is published on the Institution of Engineering and Technology (UK) website[7]. Although actual costs quoted in the PB report have escalated since publication, the report is referenced by UK TNSP—National Grid in current publications[8] and the principles and methodology, and findings of the report are still considered relevant today.

The report focussed on the *"build costs"* and *"ongoing operational costs including maintenance and losses"* for 400kV infrastructure. Social and environmental costs associated with transmission were not evaluated in the study.

Comparison Costing Model—The costing model for the study considered the following:

- Lifetime costs were evaluated using the net present value of "Build" and "Operating Costs".
- A 40-year life was assumed for all technologies and a discount rate of 6.25%.
- Cost estimates for 3km, 15km, and 75km route lengths were prepared.
- For each route length option double circuit lines for low (3190 MVA), medium (6389 MVA) and high (6930 MVA) power transfer options were evaluated.
- Cost sensitivities to variable assumptions were presented.

The cost breakdown structure used for costing study is summarised in the table below.

A summary of the costs per km and ratio of options compared to an overhead line from this study is provided in Table 4. Cost ratios of the underground options compared to overhead varied from 4.6 to 14.2 depending on the line route length, power transfer capacity and type of underground system.

The HVDC options in this study only considered subsea cables of 2 different AC/DC converter technologies. Land based HVDC lines were not considered in this study.

[7] https://www.theiet.org/impact-society/factfiles/energy-factfiles/energy-generation-and-policy/electricity-transmission-costing/.
[8] https://www.nationalgrid.com/sites/default/files/documents/39111-Undergrounding_high_voltage_electricity_transmission_lines_The_technical_issues_INT.pdf.

Table 3. Cost Breakdown Structure adapted from Electricity Transmission Costing Study (2012) [1]

Phase Cost Categories	Cost Components / Factors	
	HVAC Overhead	HVAC Underground
Fixed Build Costs	Mobilisation extras	Cable terminal compound Cable terminations and testing
Variable Build Costs	Foundations Tower materials Conductors + OPGW Access roads total Insulators + fittings materials Erection of towers + stringing Engineering & safety Project launch + mgmt. (10%) Build contingency (10%)	Special constructions (6.4%) Special constructions (6.4%)—£1.6m Build contingency (15%)—£3.7m On route cable system materials—£6.3m On route cable installation—£11.5m Reactor costs—£1.0m Project launch + mgmt. (20%)
Variable Operating Costs	Cost of power losses (power stations) Cost of energy losses (fuel) Operation & maintenance	Cost of power losses (power stations) Cost of energy losses (fuel) Operation & maintenance

Table 4. Cost Comparison Table for 400kV Transmission Lines, adapted from Electricity Transmission Costing Study (2012) [1]

Transmission Line Parameters		Overhead	Underground - Direct Buried		Underground - Tunnel		HVDC +/-400kV DC (LCC)[1]		HVDC +/- 320kV DC (VSC)[2]	
Length (km)	Power Capacity (MVA	Cost (GB £-Million/ km)	Cost (GB £-Million/ km)	Ratio cf. Overhead	Cost (GB £-Million/ km)	Ratio cf. Overhead	Cost (GB £-Million/ km)	Ratio cf. Overhead	Cost (GB £-Million/ km)	Ratio cf. Overhead
3	3190	2.4	12.8	5.3	34.0	14.2				
3	6380	4.2	22.6	5.4	42.3	10.1				
3	6930	4.2	24.0	5.7	43.0	10.2				
15	3190	2.3	10.6	4.6	22.4	9.7				
15	6380	4.1	19.4	4.7	29.6	7.2				
15	6930	4.1	20.8	5.1	30.3	7.4				
75	3190	2.2	10.3	4.7	20.5	9.3	13.4	6.1	16.4	7.5
75	6380	4.0	18.9	4.7	27.5	6.9	22.0	5.5	31.9	8.0
75	6930	4.0	20.3	5.1	28.2	7.1				

1 HVDC sub-sea cable using Line Commutated Converters
2 HVDC subsea cable using Voltage Source Converters

Cost sensitivities were evaluated in the study. Using the example of a 15km high-capacity transmission line comparing direct buried underground cable to an overhead line a cost sensitivity analysis is shown in Figure 2. From these results it is noted that:

(a) The lifetime cost of overhead is most sensitive to 2 main factors:

- the assumption of average circuit loading which determines the losses component of operating costs;
- actual route length variations.

(b) The lifetime cost of direct buried underground is most sensitive to 4 main factors:

- actual route length variations;
- cable installation base costs;
- terrain (urban vs rural);
- cable system material base costs.

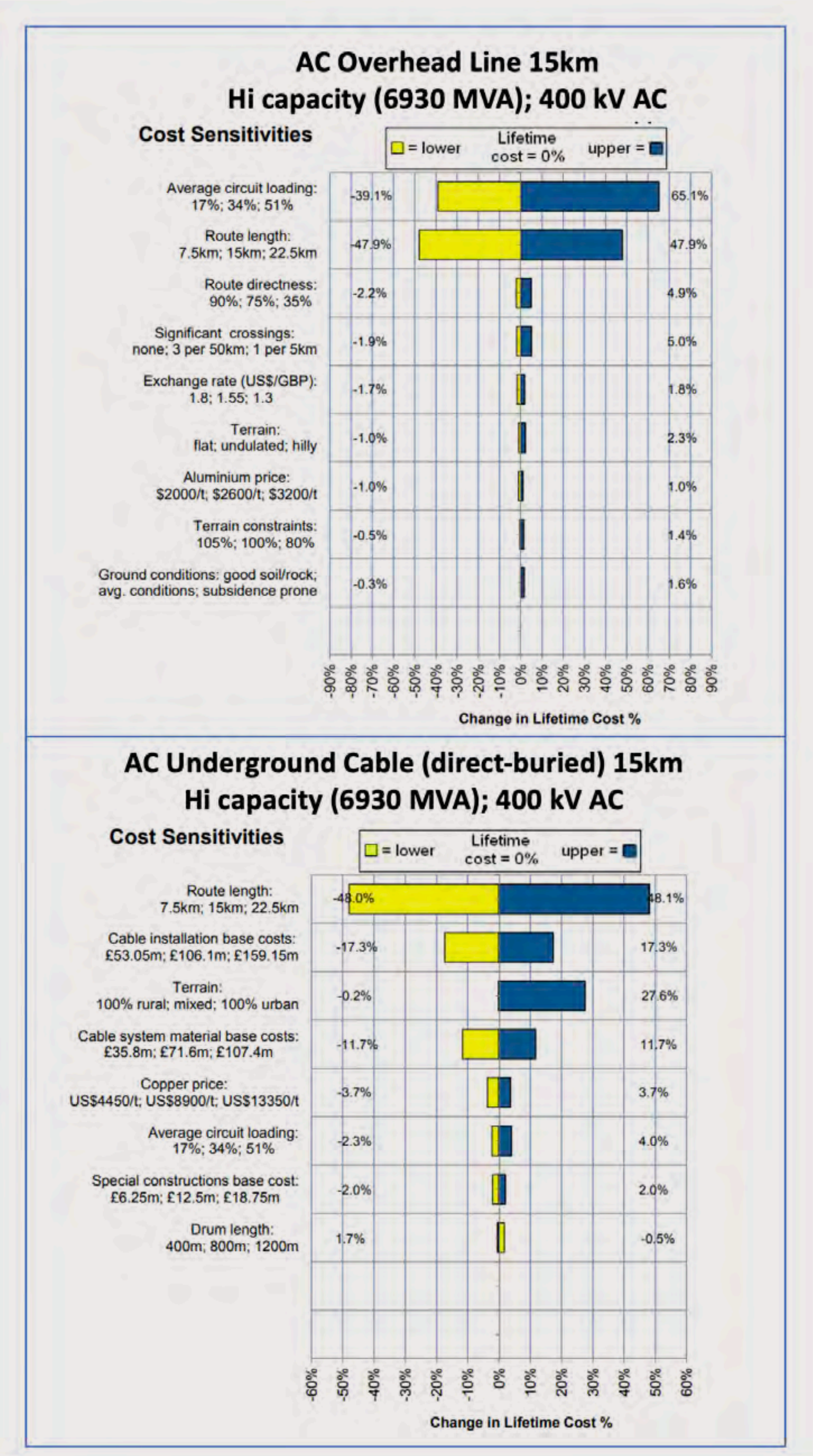

Figure 2. Cost Sensitivities for 400kV AC Direct Buried Underground Compared To Overhead Transmission Line (Electricity Transmission Costing Study (2012) [1])

For ease of reference, we have inserted the summary of relevant findings of this study below [1, p. viii]:

- *"No one technology can cover, or is appropriate in, every circumstance, and thus financial cost cannot be used as the only factor in the choice of one technology over another in a given application.*
- *Costs per kilometre, for all technologies, tend to fall with increasing route length, and tend to rise with circuit capacity.*
- *For typical National Grid system circuit loadings, the inclusion of operating costs in the technology comparisons does not significantly affect the overall differences in cost between the technologies. However, they do affect the cost ratios considerably, rendering the ratios a misleading measure when making investment decisions.*
- *Overhead line (OHL) is the cheapest transmission technology for any given route length or circuit capacity, with the lifetime cost estimates varying between £2.2m and £4.2m per kilometre; however, OHL losses are the most sensitive to circuit loading.*
- *Underground cable (UGC), direct buried, is the next cheapest technology after overhead line, for any given route length or circuit capacity. It thus also represents the least expensive underground technology, with the lifetime cost estimates varying between £10.2m and £24.1m per kilometre.*
- *For the options using a deep tunnel, the largest single cost element is invariably the tunnel itself, with costs per kilometre ranging from £12.9m to £23.9m per kilometre, depending upon overall tunnel length.*
- *The 75km high voltage direct current (HVDC) connections are estimated to cost between £13.4m and £31.8m per km and are thus more expensive than the equivalent overhead or direct buried transmission options. However, long HVDC connections are proportionally more efficient than short connections.*

We also offer two notes of caution:

- *Cost ratios are volatile, and no single cost ratio comparing overhead line costs with those of another technology adequately conveys the costs of the different technologies on a given project. Use of financial cost comparisons, rather than cost ratios, are thus recommended when making investment decisions.*
- *The transmission technologies may not all be able to use the same route as each other, so circuit lengths may vary between technologies for a given application. We therefore recommend that actual practicable routes be identified when comparing total lifetime costs of each technology for specific investment decisions."*

4.3 Industry Cost Estimation Practices

Transmission Network Service Providers project cost estimation practices are characterised as follows (based on Authors' industry experience):

- The standard building block cost estimates are based on recent projects where the design experience and construction practices are well known and involve the application of the organisations design and construction standards.
- The cost estimates are refined as a project progresses through its life cycle, consistent with the Association for Advancement of Cost Engineering (AACE) International classification system for estimates.
- If the transmission projects involve new structures, new line components and new construction practices need to be employed, then costs are escalated for example by 50% of the standard cost estimate.
- Budget cost estimates are usually obtained from preferred manufacturers, suppliers, and contractors in the planning phase before formal procurement for the project is initiated.

For an overhead transmission line, significant cost increases will be incurred if the new project involves new structures and technologies such as:

- New higher strength and height structures that incur finite element designs and structural testing will incur related costs.
- New conductor designs (e.g. high temperature, larger size, additional bundles) may require stress—strain, and creep tests to derive the relevant design parameters and new fittings for the conductor.
- New insulator assemblies (e.g. pivoting horizontal vee assemblies) will require finite element analysis and combined loading assessment.
- New construction practices (e.g. stringing, jointing and terminating conductors) may be required for the conductors and associated fittings.

Similarly for an underground transmission line, significant cost increases will be incurred if the project involves new cable technologies as follows:

- New cable design (increase in conductor size, change in insulation type, change in insulation thickness, inclusion of fibre optic cable in core) will require a desk top design analysis.
- New cable designs will also require special witness testing, during manufacture, and during type and routine testing.
- New cable designs may require new joints and terminations to be developed.
- New cable designs may also require changes to construction practices (e.g. increase cable pulling, reduction on cable radius, jointing and terminating cables).

5.

Cost Comparison – Overhead and Underground Cable Transmission Lines

This section provides an overview of the cost elements and estimated costs for Australian projects based on current NEM information and recent consultation with industry parties currently involved in transmission line projects. The costs quoted are only for general comparison purposes between overhead and underground technologies and should not be applied to specific projects.

Cost estimates and economics for HVDC options are not within the scope of this report, however comments relative to HVAC options have been included based on references.

5.1 Capital Investment Costs

The cost elements, variable factors and risks associated with capital or investment costs for a transmission line project are summarised in the table below.

HVDC Transmission generally becomes more economic for longer route interconnector transmission lines.

HVDC overhead and underground lines are generally lower cost per km to construct compared to equivalent rated HVAC, but the significant costs of AC/DC converter terminal stations must be included in the total project cost. There is a "break even distance" for the cost of HVDC versus HVAC transmission. This is illustrated in the diagram by Stan et al., in Figure 5 [4]. The "break even distance" will depend on project specific parameters such as power transfer capacity, number of circuits, system voltage, converter technology, installation conditions and environmental factors

Some economic, environmental, and social advantages are that HVDC line corridor width for overhead and underground can be reduced significantly, reducing the cost of those components of the capital costs not to mention reducing overall impacts on communities and individual landholders.

Table 5. Capital Investment Cost Elements, Factors and General Comparative Cost Estimates

Cost Elements	Variable Factors and Risks impacting on Costs	HVAC Overhead Transmission Line	HVAC Underground Transmission Line
Planning Social licence—consultation and engagement. Design and survey Approvals Environmental offsets Property—easements, right of way, landholder payments Procurement of plant and materials Construction (civil, structural, electrical) Commissioning Indirect / overhead costs	Route length Voltage Power transfer capacity Single vs double circuit Location (e.g. Urban, Rural) Topography Geotechnical Land—cost and payments Environmental Social and community sensitivities Resource market (labour, materials) Workplace health and safety Delivery model Approval delays	Indicative costs for double circuit OHTL, route 50–100km, excluding property and environmental offsets: 275kV: $2M to $3M per km •500kV: $5M to $6M per km	Indicative costs for double circuit UGTL typical 40km length excluding property and environmental offsets: 275kV: $10 to $15M per km 500kV: $25M to $30M Million per km

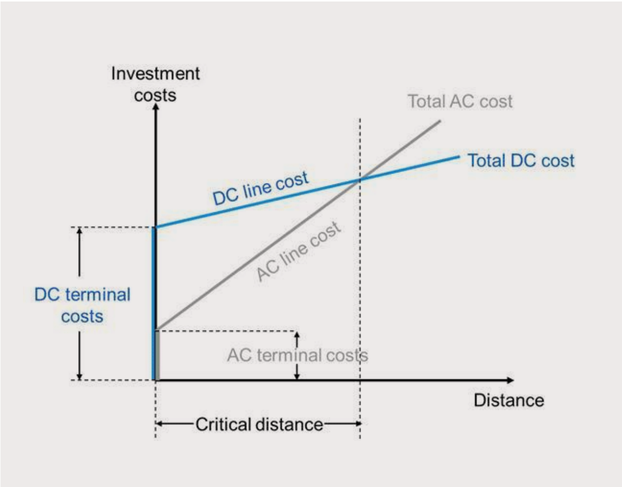

Figure 3. HVDC Transmission Line Economics (Stan et al [4])

HVDC Transmission generally becomes more economic for longer route interconnector transmission lines. HVDC overhead and underground lines are generally lower cost per km to construct compared to equivalent rated HVAC, but the significant costs of AC/DC converter terminal stations must be included in the total project cost. There is a "break even distance" for the cost of HVDC versus HVAC transmission.
This is illustrated in the diagram by Stan et al., in Figure 3 [4]. The "break even distance" will depend on project specific parameters such as power transfer capacity, number of circuits, system voltage, converter technology, installation conditions and environmental factors.

Some economic, environmental, and social advantages are that HVDC line corridor width for overhead and underground can be reduced significantly, reducing the cost of those components of the capital costs not to mention reducing overall impacts on communities and individual landholders.

HVDC and HVAC overhead and break-even point examples:

Break even distances for the cost of HVDC versus HVAC overhead have been estimated from data available from references (see Table 6). These estimates suggest it is in the range of 600km to 700km.

Acaroğlu et al [5], reported a cost ratio for HVDC underground to HVDC overhead of around 5, and a cost ratio for HVDC underground to HVAC overhead of 3.3 for a 1500MW, 1000km case study. The Suedlink 2 x 2000MW 700km underground HVDC project in Germany is currently estimated to cost €11B ($18.3B AUD). This is equivalent to around $26.1M AUD per km.

The economic feasibility for application of HVDC compared to HVAC, ultimately depends on project specific requirements, factors and constraints which determine whether HVDC should be considered. Regulatory investment test requirements also need to be satisfied.

Table 6. Comparison of HVDC Break-Even Distances Using Data from Different Sources

Data Source	System	Break-even distance HVDC vs HVAC overhead	Cost ratio HVDC Underground vs HVAC Overhead
Acaroğlu et al [5]	1500 MW, +/- 320kV HVDC	650 km	4.6
Weimers, ABB Power Technologies [6]	3500 MW, +/- 500kV HVDC	600 km	Not available
Australian references - AEMO cost database and "Western Victorian Transmission Network Project—High Level HVDC Alternative Scoping Report"[7]	2500MW, +/- 525 kV HVDC	615 km	4.0

5.2 Maintenance Costs

A summary of typical transmission line maintenance cost elements is provided in the table below.

The literature review reported a finding that the factors which impact the O&M costs are age of the line, weather conditions and length of the line. In [9], the O&M costs are assumed as 1.5% and 0.15% of capital investment cost for OHTL and UGTL respectively.

HVDC Transmission - Maintenance requirements for overhead and underground line components of HVDC are expected to be similar of HVAC overhead and underground. However, the additional maintenance requirements associated with AC/DC converter stations would be significant resulting in overall higher lifetime maintenance requirements.

Table 7. Summary of Transmission Line Maintenance Cost Elements

Cost Element	HVAC Overhead Transmission Line	HVAC Underground Transmission Line
Planned Maintenance Patrols and Inspections Testing Replacement of components Vegetation maintenance Access track maintenance	**Indicative costs:** 0.5 to 1% of capital cost per km per annum for up to 20 years. 1 to 2% of capital cost per km per annum during mid life. 5 to 10% of capital costs for mid-life replacement of certain line components (e.g., insulators).	**Indicative costs:** Expenditure per km per annum is typically around 40% of comparative overhead line but can be similar if the patrol specification and frequency of patrols is frequent.
Unplanned Maintenance Unreliability—forced outages Corrective maintenance and repairs	**Includes cost of:** Responding to forced outages, and repairs to damaged or faulty components e.g., conductors, insulators, supporting structure Minor repairs —performed with live line techniques so no outage or loss of supply time. Major repairs—require a circuit outage, but typically there is no loss of supply due to redundancy planning requirements (N-1 criteria)	**Includes cost of:** Responding to forced outages, and repairs to damaged or faulty components e.g joints, terminations, cable dig-in damage by 3rd party Repairs to damaged cable, replacement of faulty cable joints and terminations require a circuit outage but typically there is no loss of supply due to redundancy planning requirements (N-1 criteria).
Indicative Total Operating and Maintenance Costs [9] **(Excluding losses)**	Around 1.5% of Capital Investment Cost.	Around 0.15% of Capital Investment Cost.

5.3 Operating Costs - Energy Losses

Energy Losses refers to energy lost as heat to the atmosphere from conductors and other components of a HV transmission system. The main causes of losses in transmission lines are:

(1) Conductor losses are the largest source of transmission losses and are due to current flow in a conductor and the resistance of the conductors. For a 3 phase (wire) system power loss due to current flow in a conductor is derived from Ohm's Law.

PL = 3 x I^2 x R where:

PL = Losses in Watts;

I = current flowing in each of the three conductors in Amps;

R = Resistance of the conductor in Ohms (R is proportional to the length of the line).)

Resistive power losses can also be caused by "**skin effect**" which is additional resistance due to the tendency of more current to flow near the outer surface of a conductor.

(2) Dielectric losses result when an AC electric field interacts with a dielectric material such as insulation causing energy heat loss in the dielectric. Dielectric losses do not occur in HVDC lines under normal operating condition.

(3) Corona Losses—can occur in HV overhead lines when the ionization of air molecules in the vicinity of high-voltage conductors occurs due to the presence of a strong electric field (above the critical surface voltage gradient) and leads to the generation of charged particles (electrons and positive ions). These charged particles move and collide with other air molecules, causing energy dissipation through several mechanisms, including resistive effects. HVDC lines generally have very minimal corona losses due to lower electric field strengths.

(4) Inductive losses occur when transmission lines induce current in nearby conductors or metallic objects. This includes the metallic sheaths of cables. Generally, these losses are minimised by earth bonding arrangements.

In whole of life costing analysis typically only conductor losses are evaluated as the other losses are usually insignificant in comparison. Losses in other system components such as AC/DC converters required for HVDC systems are significant and must be included.

The **Cost of Energy Losses** is the sum of two components:

(1) Annual cost of energy losses is the cost of the energy (MWh) lost from the transmission line over a year.

Annual cost of energy losses = Energy lost per annum (MWh) X Energy Cost ($/MWh)

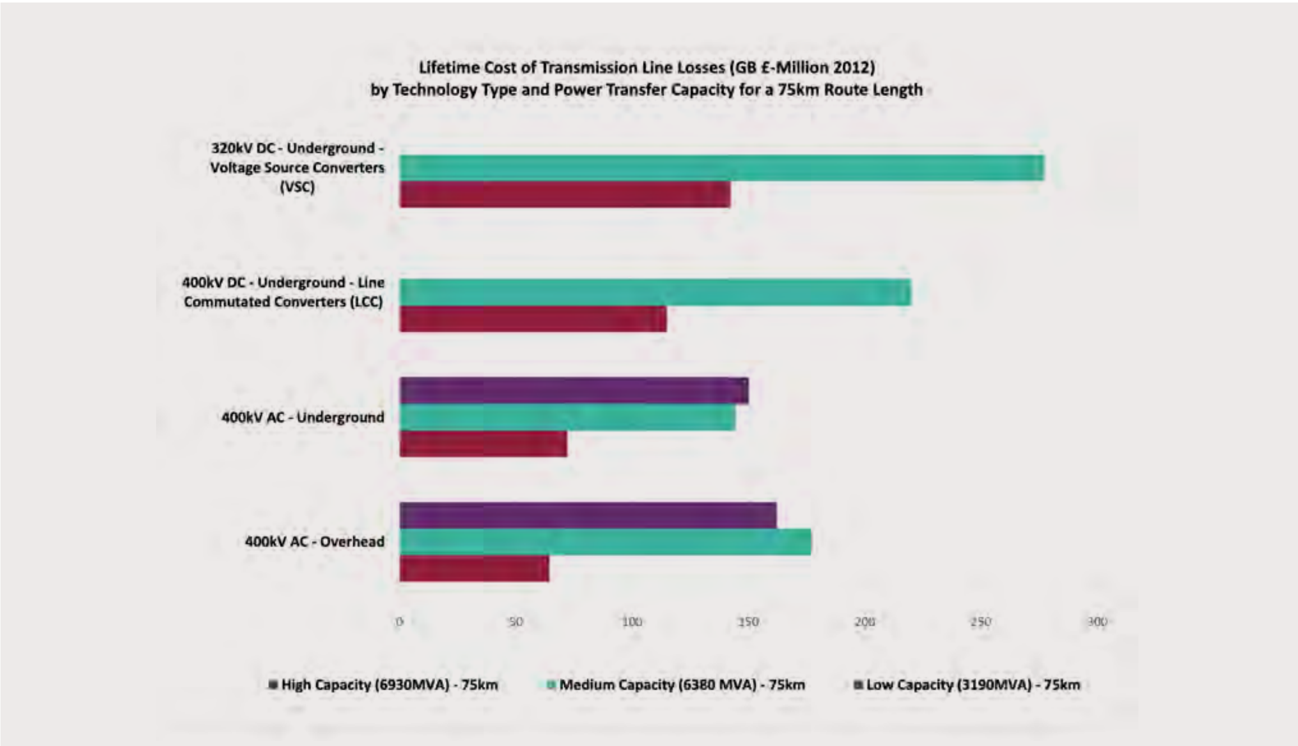

Figure 4. Comparison of Lifetime Cost of Losses, Adapted from Transmission Costing Study (2012) [1].

The energy lost per annum is calculated by assuming an average load flowing the line over a year to determine the losses.

(2) Peak Power Loss Cost ($/MW) is the cost to supply the peak losses (MW) that occur when the transmission line is carrying its peak load in each period (e.g. year).. This represents the amount of additional generation capacity that must be available just to supply peak losses. *Peak Power Loss Cost = Peak Power Loss (MW) X Power Demand Charge ($/MW)*

The above is a simplified explanation, but actual calculations involve sub-calculations to determine annual average and peak loads for the transmission line. The cost of losses is then evaluated on Net Present Value basis over the assumed life span of the transmission line with year-by-year changes due to demand growth or other events.

The graph in Figure 4 provides a comparison of losses for HVAC and HVDC overhead and underground transmission lines using data from the PB Transmission Costing Study (2012).

For HVDC transmission systems, losses in the AC/DC converters can account for up to 50% or more of total lifetime losses.

An example of a net present value calculation of losses over 20 years for an overhead and underground transmission lines with the same loading is provided in *Table 8. Net Present Value calculation of energy losses—OHTL and UGTL comparison* below. In this example the cost of losses for overhead line is about twice that of the underground line.

The difference in cost of losses largely depend on the conductor size selection for the line. While OHTL are generally designed for load factors less than 0.5 (N-1 planning criteria), UGTL may be required to operate at higher load factors (because of the highest cross section cable employed—other measures used to bring load back to rating under contingencies). If losses for the overhead transmission are considered significant, the overhead conductors can be oversized at a modest cost for the losses to be in a similar range to the underground transmission.

5.4 End of Life Costs

A summary of the considerations and costs at end of life is provided in the table below. Generally, end of life costs are considered insignificant in the lifetime costing based on NPV, unless there is a known requirement for the lifespan of the transmission line.

HVDC Transmission - end of life costs are expected to be like HVAC overhead or underground respectively. Easement corridors would be typically much narrower resulting in lower costs for that element. However, converter station decommissioning recovery would be an additional cost element.

5.5 Lifetime Costs

Lifetime costs are evaluated as a net present value (NPV) of the costs described in the preceding sections, i.e.:

1. capital investment cost;
2. operating and maintenance cost per annum;
3. cost of energy losses per annum with annual load growth factor applied;
4. end of life cost.

Key assumptions included in the NPV calculation are:

- expected asset life span, e.g., OHTLs—60 years, UGTLs—40 years;
- financial discount rate or internal rate of return, e.g., 5 to 6%.

Worked examples of lifetime costs for 275kV overhead and underground transmission lines are shown in Table 10. In this example the ratio of initial capital expenditure when comparing underground to overhead was 5, but over a 40-year period the ratio reduced to 2.9.

The literature review reported that it has been observed that the life cycle costs of underground transmission lines (UGTL) are significantly higher compared to overhead lines, primarily due to the high capital costs associated with underground installations. Overall, the life cycle costs of UGTL are two to six times more than OHTL [9].

Table 8. Net Present Value calculation of energy losses—OHTL and UGTL comparison

Cost of Losses for Single Circuit Overhead Transmission Line

Input Data:			
Load growth factor p.a.	1.02		
Cost of Energy (cents/kWh)	7.5		
Cost of Gen Plant ($/KW)	1000		
DC Resistance of Conductor (ohms/ km at 20 deg C)	0.0180	Thermal coeff =	0.00368
AC Resistance of Cable (ohms/km at 35 deg C)	0.0196	Rac/Rdc =	1.03
Length of Line (km)	1		
Load Factor	0.4		
Discount Rate	0.05		

Year	**1**	**2**	**3**	**4**	**5**	**...**	**20**	**NPV Totals**
Load (A) =	600	612.00	624.24	636.72	649.46		874.09	
Energy Loss (kW)	4	5	5	5	5		9	
Annual Energy Losses (kWhr)	38498	40053	41671	43355	45106		81704	
Cost of Energy Losses ($)	$2,887	$3,004	$3,125	$3,252	$3,383		$6,128	
PV of Energy Losses ($)	$2,750	$2,725	$2,700	$2,675	$2,651		$2,309	$50,472
Demand Cost	$21,128	$21,982	$22,870	$23,794	$24,755		$44,841	
PV of Demand Cost	$20,122	$19,938	$19,756	$19,575	$19,396		$16,900	$369,337
								$419,809

Assumptions:
Cost of Energy based on renewables in range of $50 to $100 per MWh
Cost of Generation based on $1000 M for 1000 MW plant
Conductor resistance based on Sulphur 61/3.75 AAAC conductor (673 mm2) = .0511 ohms/km

Cost of Losses for Single Circuit Underground Cable (Cross bonded System)

Input Data:			
Load growth factor p.a.	1.02		
Cost of Energy (cents/kWh)	7.5		
Cost of Gen Plant ($/kW)	1000		
DC Resistance of Cable (ohms/ km at 20 deg C)	0.009	Thermal coeff =	0.00368
(ohms/ km at 20 deg C)		Rac/Rdc =	1.03
AC Resistance of Cable (ohms/km at 35 deg C)	0.009782		
Length of Cable (km)	1		
Load Factor	0.4		
Discount Rate	0.05		

Year	**1**	**2**	**3**	**4**	**5**	**...**	**20**	**NPV Totals**
Load (A) =	600	612.00	624.24	636.72	649.46		874.09	
Energy Loss (kW)	2	2	2	2	3		5	
Annual Energy Losses (kWhr)	19249	20027	20836	21677	22553		40852	
Cost of Energy Losses ($)	$1,444	$1,502	$1,563	$1,626	$1,691		$3,064	
PV of Energy Losses ($)	$1,375	$1,362	$1,350	$1,338	$1,325		$1,155	$25,236
Demand Cost	$10,564	$10,991	$11,435	$11,897	$12,378		$22,420	
PV of Demand Cost	$10,061	$9,969	$9,878	$9,788	$9,698		$8,450	$184,669
								$209,905
							OHTL / UGTL Cost of Losses Ratio	**2.0**

Assumptions:
Cost of Energy based on renewables in range of $50 to $100 per MWh
Cost of Generation based on $1000 M for 1000 MW plant
Cable resistance based on 2000 mm2 copper = .009 ohms/km

Table 9. Summary of Transmission Line End of Life Cost Elements

Cost Element	HVAC Overhead Transmission Line	HVAC Underground Transmission Line
Decommissioning Disconnection Recovery and Assets Scrap value if applicable. Land remediation	Dependent on the line materials and scrap value of components (conductors and steel tower members) Indicative costs: Can be in range of 30 to 40% of cost of building a new line. However, on a PV basis over a life of 70+ years for the overhead line, the costs are considered insignificant.	Cable typically left in ground unless specific environmental requirements. Above ground accessories, terminations and equipment recovered and scrapped. Cable can be removed from ducts or tunnels if required. Indicative costs: Very low cost unless cable needs to be removed from ground.

Table 10. Lifetime Cost Example - 275kV OHTL and 275kV UGTL Comparison

	Annual Costs	Years						NPV Totals
		0	1	...	40	...	60	
DOUBLE CIRCUIT 275 KV OVERHEAD								
Initial Planning, Easements Acquisition and Design Costs		$300,000						$ 300,000
Materials and Construction Cost		$1,700,000						$ 1,700,000
Preventative Maintenance Cost p.a.	$20,000		$20,000		$20,000		$20,000	$ 1,200,000
Recovery Cost					$100,000		$800,000	$ 900,000
Losses			$17,400		$17,400		$17,400	$ 1,044,000
Reliability Differential			$27,500		$27,500		$27,500	$ 1,650,000
Present Value (PV) of Costs at 60 years		$2,000,000	**$63,119**		**$47,017**		**$72,331**	**$ 4,414,988**
Present Value (PV) of Costs at 40 years								**$ 3,755,954**
Note: Expected life of 60 years								
DOUBLE CIRCUIT 275 KV UNDERGROUND								
Initial Planning, Easements Acquisition and Design Costs		$500,000						$ 500,000
Materials and Construction Cost		$9,500,000						$ 9,500,000
Preventative Maintenance Cost p.a.	$50,000		$50,000		$50,000			$ 2,000,000
Recovery Cost					$500,000			$ 500,000
Losses			$8,400		$8,400			$ 336,000
Present Value (PV) of Costs		$10,000,000	**$55,619**		**$79,318**			**$ 11,073,113**
Note: Expected life of 40 years								
Results:								
Ratio UGTL to OHTL Initial Capital Costs =	**5.0**							
Ratio UGTL to OHTL Total Costs at 40 yrs =	**2.9**							
Assumptions								
Internal Rate of Return	5.0%							

6.

Australian Market Trends—What will affect Delivery of Transmission Infrastructure Projects

Key Challenges—Infrastructure projects in Australia are facing challenging times because of global and national economic factors. Infrastructure Australia's Infrastructure Market Capacity 2020 Report [10] reported key challenges as:

- Demand driven risks have increased over the last 12 months ($15B of new projects in 1 year).
- Supply side risks have surged in 2021–22 (effects of COVID-19, Ukraine War, labour shortages).
- Increasing project costs and complexities, plus truncated risk allocation and planning practices are driving insolvencies and consolidation, thus threatening capacity.
- The market is arguably at capacity, so project slippage is now expected.
- Construction sector multifactor productivity has stagnated for 30 years.

Workforce Demand—A joint report by the Institute for Sustainable Futures, University of Technology Sydney (ISF) in collaboration with AEMO [11] was undertaken to support the 2020 AEMO Integrated System Plan. The study developed workforce projections for different growth scenarios. The projection for the mid-range scenario is shown in Figure 5. Although transmission represents only a small segment of the market, competition from other segments for the same type of resources will occur, particularly for the largest category of labour—trades and technicians.

Cost Projections—AEMO have presented cost projections for transmission infrastructure in the Draft 2023 Transmission Expansion Options Report [2] as illustrated in Figure 6.

AEMO also stated in the report: "This cost forecast does not address the future cost of biodiversity offsets, as AEMO's position is to address this through operational expenditure given the nature of jurisdictional schemes."

The large projected increases in easement and property costs reflects increased landowner payment schemes which provide payments of around $200,000/km in New South Wales and Victoria and $300,000/km in Queensland[9].

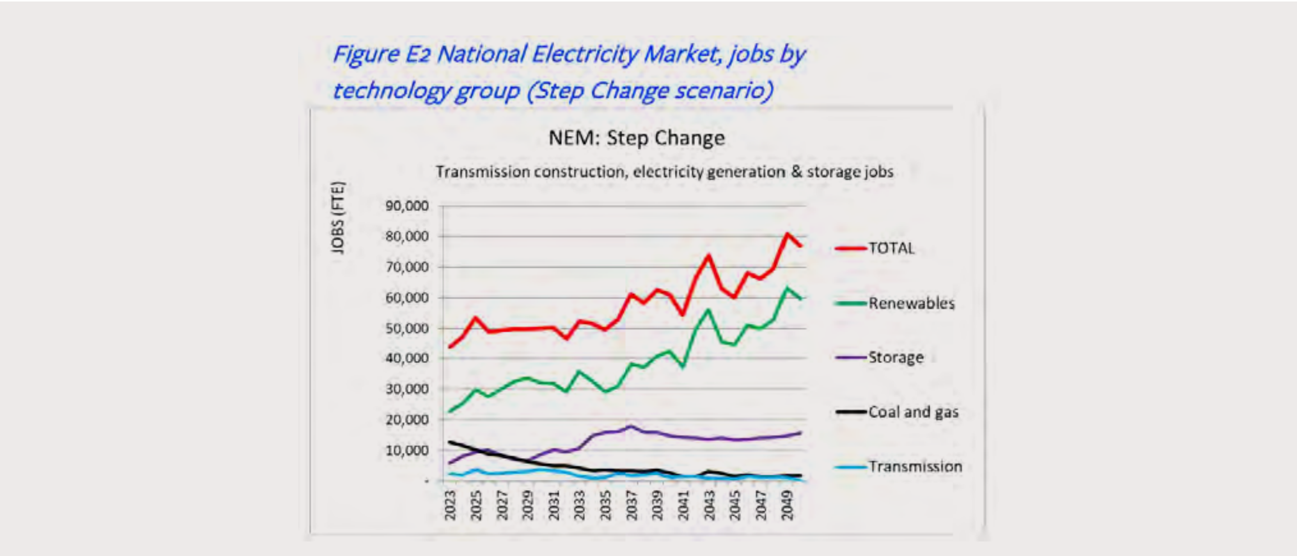

Figure 5. Projections for Jobs by Technology Group in Australian NEM (Rutovitz et al [11, p. 5])

[9] https://reneweconomy.com.au/landowners-set-for-huge-windfall-as-queensland-accelerates-its-supergrid-transition/

Project Timeframes—Delays in delivery of transmission infrastructure is now considered to be one of the biggest challenges in meeting renewable energy targets. Apart from supply chain and workforce constraints and increasing costs—approvals and community opposition is delaying many projects. Gaining community acceptance or social licence has become critical for major transmission projects. There has been much commentary in recent media on this topic[10 11].

Undergrounding of transmission lines has become a significant issue in stakeholder and community engagement as evidenced in current Australian NEM projects (i.e., Humelink, Western Renewables Link) and overseas, as presented in the case studies in this report. HVDC is also being seen as a feasible alternative to AC transmission.

Figure 6. Projected Cost Increases for Transmission Infrastructure (AEMO [2, p. 38])

[10] https://reneweconomy.com.au/broken-regulations-not-community-opposition-are-delaying-transmission/.
[11] The Australian, June 9, 2023—Transmission line delays are putting a handbrake on renewable electricity supply.

7.

Conclusions

7.1 Key Findings

1. It is difficult to get accurate cost estimates for 500kV transmission infrastructure in Australia due to the lack of recent projects at this voltage, current global and local economic factors influencing the cost and availability of resources.
2. There have been many studies by government bodies, TNSP's, industry organisations and stakeholders comparing the cost of overhead and underground cable transmission either generally or for a specific project. Based on published literature including Parsons Brinkerhoff [1] and AEMO [2], the ratios are generally in the range of 3 to 20 depending upon type of construction, route length and other project specific factors. The Parson Brinkerhoff transmission costing study from the UK is often referred to by industry for its methodology for evaluating lifetime costs. This study concluded "Cost ratios are volatile, ... Use of financial cost comparisons, rather than cost ratios, are thus recommended when making investment decisions." A lower cost ratio of 3 to 5, for example would tend to apply for the lowest cost option of direct buried underground, or long cable routes (with better economies of scale). A ratio of 5 to 10 would correspond to higher cost options of cable in ducts or for shorter lengths of underground cable. A higher ratio of 10 to 20 would tend to apply to more expensive cable tunnel installations.
3. HVDC Transmission generally becomes more economic for longer route interconnector transmission lines due to the high costs of AC/DC converter terminal stations that need to be included in HVDC projects. There is a "break even distance "for the cost of HVDC versus HVAC transmission. As an indication, based on data from Acaroğlu et al [5], ABB [6], Amplitude Consultants [7], and the AEMO Transmission Cost Database, the break-even cost for HVDC overhead transmission is around at a route length of around 600 to 700 km when compared to an 500kV HVAC line. The cost ratio of HVDC underground to HVDC overhead is around 5, and the cost ratio of HVDC underground to HVAC overhead was 3.3 for a 1500MW, 1000km case study [5].
4. There is no doubt that transmission infrastructure projects are facing several challenges because of global and national factors. Reports published by Infrastructure Australia [10] and AEMO [11] highlight challenges such as:
   - Demand driven risks have increased over the last 12 months.
   - Supply side risks have surged in 2021-22 (COVID-19, Ukraine War, labour shortages)
   - Increasing project costs and complexities
   - The market is arguably at capacity, so project slippage is now expected.
   - Availability of skilled labour resources in the energy industry
   - Internationally, many countries have similar large scale grid expansion programs linked to renewable energy targets and requiring the same material and labour resources.
   - Delays in gaining approvals due to social licence issues and other factors tend to exacerbate the cost challenges.

7.2 Comparison Table – Economic Factors of HV Transmission Infrastructure

A summary comparing the economic factors of overhead and underground infrastructure is presented in Table 11 below.

Table 11. Comparison of HV Overhead and Underground Cable Transmission Lines

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Under-ground
	Technical Factors - System Design, Installation and Performance				
1	**Capital Investment Costs:** Planning Social licence - consultation and engagement. Design and survey Approvals Environmental offsets Property – easements, right of way, landholder payments Procurement of plant and materials Construction (civil, structural, electrical) Commissioning Indirect costs (overheads)	Indicative costs for double circuit OHTL, route 50-100km, including project construction (materials, labour and plant) and excluding property and environmental offsets: 275 kV: $2M to $3M per km 500 kV: $5M to $6M per km	Indicative costs for double circuit UGTL typical 40 km length including project construction (materials, labour and plant) and excluding property and environmental offsets: 275 kV: $10 M to $15M per km 500 kV: $25M to $30M per km	Project costs were not in the scope of this study. "Break even" distance for HVDC overhead comparted to HVAC overhead is around 600 to 650km for EHV.	
2	**Operating and Maintenance:** Planned maintenance. Corrective maintenance Unplanned maintenance	**Indicative costs:** 0.5 to 1% of capital cost per km per annum for up to 20 years. 1 to 2% of capital cost per km per annum during mid life 5 to 10% of capital costs for mid-life replacement of certain line components (e.g., insulators).	**Indicative costs:** Expenditure per km per annum is typically around 40% of comparative overhead line but can be similar if the patrol specification and frequency of patrols is frequent.	HVDC Transmission lines – Maintenance requirements for overhead and underground line components are expected to be similar to HVAC overhead and underground. However, the additional maintenance requirements associated with AC/DC converter stations would be significant resulting in overall higher lifetime maintenance requirements.	
3	**Operating - Energy Losses**	Cost of losses depend on conductor size selection. Typically, overhead lines losses can be 1.5 to 2.5 times greater than an equivalent underground line.	Cost of losses depend on conductor size selection. Typically, underground cable losses will be less than an equivalent overhead line. Reactive compensation losses need to be considered for longer route lengths (e.g., > 10km).	Losses for HVDC systems can be up to twice that of the equivalent HVAC overhead or underground system due to the additional losses from the AC/DC converter.	
4	**Lifetime Cost:** Net Present Value (NPV) of: Capital Investment cost. Operating and Maintenance costs over life Cost of energy losses with annual load growth factor applied over life. End of life cost (not significant) Key assumptions included in the NPV calculation are: Expected asset life span e.g., OHTLs – 60 years, UGTLs – 40 years. Financial discount rate or internal rate of return e.g., 5 to 6%	275 kV OHTL PV costs at 40 years indicates the following: $3.76 M (Initial cost of $2 M + $1.76 M for maintenance and operating costs (losses and unreliability). It should be noted that 40 years is typically only half the life of an overhead line.	275 kV UGTL PV costs at 40 years indicates the following: $11.1 M (Initial cost of $10 M + $1.0M of maintenance It should be noted that 40 years is typically only 70% life of underground transmission line. The UGTL to OHTL lifetime cost ratio at 40 years is around 2.9. Lifetime costs have been performed for 275 kV transmission (because parameters for OHTL and UGTL were known). It is expected that the UGTL to OHTL lifetime cost ratio for a 500 kV line at 40 years would be similar to 275 kV transmission.	Not in scope of this study.	

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SEPTEMBER 2023

5.

Environmental Aspects

Comparing high voltage overhead and underground transmission infrastructure (up to 500 kV)

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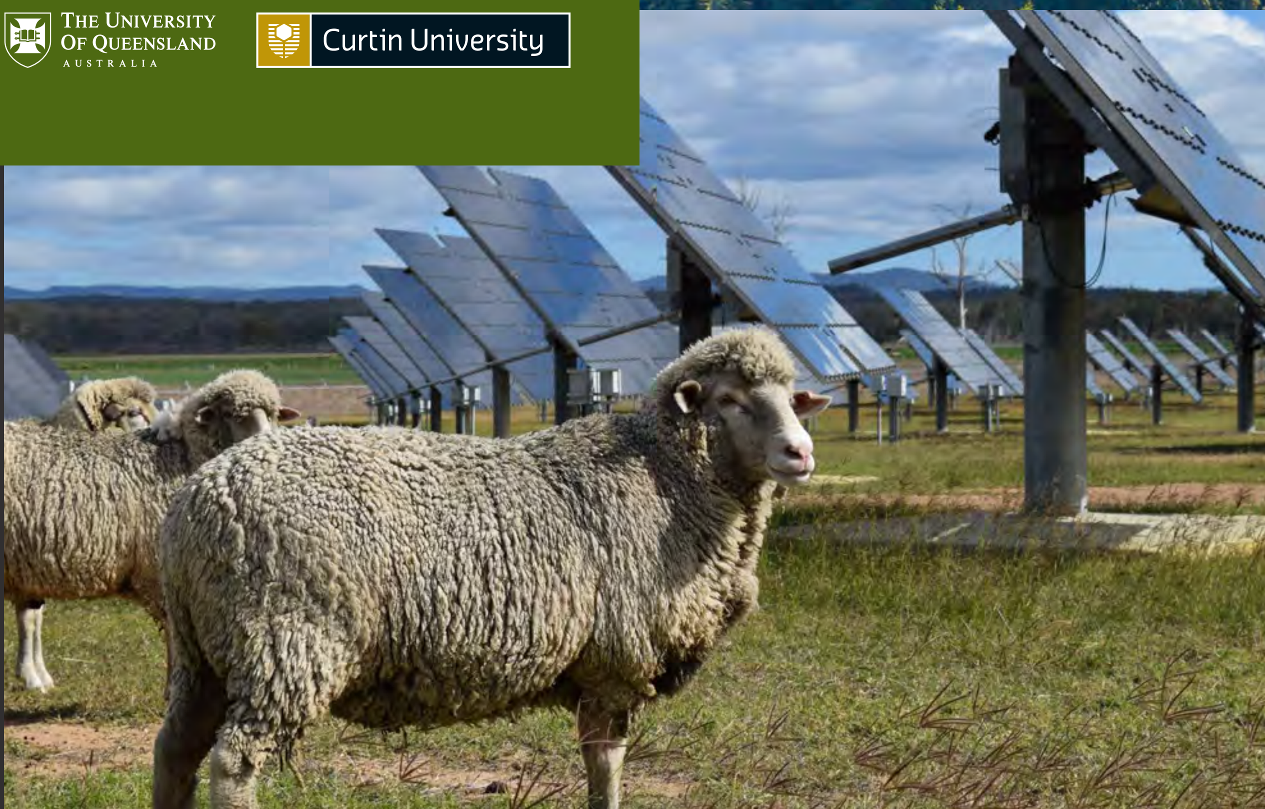
The University of Queensland Australia

Curtin University



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1.

Introduction

This study aims to investigate the benefits and trade-offs between overhead and underground transmission line infrastructure, specifically focusing on issues associated with under-grounding new transmission infrastructure. It seeks to establish a clear and consistent approach to the evaluation of overhead lines and underground cable transmission, including the consideration of community concerns around the need for new transmission infrastructure to connect large renewable energy generation projects. It does this through systematic reviews of the literature as well as incorporating experiences of Transmission Network Service Providers (TNSPs) in Australia and overseas. The study has a particular focus on 500kV transmission infrastructure which are projected to figure in most large projects in Australia going forward.

Historically, transmission networks in Australia developed from the need to transfer large amounts of power from large coal fired power stations, typically co-located near coal reserves, over long distances to major cities and industrial load centres. In contrast, the proposed large scale renewable generation facilities, mainly solar and wind farms, require greater land areas and are largely being located in greenfield areas with little or no existing transmission network infrastructure. These new developments are naturally creating community interest and concerns around a range of potential impacts, including but not limited to: visual amenity; environment; Traditional Owner lands; agricultural land use; and social licence to operate concerns This has led to questions surrounding when it is appropriate to underground transmission infrastructure and the likely implications of doing so.

This chapter focuses on the environmental aspects of overhead and underground transmission lines. A systematic review of papers published between January 1996 and February 2016 on the environmental impacts of power lines on biodiversity was undertaken by Biasotto and Kindel in 2018 [1]. Their review showed that the life cycle of transmission lines lead to impacts which can have multiple effects on the environment and biodiversity This review summarises and updates the Biasotto and Kindel, 2018 study with the published literature up to June 2023.

According to the search strategy, 823 publications about transmission lines were found through the Web of Science and Scopus, after removal of duplicates and papers outside of the inclusion criteria, 427 were determined to be potentially contributing to the scope of this study. The papers were then screened by reading all publications' titles and abstracts and 56 were deemed within scope. These shortlisted publications were read in detail resulting in 35 publications selected. Citation and purposeful (fire, EMF and noise) searches were also used resulting in an additional 14 publications selected. In total, 49 studies were considered for further analysis in this review, none of which focused on Australia.

Biasotto and Kindel (2018)'s review was aimed at all powerlines—distribution and transmission—and did not distinguish between overhead and underground. Where possible, this review focussed on transmission lines and specifically findings relating to underground powerlines. Of the life cycle of transmission lines, impacts during operation tended to be evaluated in the environmental peer-reviewed literature. Construction, decommissioning and removal were rarely addressed. While these potential impacts are described within Environmental Impact Assessments (EIAs) of which the process is detailed in section 3, the mitigation of EIAs through Environmental Management Plans (EMPs) are outside the scope of this review. Only eight publications mentioned underground transmission cables, and none were specifically aimed at the environmental impacts of underground cables.

2.

Results

2.1 Framework

This review used a simplified version of Biasotto and Kindel's (2018) framework to analyse the data in the literature. It includes phases, actions, abiotic (physical) impacts, and their impacts on organisms [1]. Importantly, Biasotto and Kindel's framework was developed for all power lines - both distribution and transmission lines.

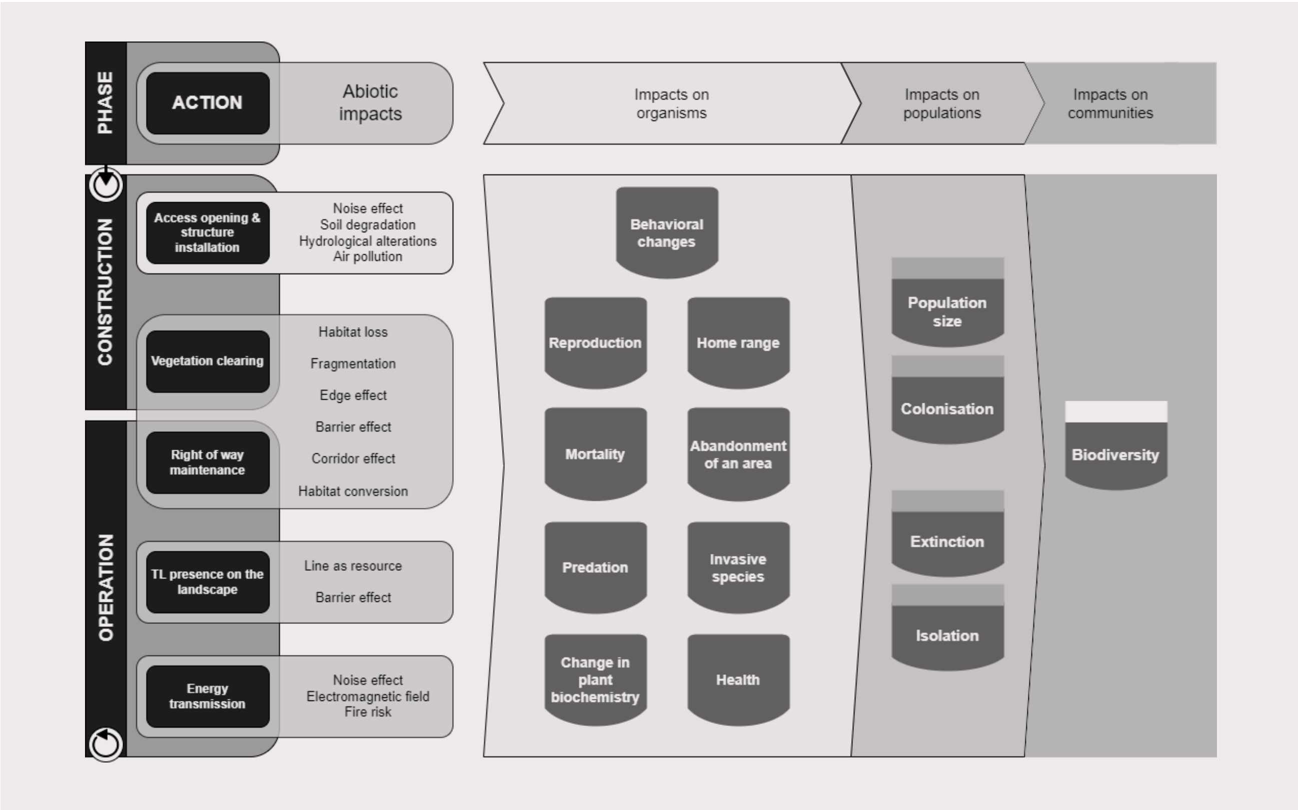

Figure 1. Study Framework Adapted from Biasotto and Kindel (2018)

2.2 Context dependency

Every publication reviewed emphasised the difficulty in applying their findings in different contexts and to different communities or species. While some of the literature findings may be applicable in an Australian context, without any major studies emerging from this review in Australia since 2016, any extrapolation of findings needs to be made with caution. Particularly, given Australia's unique biosphere and its high level of endemism (i.e., species specific to Australia). However, this review does describe the range of potential impacts observed in other regions that provide an indication of potential impacts in Australia.

2.3 Barrier effect

Transmission lines can act as a physical barrier hindering movement across and along them for some fauna. According to Biasotto and Kindel (2018), the barrier effect can occur for a variety of reasons. These include easement vegetation clearance along with the physical presence (size, shape etc.) of transmission lines and towers. This effect can start as early as the construction phase and endure throughout operation and decommissioning activities [1].

In Biasotto and Kindel's (2018) review "*28% of the papers (n = 57) focused on bird collisions*" [1, p. 114] and was featured in 61 % of the papers in this systematic review. Unsurprisingly, the main barrier effect noted in the literature is bird collision and electrocution with overhead lines. It can be a major cause of death and population decline for some species, including some endangered ones. These effects might only be noticed several decades after construction, making restoration difficult. It is also worth noting that it is difficult to generalise and compare such impacts between distribution and transmission lines because of the significant difference in midspan clearance. Similarly, while there is a barrier effect, they are significantly less than many other linear assets such as roads and railway lines.

The factors potentially increasing bird collision, electrocution and mortality are multiple and were found to fall into three categories. These include:

1. **Bird morphology and behaviour** - such as birds having a narrow visual field, a heavy body and either small or wide wingspans; low manoeuvrability; gregariousness; whether they are migratory or nocturnal birds ;and whether they use the line as a resource (section 2.4) [2].
2. **The geography** which includes considerations around the lines' proximity to wetlands, coastline, valleys, hilltops, and forest edges [2]–[5] and weather such as fog, rain and wind [2]. Other issues include if the line is the only tall structure in the area or is higher than the forest canopy surrounding it [6] and whether the lines intersect daily flight paths e.g. between foraging and nesting locations, and migration paths [6], [7].
3. **The transmission line design** including if distance is increased between towers [6]; lines are thinner; the presence and position of insulators [2]; heights of towers [8]; and the use of overhead shield wires [9].

The literature also reported that bird electrocution and collision have flow-on impacts such as abandonment of territories where the risk of collision is high; bird carcasses serving as hosts for botulism can increase affliction and mortality of other birds; scavenger activity [10, p. 1807]; and population decline leading to eventual extinction [12].

Mitigation measures proposed in the literature include the use of line markers, different tower designs, and sounds to scare the birds away[6]. While there has been a limited number of tests of their effectiveness, those that were tested, exhibited a broad range of efficacy between bird species [8], [9], [13], [14]. Line marking, for example using large, coloured balls, specifically in highly frequented areas was often suggested. A systematic review of line marker effectiveness did show that they reduced collision with the overhead line by half. However, multiple limitations and biases were highlighted with no explanatory variables being statistically significant [15]. A systematic review of factors driving bird electrocution revealed that tower design was the least influential factor, and climate was found to be the most influential [16]. Undergrounding was suggested in eight studies as a way to entirely prevent collision.

Some studies suggested that lines should run with, or parallel to, other linear developments to potentially make the lines more visible or create a form of habituation. However, the effect of such a measure on collision and electrocution rates has not been verified [6], nor does it take into account negative outcomes from increased flight path alteration or the cumulative impacts from housing several infrastructures in close proximity to each other.

The barrier effect also includes avoidance behaviour in animals. Biasotto and Kindel (2018) documented such behaviour for birds (grassland, forest and raptors) and smaller arboreal mammals and vertebrates. However, it did not seem to effect reptiles [1]. Avoidance behaviour was noted for several bird species [2], [7], [17], [18], and bats [19] and could lead to habitat loss and fragmentation. Ungulates (reindeers) in Sweden showed no long-term impacts from the barrier effect [20].

2.4 Line as resource

One of the most recognised benefits of transmission lines for biodiversity is the use of the infrastructure itself, as a resource. Transmission towers provide a tall, permanent structure, mostly free of human interaction which makes them suitable for birds perching, resting, hunting and nesting. Biasotto and Kindel (2018) highlighted that while the impacts can be positive (e.g. expanded home range, population size), increased use of lines and towers may lead to increased collision and other negative impacts such as nest overexposure to weather or predation compared to natural nesting settings [1].

The literature since 2016, confirmed and expanded on those findings and highlighted the requirement to balance the positive aspects of line as a resource with the negative impacts on specific species, overall biodiversity and the operation of the powerlines. D'Amico et al. (2018) were critical of the lack of studies that focused on the cost benefit analysis at a population level and "s*uggested establishing a collaborative dialogue among the scientific community, governments, and electricity companies, with the aim to produce a win–win scenario in which both biodiversity conservation and infrastructure development are integrated in a common strategy*" [2, p. 650].

In Spain and Portugal, storks used transmission line towers for nesting, allowing for an increase in their home range and abundance. Their occupation increased near landfills, where the lines are the only tall structures in the landscape, in proximity of water [2], [21]. Whilst stork electrocution remains an issue, Moriera et al. (2017) showed a correlation between increasing stork population and transmission network expansion [22]. This positive impact on population size and range has become problematic for power companies, specifically for large nests as it may compromise the operation (e.g. power outages), maintenance (e.g. removal of nests) and the structural stability (e.g. load distribution and aerodynamics) of transmission line towers [11], [21].

Raptors (birds of prey) use transmission line towers and the area surrounding it extensively [23], [24], because of their proximity to abundant food sources and from roads [24]. This can lead to collisions and electrocutions - the main cause of mortality for some populations predominantly in 132kV transmission lines. In the US, corvid's (ravens and crows) extensive use of transmission lines is associated with an expansion of their home range and population, which leads to increased predation on other species [5], [17], [18], [25].

Because the risk of collision increases with transmission line tower use, locating transmission lines within or near known habitats of endangered bird species needs to be collaboratively assessed to avoid significant impacts [26].

Line as resource is unlikely to occur for underground cables.

2.5 Habitat loss

Habitat loss, destruction or reduction is defined as a loss in capacity to sustain life and/or functions (i.e. foraging or nesting) of an area due to the construction and operation of transmission lines. It can occur through vegetation clearing, particularly in forested areas [27], from the edge effect (section 2.7) and/or the infrastructure itself (section 2.4) [5].

Biasotto and Kindel (2018) highlight that habitat loss was understudied, with all studies focussing on birds and reporting negative impacts on reproduction, and that area abandonment by certain species is inversely proportional to powerline density. In this review, we found only three studies addressing powerlines and habitat loss and they focussed solely on their impacts on the behaviour and population of the grassland species sage grouse in the US. Declines in sage-grouse populations were shown to be affected by the destruction of sagebrush habitat as well as transmission line influence on the distribution and abundance of raptors and corvids and the associated increased predation. The buffer area to mitigate these impacts was reported to extend from 2.5 km to 12.5 km from the transmission lines [17], [18], [25].

Habitat loss will occur for underground cables due to vegetation clearance, however specific findings did not emerge within the peer-reviewed literature. The Renewables Grid Initiative in Europe suggested that ground nesting birds would be particularly affected during underground transmission cable construction, suggesting those effects could be mitigated by avoiding work during the breeding season [28].

2.6 Habitat Fragmentation

Habitat fragmentation has several definitions in the literature. It can lead to a loss of surface area and connectivity in previously connected landscapes and is a consequence of easement vegetation clearance and access openings for construction [1]. The degree of fragmentation can depend upon transmission voltage, the associated easement width, the type of tower (lattice, tubular...), and their location within the landscape [18]. In their review, Richardson et al. (2017) highlight that habitat fragmentation is an understudied area and, as most of the studies in the literature focus on single species population impacts rather than community or ecosystem impacts, they do not evaluate the impact of connectivity loss across areas interrupted by transmission lines [10].

Biasotto and Kindel (2018) reported that fragmentation resulted in negative impacts on mammals, birds, and amphibians from altered movement patterns, isolation and population [1]. Since 2016, only one study directly aimed at evaluating movement across powerlines, based on the Indian Thar Desert, found a decrease in bird crossings with increasing powerline voltage [29]. Hyde et al. (2018) concluded that transmission lines in the Amazon did lead to habitat fragmentation, however its biodiversity impacts required further investigations [27].

Richardson et al.'s (2017) review of powerline impacts on biodiversity highlighted that fragmentation not only arises from powerlines but also from other infrastructure such as pipelines, oil and gas wells, road, forestry and agriculture. When those developments are in proximity their impacts become cumulative. Although, once again this remains an understudied area [10].

Aerial wildlife (e.g. birds, small mammals, insects) can alleviate some negative impacts of fragmentation by maintaining ecological functions between fragmented landscapes. As such, the barrier effect (section 2.3) of transmission lines was considered particularly damaging due to its potential reduction of aerial wildlife mobility, population and diversity across landscapes, and loss of ecological functions across landscapes [30].

Habitat fragmentation will occur for underground cables due to vegetation clearance.

2.7 Edge effect

An edge effect arises at the interface of two or more habitats. When access openings and easements are created with vegetation clearance, habitats within are modified and an edge is created between the access opening or transmission lines easement's new habitat and the original surrounding habitats. Biasotto and Kindel (2018) raised the issue of changes in abiotic conditions at the edge, with distinct microclimates (sun exposure, temperature, humidity etc.) and was seen to be particularly important for forest openings.

The impacts of edge effect reported can be positive, neutral or negative depending on species and their habitat. Froidevaux et al. (2023) showed that edge specialist bats benefitted from increased available habitat, however forest foraging bats suffered [19]. Hrouda and Brlìk (2021) posited that the trees at the edge of the easement died because of stress due to direct sun exposure and continuous vegetation clearing. Those dead trees provided a habitat for rich insect communities as well as foraging and nesting for forest bird species which would not normally occupy open habitat [31].

Hyde et al. (2018) highlighted that, in the Amazon tropical forests, transmission line easements' edge had a warmer and drier climate than the surrounding forest. This could result in "*altered vegetation community structure and composition*" [27, p. 347] and the authors expected "*a cascade of edge related changes to most of the forest within the impact areas*" [27, p. 348] as the network expands.

Edge effect will occur for underground cables due to vegetation clearance.

2.8 Habitat conversion

Transmission lines construction and operation result in significant habitat change within easements due to vegetation clearing which can result in positive, neutral or negative impacts on biodiversity. Biasotto and Kindel (2018) reported mostly positive impacts such as new species' (rarer in the area) establishment within the easement such as plants, gastropods, beetles and bees, as well as increased home range from some birds, butterflies and lizards. Because sites under towers are often undisturbed for extended periods of time and are located below perching sites for birds, this facilitates seed dispersal and plant development including native, non-native and invasive species. As such, biodiversity abundance and richness within easements were reported to potentially increase. [1].

The literature confirms potential positive impacts in agricultural and forested areas for some birds, mammals, insects and plants if the easement vegetation is effectively managed. Because powerline easements are typically maintained in an early successional stage permanently, without tall woody species, they can offer significant ecosystems for a variety of species [32, pp. 9–10]. D'Amico et al. (2018) also highlighted that positive impacts occurred in effectively managed easements, specifically for densely forested and intense agricultural land resulting in a shrubland ecosystem being developed that was suitable for bush birds [2].

Easements also have the potential to provide habitat for pollinators if managed effectively. However, it was recognised that they should not be considered as a replacement for natural and semi-natural habitats for the most specialised species [33]–[35]. This effect was also observed on road verges and railways [35]–[37]. Easements tend to have distinct biodiversity from nearby natural or semi-natural (pastoral) lands, for both plants and pollinators such as butterflies and bumblebees. As such, they can be assets for conservation [33]–[35]. Hill and Bartomeus (2016) and Russo et al. (2021) showed that mowing could be beneficial to establish and maintain pollinator habitats [32], [35]. However, mowing frequency and timing combined with other easement management practices (e.g. use of herbicides) can also be detrimental to pollinator community richness and abundance, highlighting the importance of developing targeted management practices [37]. Because of their large spatial and temporal extent, transmission line easements have the potential to provide long-term habitat for wild pollinators [35] if managed adequately. Within agricultural land, the non-farmed sections under pylons have been known to be attractive to some medium-size mammals, particularly if located in landscapes lacking semi-natural habitats [38].

Transmission lines easement have specific impacts on forests and woodland areas, as their regular maintenance leads to changed climatic and ecological conditions compared to the nearby forest interior. Within forested areas, the cleared transmission line easements provide open habitat for insect species e.g. butterflies and beetles and as such increase biodiversity [39]. Hrouda and Brlìk (2021) showed transmission lines in woodlands hosted a greater abundance of bird species, particularly open-habitat varieties, than the surrounding woodland habitats [31].

The European Renewables Grid Initiative and Ecofirst are developing a database of practices to enhance the positive effect of habitat conversion in transmission line easements. In the European Renewable Grid Initiative document (2012), practices such as selective tree cutting to create natural progressive forest edges, restoration of natural and semi natural grasslands e.g. sowing of local seed mixes, restoring heathland and peatbogs through soil scraping and intentional waterlogging, digging new ponds and invasive species control were explored with positive effects on environmental quality and biodiversity [40].

Habitat conversion will occur for underground cables due to vegetation clearance.

2.9 Corridor effect

The corridor effect arises from easements providing a connection between areas of habitat. The transmission lines' linear profile can have positive, neutral and negative effects. This is because native, non-native and invasive species can spread using the easement corridor [33]. Biasotto and Kindel (2018) reported that "*large carnivores exhibited a strong preference to move*" through powerline easements [1, p. 115]. The authors also highlighted that corridors may facilitate access for poachers and hunters. The corridor effect arises from the easement providing a connection between areas of habitat.

There appears to be a correlation between powerlines and corvid range expansion [5], which would have consequences for species they compete with for habitat and prey upon. Gibson et al. (2018) reported an annual rate of increase of ravens along the Falcon-Gondor transmission line in Nevada, in the US was about three times greater that the annual rate of increase for North America, leading to a decline in grassland bird (greater sage-grouse) populations due to increased predation [17].

Improved corridor effects can be planned, for example, by planting native shrubs within the easement in already degraded environments such as forestry and farmlands [2] to provide ecological or green corridors. However this positive effect requires further study as one study showed that the transmission lines linear shaped novel grasslands did not provide effective connectivity for pollinators and did not lead to homogenised communities along and around it [34].

Corridor effect will also occur for underground cables due to vegetation clearance.

2.10 Electro Magnetic Field

Biasotto and Kindel (2018) reported that continuous exposure to EMF could lead to behavioural and reproductive effects, potentially leading to survival impacts, as well as "*other "silent" disturbances in biochemical processes*" [1, p. 115]. The authors found studies on cattle, birds and plants showing negative or neutral impacts. The search term of our review only returned one study however, a subsequent purposeful search for "EMF" AND "biodiversity" returned three more studies related to transmission lines and these were included in this review.

Froidevaux et al.'s (2023) study on insectivore bats showed that EMF was the most likely reason for powerline avoidance [19]. Balmori (2021) reported negative impacts on honey bees from exposure to EMF from transmission lines [40]. A lab study on honey bees reproducing transmission lines EMF directly under, or immediately next to conductors, showed the following effects: "*reduced learning, altered flight dynamics, reduced the success of foraging flights towards food sources, and feeding*" [41, p. 1]. Similarly in Italy, Lupi et al. (2021), studied the impacts of pesticide and EMF on honey bees and they found that the combination of stressors induced "biochemical, physiological and behavioural alterations" [42, p. 1]. Those studies concluded that EMF posed a threat to pollination and survival of bee colonies in direct proximity of transmission lines. However, these negative impacts on bee colonies contradict the findings in the Habitat Conversion section.

EMF impacts will also occur for underground cables.

2.11 Fire

According to Biasotto and Kindel (2018), transmission lines presented an increased fire ignition risk due to bird electrocution and allow fires to spread and intensify because of invasive plant species within the easement.

In this review, fire risk was found to be understudied, rarely differentiated between distribution and transmission lines and solely focused on bird electrocution. The rate of fire ignition from bird electrocution from distribution lines versus transmission lines is unknown, (but is unlikely for transmission lines above 100kV, which have larger phase to phase clearances). Barnes et al. (2022) cited a study from Dwyer et al. (2019) calculating that worldwide, 84% of fires induced by bird electrocution occurred in North America, of which 22% were in California with Mediterranean regions being most affected [43]. Guil et al. (2018) showed that in Spain, between 2000 and 2012, 1.22% of fires were powerline induced and that of those 2.4% were due to bird electrocution. Raptors and corvids were the main cause of fire ignition from electrocution [44].

A purposeful search returned studies relating to fire impacting powerlines rather than powerlines igniting fires. Fire is unlikely to occur for underground cables.

In Australia, recent bushfire seasons have resulted in several inquiries. Of the 32 fires listed in the 2019 NSW Inquiry, two were started by powerlines and no distinction was made in the document between distribution or transmission lines [45]. The Royal Commission into National Natural Disaster Arrangements Report 2020 also highlighted the vulnerability of power lines to bushfires and noted that underground power lines were damaged by the fires [46]. Nonetheless both inquiries recommended undergrounding to improve electricity systems and community resilience. They did not mention undergrounding to mitigate power line induced fire risk.

2.12 Noise

Noise around transmission lines is caused by construction and maintenance, corona discharge from the power moving through the line and cable vibration induced by wind. Biasotto and Kindel (2018) highlighted that the area was significantly understudied with only one investigation showing that corona noise could be perceived by reindeers up to 79 metres away. The authors also raised that noise during construction could trigger change in animal behaviours and interfere with animal communication [1].

This review only found one study by Froidevaux et al. (2023), that showed corona noise effects were neutral on insectivore bats in France [19]. A purposeful search did not return further results. No study related to noise induced by wind and construction activities was found. Noise impacts are unlikely to occur for underground cables during operation, however, noise would be an issue during construction activities. It was not the subject of investigation within the reviewed literature.

2.13 Ultra Violet light

Ultra Violet (UV) light was not identified in the Biasotto and Kindel review. The ability of birds to detect UV light from transmission lines is debated and has not been verified through any experiments [6]. Froidevaux et al. (2023) showed that UV light attracted insects which in turn attracted insectivore bats. The effect increased during high humidity nights when corona discharge is more intense [19]. UV light impacts do not occur for underground cables.

2.14 Electric fields

The impact of electric fields (EF) was not identified by Biasotto and Kindel's review which is not surprising since HVDC transmission line use has only begun to increase in the last few years. Petri et al. (2017) conducted a PRISMA systematic review of HVDC transmission lines' static EF effects on humans and vertebrates [47], followed by Schmiedchen et al. (2018)'s review on plants and invertebrates [48]. Both studies drew similar conclusions showing that all groups can perceive DC EF. Whilst EF do not appear to result in adverse effects, in humans and animals, EF superficially stimulates hair and skin and Schmiedchen et al. (2018) suggested that annoyance levels may require further investigation [49].

EF impacts do not occur for underground cables, and thus were not investigated within the reviewed literature.

2.15 Soil degradation and hydrological alterations

As highlighted in Biasotto and Kindel, soil degradation is not addressed in the peer-reviewed literature [1]. Richardson et al.'s 2017 review posited that soil microbes and invertebrates which are responsible for soil functionality could be impacted by transmission lines construction and operation. However, soil degradation and recovery remained understudied in relation to powerlines [10]. Hydrological alterations also appear to remain unstudied, although the investigation of such impacts are important, especially for underground transmission cables.

Soil degradation and hydrological alterations would be markedly different and likely more significant for underground cables for the life cycle of the infrastructure. Horizontal drilling and open trench have different soil and hydrological impacts, each method impact requires careful investigation in local contexts. The European Renewables Grid Initiative highlighted the risk of soil compaction, wetting, erosion, contamination and loss of primary function as well as disruption of hydrological process, drainage and reduced water quality as a result of underground transmission line construction. Their publication recommended to engage with experts in local farming practices, soil and hydrological issues, to design construction and restoration methods allowing for soil and hydrological function to be maintained or restored [28].[28]. The thermal impact from operational heat dissipation on soil and soil biota required further investigation [28].

2.16 Air pollution

Air pollution is associated with the construction phase and was not the subject of any peer-reviewed studies in Biasotto and Kindel review or ours. Air pollution is likely to occur for underground cables during construction and removal, but would not be an issue during operational activities.

3.

Environmental Assessment Processes

3.1 Overview of Regulatory Requirements

Environmental Impact Assessments (EIA) are an essential and critical stakeholder engagement activity forming part of the approval process for a transmission project. The purpose of an EIA is to systematically evaluate and understand the potential environmental, social, cultural and economic impacts associated with the construction and on-going operation of a project. The triggers, requirements and process for EIA's are stipulated in legislation which in principle, is similar around the world. The following discussion focusses on the legislation that applies nationally and in the state of Queensland, for environmental assessments and approval of developments and infrastructure projects.

The Federal **Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)**[1] and regulations are Australia's main environmental law. It provides a regulatory framework to protect and manage matters of national environmental significance including unique plants, animals, habitats and places. These include heritage sites, marine areas and some wetlands. The Act also protects listed threatened and migratory species (Australian Government [49]). It requires detailed assessments and surveys with a typical timeframe to complete the process being approximately two years.

The Queensland **Environmental Protection Act 1994**[2] is the key legislation in Queensland to manage and regulate environmental protection and conservation. Its primary purpose is to safeguard Queensland's natural environment, including land, air, water, and biodiversity. An Environmental Impact Statement (EIS) is a key element of the Environmental Protection Act and is applied to evaluate and assess the potential environmental impacts of proposed activities, developments, or projects.

To streamline the process and avoid duplication between Federal and State regulatory processes, the Australian government and state governments, including Queensland, can enter into **bilateral agreements**. These agreements aim to harmonise and integrate the environmental assessment and approval processes between the Commonwealth (EPBC Act) and the state (Queensland's environmental legislation). In Queensland, the bilateral agreement applies to proposals that are 'controlled actions' requiring assessment under Part 8 of the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). Controlled actions are defined in Section 75 of the EPBC Act. They include actions that are likely to have a significant impact on a matter of national environmental significance, or that involve a change in the population, distribution, or migration of a listed migratory species.

There are two broad categories of EIA and approval processes that are applicable to transmission projects in Queensland (Queensland Government [50]):

(1) **'Infrastructure' assessable under the Planning Act 2016**[3] **Infrastructure Designation (ID) process**. ID is a planning process under Chapter 2, Part 5 of the Planning Act 2016 that allows the Minister to designate premises for a type of infrastructure. Most transmission line projects are in this category and will require an Environmental Assessment Report (EAR). Planning Regulation 2017[4], which identifies the types of infrastructure that may be designated. Minister's Guidelines and Rules (MGR)[5], which includes processes for making or amending ministerial designations (Chapter 7 of the MGR).

(2) **'Coordinated projects requiring an environmental impact statement' (EIS), declared by the Coordinator-General under Part 4, section 26(1)(a) of the State Development and Public Works Organisation Act 1971 (SDPWO Act)**[6]**.** This category of projects are typically large infrastructure projects in the mining and resource sector. However larger transmission line projects can be

[1] Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) - DCCEEW
[2] Environmental Protection Act 1994 - Queensland Legislation - Queensland Government
[3] Planning Act 2016 - Queensland Legislation - Queensland Government
[4] Planning Regulation 2017 - Queensland Legislation - Queensland Government
[5] Minister's Guidelines and Rules | Planning (statedevelopment.qld.gov.au)
[6] State Development and Public Works Organisation Act 1971 - Queensland Legislation - Queensland Government

declared a 'coordinated project'. An example is the CopperString project[7] in North Queensland.

Under the Environmental Protection Act 1994, a proponent for a project may also voluntarily prepare an EIS for the project by using the EIS process, if it is appropriate to do so.

3.2 Purpose of Environmental Impact Assessment

The main purpose and objectives of an EIA is to:

(a) **Identify Environmental Impacts:** The EIA process helps identify and assess the potential adverse effects that the construction and operation of the transmission line may have on the natural environment, including ecosystems, wildlife, water bodies, and air quality. This includes considering the potential impacts on endangered species, habitats, and protected areas.

(b) **Evaluate Social and Cultural Impacts:** An EIA also considers the social and cultural aspects of the project. This includes assessing the potential impacts on local communities, such as changes in land use, noise, visual aesthetics, and impacts on cultural heritage sites or Indigenous communities. It may also consider community concerns and gather input from stakeholders.

(c) **Assess Economic Impacts:** EIAs examine the economic implications of the transmission line project, including its potential to create jobs, stimulate economic growth, or affect property values. This assessment can help stakeholders understand the project's economic benefits and challenges.

(d) **Mitigation and Alternatives:** EIAs provide an opportunity to identify measures to mitigate or minimise adverse impacts. Project developers can propose mitigation strategies to lessen environmental and social harm, which may include modifications to the project design, construction techniques, or operational practices. The EIA process also considers alternative project designs or locations that might have fewer negative effects.

(e) **Compliance with Regulations:** In many jurisdictions, regulatory authorities require an EIA as part of the permitting process for certain projects. Conducting an EIA helps ensure compliance with legal requirements and environmental regulations. This also includes any assessment requirements under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act; projects that are a controlled action under the EPBC Act and being assessed by EIS under the bilateral agreement).

(f) **Informed Decision-Making:** The findings of the EIA are used to inform decision-makers, including government agencies, regulatory bodies, and the public, about the potential impacts and benefits of the transmission line project. This information is crucial for making informed decisions regarding project approval, permitting, and conditions.

(g) **Transparency and Public Engagement:** The EIA process often involves public consultation and engagement, allowing affected communities and stakeholders to provide input, express concerns, and offer suggestions. This transparency helps build trust and allows for a more comprehensive assessment of potential impacts.

(h) **Long-Term Sustainability:** By considering the environmental, social, and economic consequences of a transmission line project, an EIA aims to ensure that the project is developed and operated in a way that is environmentally sustainable and contributes positively to the well-being of communities.

In summary, an environmental impact assessment for a transmission line project serves to identify, assess, and address potential adverse effects while promoting sustainable development and informed decision-making. It plays a crucial role in balancing the need for infrastructure development with environmental and social protection.

3.3 Typical Content for a Transmission Line Environmental Impact Statement or Report

An EIS or EAR for a transmission project covers a range of factors and impacts that may arise during the design, construction, operation, or maintenance of the infrastructure including:

- a description of the project
- project need, justification and feasibility, and any alternatives that have been considered
- a review of the planning laws and approvals which are relevant to the proposed infrastructure.
- environmental considerations including the existing environment and any potential impact on factors such as biodiversity, flora, fauna, air quality, noise, waterways, vegetation, and soils
- matters of environmental significance in the area
- transport and traffic

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- bushfire risk
- health and safety
- land use
- social considerations
- economic considerations including benefits such as local jobs
- current and future land use
- visual amenity
- electric and magnetic fields
- cultural heritage – Indigenous and non-Indigenous
- the community and stakeholder engagement and consultation process
- the location of other infrastructure and industry
- the actions the proponent will take to manage and minimise environmental and social impacts that may result from the design, construction, operation, or maintenance of the new infrastructure.

3.4 Environmental Impact Assessment Process

The regulatory requirements for environmental impact assessment process typically include the following formal stages (Queensland Government [50]):

1. Submission of a draft Terms of Reference (ToR)
2. Publication notification of a draft (ToR)
3. Final ToR issues – EIS in preparation
4. Public notification of EIS
5. Proponent responds to submissions
6. EIS Assessment report

For a transmission line project the process however starts with early engagement of key stakeholders to develop alternative solutions including route corridor options to inform the draft Terms of Reference for the environmental impact assessment.

4.

Discussion

As highlighted in the original framework by Biasotto and Kindel (2018), all abiotic factors studied are interlinked. While such categorisation can be helpful for study purposes, it is recognised that it may preclude generating a more holistic view of transmission lines' environmental impacts.

The literature review highlighted several shortcomings in the current body of knowledge which include:

- Studies' methodologies varied greatly rendering meta-analyses difficult.
- There was a lack of studies addressing cumulative impacts from infrastructure developments in regions.
- There was a lack of studies considering impacts on communities (interacting species sharing a location) from all abiotic impacts.
- No studies addressed regional biosphere impacts for the whole length of transmission lines
- There was a lack of studies pre- and post-transmission line installation.
- Construction and removal phase impacts, however remained unstudied in the peer reviewed literature.

Despite these shortcomings the regulatory requirements of EIA's are fundamental to the development of any new transmission project. As such, they are well entrenched in the processes of TNSPs and other providers globally. However, with the growing focus on biodiversity impacts and a call to net-positive biodiversity impacts overall, means that increased scrutiny of EIA's is likely to occur. With the scale of renewable energy projects proposed, we are already seeing some environmental groups and others insist on a much more precautionary approach to project development as they relate to the environment. This again highlights the complexity for decision makers as the longer term impacts of climate change will be far more devastating to the environment and impacted biodiversity than a single project. Again pointing to the need for a nuanced understanding and pragmatic approach when trading off potentially near term negative impacts, often quite locally based, for a longer term environmental gain.

Regardless of the EIA process, while the body of knowledge regarding overhead transmission line impacts on biodiversity has grown over the years and points to an overall negative impact on local biodiversity, quantification of the magnitude, pathways and details of this loss are not well known. Undergrounding has been suggested as a mitigation measure for bird collision and electrocution, specifically in protected areas and in endangered species' habitats. However, the studies also highlight that the biodiversity impacts from habitat loss, conversion and fragmentation, and edge and corridor effects would remain. Additionally, the underground cable impacts on surface and underground soil, water and their associated life over time is less well known and documented.

Beyond the local biosphere impacts, both overhead and underground technology accrue environmental impacts to the global biosphere from material extraction, manufacturing, transport, installation, and operation to removal and recycling impacts such as greenhouse gas emissions, resource depletion, acidification, eutrophication, and toxicity. Those impacts are accounted for in lifecycle assessments (LCAs). A purposeful search of the LCA literature revealed that power losses during the operation of transmission lines is the main contributor to environmental impacts over the lifecycle of the infrastructure. Those environmental impacts are due the extra power required to compensate for the power losses. This extra power results in additional greenhouse gas emissions throughout the operational phase [51], [52]. Considering the current Queensland electricity generation mix that is dominated by coal, the emissions would be significant. However, the new transmission lines are built to connect renewable energy rendering this calculation inadequate. LCAs comparing overhead and underground technologies concluded that underground had the greatest footprint due to cable production, however this equation may be changed by HVDC cable [51]. Finally, all these impacts have to be weighed against the impacts of not building sufficient transmission line capacity in an adequate timeframe to counteract climate change impacts.

The lack of studies considering the environmental impacts through an Indigenous lens and utilising traditional knowledge is a gap in the literature and more work in this area will provide a valuable perspective and understanding of other dimensions of environmental impacts.

5.

Limitations

Overall, there is limited data in the peer reviewed literature regarding the construction and removal phase. Those potential impacts are described within Environmental Impact Assessments (EIAs) the scope of which has been detailed above. However, they are mitigated through Environmental Management Plans (EMP) which are not included as part of this systematic review. It is important to note that EIAs are not subject to long-term monitoring and evaluation. As such, the data within those documents offers a view of the anticipated impacts not the actual impacts, nor the effectiveness of the mitigation measures recommended to be implemented.

6.

Conclusions

6.1 Key Findings

1. As with any large infrastructure projects, the environment is generally negatively impacted by transmission line infrastructure projects, whether they are overhead or underground, with regulated EIAs forming a critical part of the process for ensuring such impacts are minimised wherever possible. Such regulations are considered important elements for ensuring a social licence to operate providing comfort that all likely impacts are acknowledged and accordingly accounted for. Regardless, as with communities, each environment is context dependent and needs to be considered independently to ensure all likely impacts are identified.
2. Principally, habitat loss, fragmentation, and the alteration of environmentally sensitive areas are key negative outcomes of the construction of transmission infrastructure on the natural environment. Overhead lines are more likely to create a barrier effect, where biodiversity is negatively impacted through changes in bird migration patterns because of collision and avoidance of the transmission lines but mitigation measures through the use of markers such as bright coloured balls have been successful in reducing such impacts.
3. The clearing of vegetation for easements is also likely to have a significant impact on wildlife habitats as well as cause changes in the microclimate by restricting the growth of plants and trees, with secondary impacts on some species including insects, birds, and other mammals.
4. Avoiding transmission lines being constructed in highly sensitive natural environments including watercourses, wetlands, and national parks is also a high priority, although not always possible given the scale of developments required.
5. Bushfires are raised as an environmental concern and according to Biasotto and Kindel (2018), transmission lines can present an increased fire ignition risk at times due to bird electrocution. They also mention fires spreading and intensifying as a result of invasive plant species in easements. In Australia, the 2019 NSW Inquiry into bushfires suggested two were started by powerlines but no distinction was made between distribution or transmission lines. While undergrounding may help mitigate these risks, reviews have also highlighted they can also be vulnerable to fire impacts.
6. Understanding the interplay between the environment and other cultural heritage considerations is also an important consideration that is starting to gain more attention but requires further research and engagement.
7. There is no one size fits all when deciding between overhead and underground transmission infrastructure based on environmental considerations and as the increasing severe weather impacts occur including floods and fires the ability to maintain and have transmission lines continue to operate will be of utmost importance when considering how and where they should be constructed.
8. Environmental Impact Processes through both the EPBC Act and Queensland's Environmental Protection Act, are critical components of the approval process for all transmission projects with a typical timeframe to complete the process being approximately two years.

6.2 Comparison Table - Environmental Factors of HV Transmission Infrastructure

A summary comparing the environmental factors of HV overhead and underground transmission infrastructure is presented in Table 1.

Table 1. Comparison of HV Overhead and Underground Cable Transmission – Environmental Factors

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Under-ground
		Environmental Factors			
1	**Overall environmental impacts**	Overall negative impacts on the local biodiversity. The geographical context as well as the local ecosystem influence overall impacts. Transmission line add to the cumulative impacts from all infrastructures and developments in a region.	Likely overall negative impacts on the local biodiversity.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.
2	**Barrier effect**	Barrier effect impacts biodiversity negatively. Bird collision and avoidance are the most cited impacts. Flow-on impacts are multiple, including change in migration path and extinction. Potential mitigation measures are through line routing and line markers.	Undergrounding is an effective mitigation measure for the barrier effect.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.
3	**Line as resource**	Line as resource is considered positive though with potential negative impacts, particularly on birds. Positive impacts include increased population size and home range. Negative impacts include increased collision, electrocution, predation and invasive species colonisation.	Underground lines cannot act as a resource.	*Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.
4	**Habitat loss**	Habitat loss arises mostly from vegetation clearance, particularly in forested area. The most cited impacts are area abandonment and population decline.	Underground line would result in habitat loss from vegetation clearance.	*Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.
5	**Habitat fragmentation**	Habitat fragmentation arises mostly from vegetation clearance and the barrier effect. Negative impact such as altered movement for mammals and amphibians, and reduced bird crossings with increasing voltage.	Underground line would result in habitat fragmentation from vegetation clearance.	*Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.
6	**Edge effect**	Edge effect arises from vegetation clearance and can have positive, neutral or negative impacts on biodiversity. Most intense impacts are in forested areas. Impact on vegetation from change in microclimate and associated species in those communities such as insects, birds, bats and mammals.	Underground line would result in edge effect from vegetation clearance.	*Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Under-ground
7	Habitat conversion	Habitat conversion arises from vegetation clearance and can overall be positive, particularly in forestry and intense agricultural land. Maintenance in semi-natural grassland can provide significant ecosystems for a variety of species, notably pollinators and open habitat bird species. To be positive, it requires management practices designed for the local context.	Underground line would result in habitat conversion from vegetation clearance.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.
8	Corridor effect	Corridor effect arises from the easement providing a connection between areas and can have positive, neutral, and negative impacts. Increased home range for native, non-native, and invasive species. Large carnivores and birds expand their home range, most notably the crow or raven. Limited home range expansion for pollinators. To be positive, it requires management practices designed for the local context.	Underground line would result in corridor effect from vegetation clearance.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.
9	EMF	Potential behavioural, reproductive effects. Some bat species powerline avoidance behaviour is attributed to EMF. EMF affects bees and may pose threat to pollination and colonies survival.	EMF impacts are likely to occur for underground.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.
10	Fire	Overhead lines can be a source of fire ignition (1.2% of fires in Spain). Bird electrocution can induce fire – mainly distribution lines (2.4% of the 1.2% in Spain).	Undergrounding would mitigate power line induced fires.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.
11	Noise	Noise arises from construction and maintenance, corona discharge and cable vibration from wind. Noise may alter animal behaviours and interfere with animal communication.	Undergrounding would mitigate corona discharge and wind induced noise.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.
12	Soil degradation, hydrological alterations, air pollution	Those impacts are mostly associated with the construction and removal phase. Limited data on their impacts in the peer-reviewed literature.	Those impacts would be markedly different and likely more significant for underground cables for the life cycle of the infrastructure.	Expected to be similar to HVAC overhead.	Expected to be similar to HVAC under-ground.
13	Environmental Assessment Processes	The Federal Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) and the State's Queensland Environmental Protection Act 1994 are the key legislative requirements for all projects. Detailed Environmental Impact Assessments (EIAs) and surveys are required to ensure protection of environmental significance including unique plants, animals, habitats and places.			

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Appendix A:

PRISMA Methodology for Environmental Aspects

1. Eligibility Criteria (Inclusion & Exclusion):

Inclusion criteria

- Studies which cover environmental impact of overhead transmission line and underground cables
- "Transmission line" and "powerlines" rather than voltage levels were used as this is common practice in this type of literature

Exclusion criteria

- Any duplicated studies
- Distribution powerlines
- Studies that are irrelevant to the scope of this review for example, technology other than transmission lines and impact on humans as well as the environment impacting the transmission lines
- Language other than English

2. Information Sources

Both Scopus and Web of Science databases were used to find peer reviewed articles.

3. Search Strategy

An initial search was conducted to refine search terms and through this a systematic literature review by Biasotto and Kindel (2018) on the impact of power lines on biodiversity was found. The Biasotto and Kindel review analysed publications between January 1996 and February 2016. The authors developed a framework to categorise their findings. This review built on their findings, it adapts the framework, used the same search terms and included literature between 2016 and June 2023.

The final search terms were:

To establish the domain of enquiry: ("transmission" OR "High voltage" OR "electric*") AND ("powerline" or "power line") AND (impact* OR effect* OR loss* OR damage*)

To target specific impacts, the following groups were used:

- "habitat*" OR "environment*" OR "landscape*" OR "terrestrial*" OR "soil*" OR "water bod*"
- "biodiversity" OR "population*" OR "communit*" OR "specie*" OR "assemblage*" OR "biota"
- "*vertebrate*" OR "avian" OR "bird*" OR "mammal*" OR "amphibian*" OR "reptile*" OR "wild*life"
- "vegetation*" OR "plant*" OR "grassland*" OR "forest*" OR "wetland*" OR "artificial*land*" OR "land use" OR "agricultur*"

Both databases were searched for Title, Abstract and Keywords.

4. Data Collection Process

Based on the eligibility criteria, information sources and search strategy, publications are identified as per the procedures presented in the flow chart in Figure 2. According to the search strategy, 823 publications about transmission lines were found through the Web of Science and Scopus, after removal of duplicates and papers outside of the inclusion criteria, 427 were determined to be potentially contributing to the scope of this study. The papers were then screened by reading all publications' titles and abstracts and 56 were deemed within scope. These shortlisted publications were read in detail resulting in 35 publications selected, citation and purposeful (fire, EMF and noise) searches were also used resulting in an additional 14 publications selected. In total, 49 studies were considered for further analysis in this review.

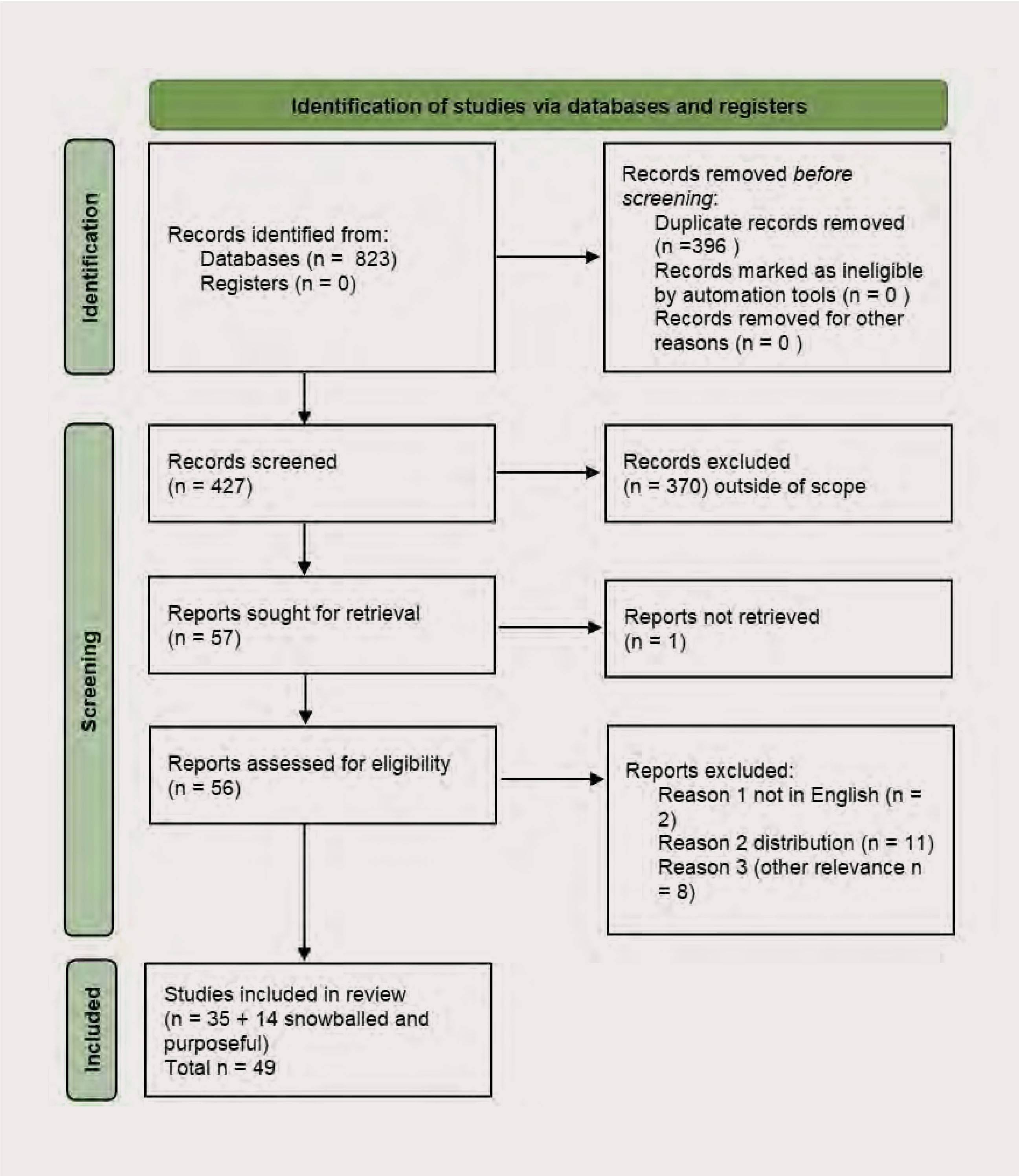

Figure 2 - Prisma flow diagram of studies to be included in the systematic literature review

5. Data Analysis

The 49 articles were analysed. See Table 2 for the further details on the 49 papers analysed for this review. Data analysis was performed using the software NVivo 12, used to organise and help analyse the data through the following methods. This first stage of the analysis consisted of sorting text extracts to the categories within the Biasotto and Kindel framework and identifying any missing categories since 2016. The second stage consisted of categorising extracts further and organising the findings to update and further the Biasotto and Kindel analysis.

Literature characteristics

Biasotto and Kindel (2018)'s review was aimed at all powerlines—distribution and transmission—and did not distinguish between overhead and underground. Where possible, this review focussed on transmission lines and specifically findings relating to underground powerlines. In this review, since 2016, 37% of the studies took place in Europe and 27% in North America (Figure 3) and none were conducted in Australia.

The distribution of abiotic impacts evaluated is similar to Biasotto and Kindel's with a strong prevalence of barrier effect studies (Figure 4). We note that 39 per cent of studies assessed two or more abiotic impacts, which is essential to gauge the overall effect of transmissions lines.

This review revealed a similar distribution of biotic components (fauna and flora) to the Biasotto and Kindel (2018) review (Figure 5). Three studies evaluated a combination of biotic components which are again essential to gauge the overall effects of transmissions lines on the environment.

Of the life cycle of transmission lines, impacts during operation tended to be evaluated in the environmental peer-reviewed literature. Construction, decommissioning and removal were rarely addressed. Only eight publications mentioned underground transmission cables, and none were specifically aimed at the environmental impact of underground cables.

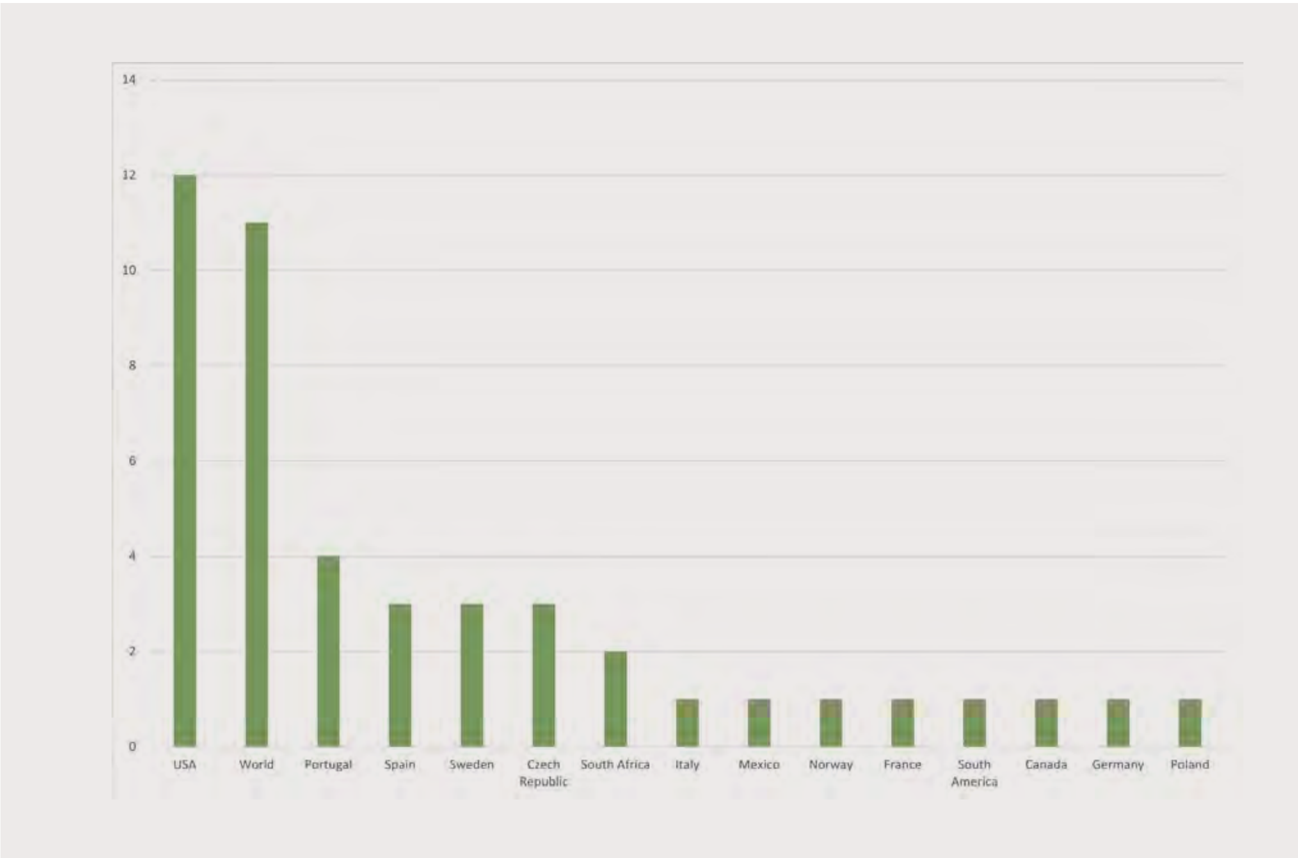

Figure 3. Number of Publications per Country or Region

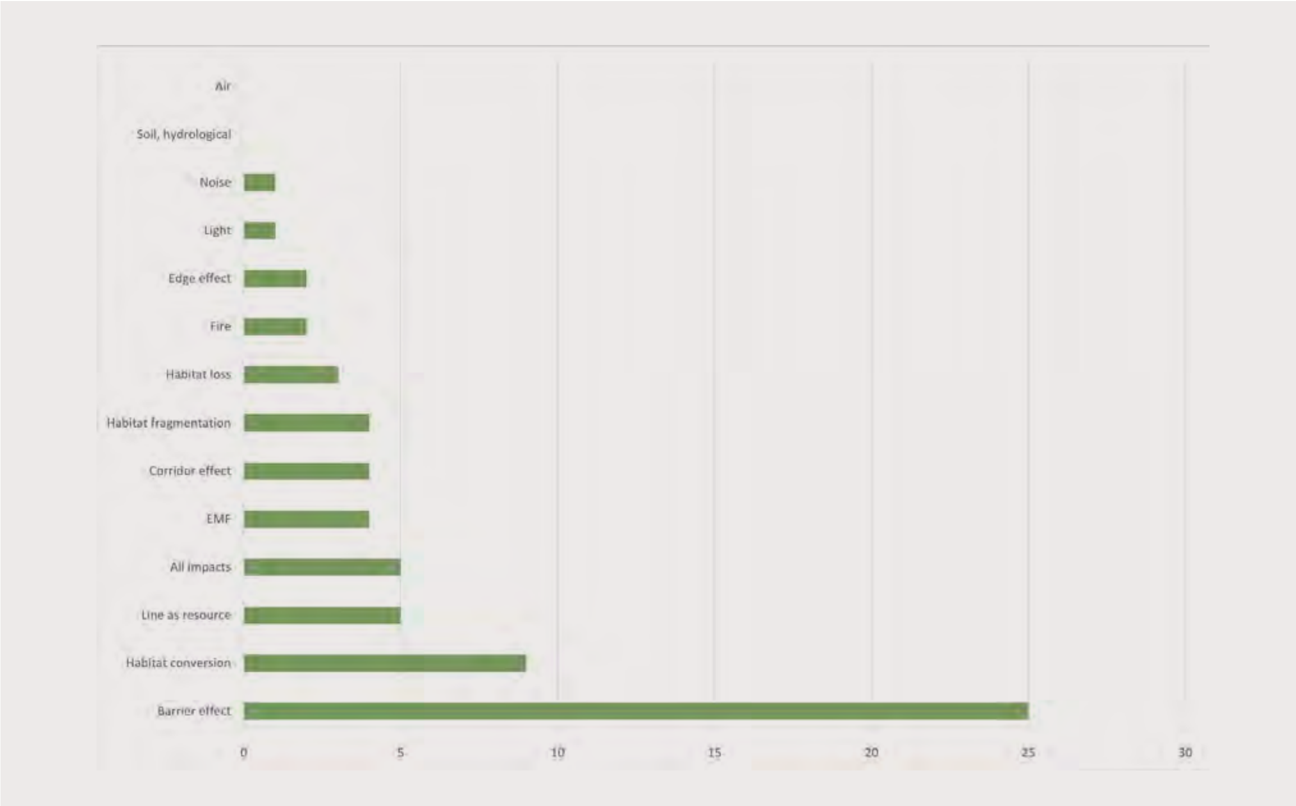

Figure 4. Number of Publications per Abiotic Impacts Assessed

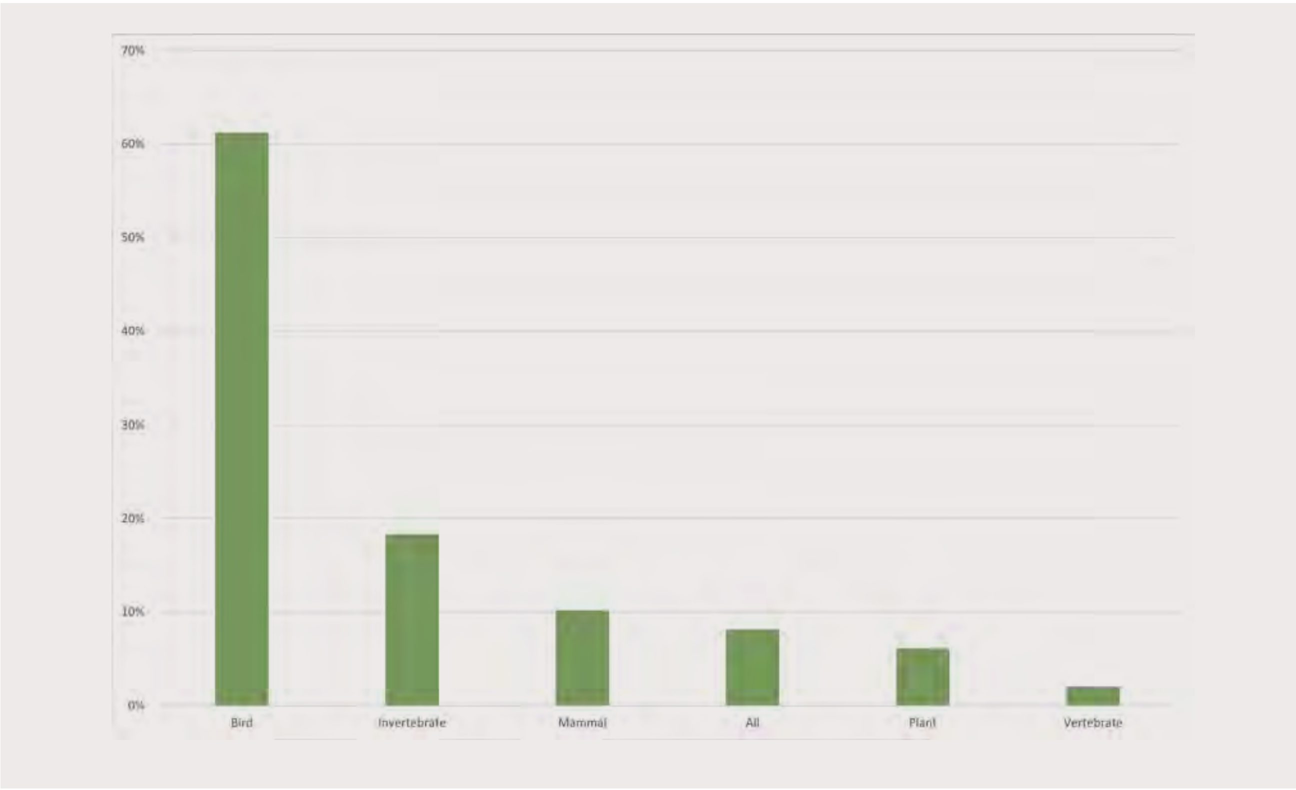

Figure 5. Target of Publications on Biotic Components

Table 2 - Summary of references

Authors	Year	Title	Abiotic factors	Country	Target
Balmori, A	2021	Electromagnetic radiation as an emerging driver factor for the decline of insects	EMF	World	Invertebrate
Barnes, TA; Dwyer, JF; Mojica, EK; Petersen, PA; Harness, RE	2022	Wildland fires ignited by avian electrocutions	Fire, barrier	USA	Bird
Bernardino, J.; Martins, R. C.; Bispo, R.; Moreira, F.	2019	Re-assessing the effectiveness of wire-marking to mitigate bird collisions with power lines: A meta-analysis and guidelines for field studies	Barrier effect	World	Bird
Bernardino, J.; Bevanger, K.; Barrientos, R.; Dwyer, J.F.; Marques, A.T.; Martins, R.C.; Shaw, J.M.; Silva, J.P.; Moreira, F.	2018	Bird collisions with power lines: State of the art and priority areas for research	Barrier effect	World	Bird
Biasotto, L.D.; Kindel, A.	2018	Power lines and impacts on biodiversity: A systematic review	All	World	All
Burdett, E.M.; Muriel, R.; Morandini, V.; Kolnegari, M.; Ferrer, M.	2022	Power Lines and Birds: Drivers of Conflict-Prone Use of Pylons by Nesting White Storks (Ciconia ciconia)	Line as resource	Spain	Bird
D'Amico, M; Catry, I; Martins, RC; Ascensao, F; Barrientos, R; Moreira, F	2018	Bird on the wire: Landscape planning considering costs and benefits for bird populations coexisting with power lines	All	World	Bird
Daniel-Ferreira, J; Bommarco, R; Wissman, J; Ockinger, E	2020	Linear infrastructure habitats increase landscape-scale diversity of plants but not of flower-visiting insects	Habitat conversion	Sweden	Plant
Dániel-Ferreira, J; Fourcade, Y; Bommarco, R; Wissman, J; Öckinger, E	2023	Communities in infrastructure habitats are species rich but only partly support species associated with semi-natural grasslands	Habitat conversion, corridor effect	Sweden	Invertebrate, plant
Day, RH; Cooper, BA	2022	Behavior of Hawaiian Petrels and Newell's Shearwaters (Ayes: Procellariiformes) Around Electrical-Transmission Lines on Kaua'i Island, Hawaiian Islands	Barrier effect	USA	Bird
Dean, W.R.J.; Seymour, C.L.; Joseph, G.S.	2018	Linear structures in the Karoo, South Africa, and their impacts on biota	All	South Africa	All
Eftestol, S; Tsegaye, D; Flydal, K; Colman, JE	2016	From high voltage (300 kV) to higher voltage (420 kV) power lines: reindeer avoid construction activities	Barrier effect	Norway	Mammal
Escobar-Ibáñez, J.F.; Aguilar-López, J.L.; Muñoz-Jiménez, O.; Villegas-Patraca, R.	2022	Power Lines, an Understudied Cause of Avian Mortality in Mexico	Barrier effect	Mexico	Bird
Froidevaux, J.S.P.; Jones, G.; Kerbiriou, C.; Park, K.J.	2023	Acoustic activity of bats at power lines correlates with relative humidity: a potential role for corona discharges	Barrier, edge effect, noise, light, EMF	France	Mammal

Authors	Year	Title	Abiotic factors	Country	Target
García-Alfonso, M; van Overveld, T; Gangoso, L; Serrano, David; D, Donázar, J. A.	2021	Disentangling drivers of power line use by vultures: Potential to reduce electrocutions	Line as resource, Barrier effect	Spain	Bird
Garfinkel, M; Yakandawala, K; Hosler, S; Roberts, M; Whelan, C; Minor, E	2023	Testing the accuracy of a Rights-of-Way pollinator habitat scoring system	Habitat conversion	USA	Invertebrate
Gibson, D; Blomberg, EJ; Atamian, MT; Espinosa, SP; Sedinger, JS	2018	Effects of power lines on habitat use and demography of greater sage-grouse (Centrocercus urophasianus)	Habitat loss, corridor effect	USA	Bird
Guil, F.; Pérez-García, J. M.	2022	Bird electrocution on power lines: Spatial gaps and identification of driving factors at global scales	Barrier effect	World	Bird
Guil, F.; Soria, MA, Margalida, A, Perez-Garcia, J.	2018	Wildfires as collateral effects of wildlife electrocution: An economic approach to the situation in Spain in recent years	Fire, barrier	Spain	Bird
Hays, QR; Tredennick, AT; Carlisle, JD; Collins, DP; Carleton, SA	2021	Spatially Explicit Assessment of Sandhill Crane Exposure to Potential Transmission Line Collision Risk	Barrier effect	USA	Bird
Hill, B; Bartomeus, I	2016	The potential of electricity transmission corridors in forested areas as bumblebee habitat	Habitat conversion, corridor effect	Sweden	Invertebrate
Hrouda, J; Brlik, V	2021	Birds in power-line corridors: effects of vegetation mowing on avian diversity and abundance	Habitat conversion, edge effect	Czech Republic	Bird
Hyde, JL; Bohlman, SA; Valle, D	2018	Transmission lines are an under-acknowledged conservation threat to the Brazilian Amazon	All	Brazil	All
Kohl, MT; Messmer, TA; Crabb, BA; Guttery, MR; Dahlgren, DK; Larsen, RT; Frey, SN; Liguori, S; Baxter, RJ	2019	The effects of electric power lines on the breeding ecology of greater sage-grouse	Habitat loss, fragmentation	USA	Bird
Lebeau, CW; Smith, KT; Holloran, MJ; Beck, JL; Kauffman, ME; Johnson, GD	2019	Greater sage-grouse habitat function relative to 230-kV transmission lines	Habitat loss, fragmentation	USA	Bird
Lupi, D.; Palamara Mesiano, M.; Adani, A.; Benocci, R.; Giacchini, R.; Parenti, P.; Zambon, G.; Lavazza, A.; Boniotti, M. B.; Bassi, S.; Colombo, M.; Tremolada, P.	2021	Combined Effects of Pesticides and Electromagnetic-Fields on Honeybees: Multi-Stress Exposure	EMF	Italy	Invertebrate
Luzenski, Jeff; Rocca, Claudia E; Harness, Richard E; Cummings, John L; Austin, Daryl D; Landon, Melissa A; Dwyer, James F	2016	Collision avoidance by migrating raptors encountering a new electric power transmission line	Barrier effect	USA	Bird
Marques, A.T.; Palma, L.; Lourenço, R.; Cangarato, R.; Leitão, A.; Mascarenhas, M.; Tavares, J.T.; Tomé, R.; Moreira, F.; Beja, P.	2022	Individual variability in space use near power lines by a long-lived territorial raptor	Barrier effect, line as resource	Portugal	Bird

Authors	Year	Title	Abiotic factors	Country	Target
Marques, AT; Martins, RC; Silva, JP; Palmeirim, JM; Moreira, F	2021	Power line routing and configuration as major drivers of collision risk in two bustard species	Barrier effect	Portugal	Bird
Martin, CJ; Bork, EW; Nielsen, SE	2022	Mortality of grassland birds increases with transmission lines	Barrier effect	Canada	Bird
Mercker, M; Jodicke, K	2021	Beyond BACI: Offsetting carcass numbers with flight intensity to improve risk assessments of bird collisions with power lines	Barrier effect	Germany	Bird
Moreira, F; Encarnacao, V; Rosa, G; Gilbert, N; Infante, S; Costa, J; D'Amico, M; Martins, RC; Catry, I	2017	Wired: impacts of increasing power line use by a growing bird population	Barrier effect, line as resource	Portugal	Bird
Moreira, F; Martins, RC; Catry, I; D'Amico, M	2018	Drivers of power line use by white storks: A case study of birds nesting on anthropogenic structures	Line as resource	Portugal	Bird
Murphy, RK; Dwyer, JF; Mojica, EK; McPherron, MM; Harness, RE	2016	Reactions of Sandhill Cranes Approaching a Marked Transmission Power Line	Barrier effect	USA	Bird
Petri, AK; Schmiedchen, K; Stunder, D; Dechent, D; Kraus, T; Bailey, WH; Driessen, S	2017	Biological effects of exposure to static electric fields in humans and vertebrates: a systematic review	Static field	World	Vertebrate
Plewa, R; Jaworski, T; Tarwacki, G; Gil, W; Horak, J	2020	Establishment and Maintenance of Power Lines are Important for Insect Diversity in Central Europe	Habitat conversion	Poland	Invertebrate
Rebolo-Ifran, N; Plaza, P; Perez-Garcia, JM; Gamarra-Toledo, V; Santander, F; Lambertucci, SA	2023	Power lines and birds: An overlooked threat in South America	Barrier effect	South America	Bird
Richardson, M. L.; Wilson, B. A.; Aiuto, D. A. S.; Crosby, J. E.; Alonso, A.; Dallmeier, F.; Golinski, G. K.	2017	A review of the impact of pipelines and power lines on biodiversity and strategies for mitigation	All	World	All
Russo, L; Stout, H; Roberts, D; Ross, BD; Mahan, CG	2021	Powerline right-of-way management and flower-visiting insects: How vegetation management can promote pollinator diversity	Habitat conversion	USA	Invertebrate
Šálek, M; Riegert, J; Krivopalova, A; Cukor, J.	2023	Small islands in the wide open sea: The importance of non-farmed habitats under power pylons for mammals in agricultural landscape	Habitat conversion	Czech Republic	Mammal
Šálek, M; Václav, R; Sedláček, F	2020	Uncropped habitats under power pylons are overlooked refuges for small mammals in agricultural landscapes	Habitat conversion	Czech Republic	Mammal
Schmiedchen, K.; Petri, A.-K.; Driessen, S.; Bailey, W.H.	2018	Systematic review of biological effects of exposure to static electric fields. Part II: Invertebrates and plants	Static field	World	Invertebrate, plant

Authors	Year	Title	Abiotic factors	Country	Target
Shaw, J.; Reid, T.; Gibbons, B.; Pretorius, M.; Jenkins, A.; Visagie, R.; Michael, M.; & Ryan, P.	2021	A large-scale experiment demonstrates that line marking reduces power line collision mortality for large terrestrial birds, but not bustards, in the Karoo, South Africa	Barrier effect	World	Bird
Shaw, J.M.; Reid, T.A.; Schutgens, M.; Jenkins, A.R.; Ryan, P.G.	2018	High power line collision mortality of threatened bustards at a regional scale in the Karoo, South Africa	Barrier effect	South Africa	Bird
Shepherd, S.; Lima, M. A. P.; Oliveira, E. E.; Sharkh, S. M.; Jackson, C. W.; Newland, P. L.	2018	Extremely Low Frequency Electromagnetic Fields impair the Cognitive and Motor Abilities of Honey Bees	EMF	Lab	Invertebrate
Slater, S. J.; Dwyer, J. F.; Murgatroyd, M.	2020	Conservation Letter: Raptors and Overhead Electrical Systems	Barrier effect	USA	Bird
Smith, JA; Dwyer, JF	2016	Avian interactions with renewable energy infrastructure: An update	Barrier, corridor effect	USA	Bird
Uddin, M; Dutta, S; Kolipakam, V; Sharma, H; Usmani, F; Jhala, Y	2021	High bird mortality due to power lines invokes urgent environmental mitigation in a tropical desert	Barrier effect, fragmentation	India	Bird
Zuluaga, S.; Speziale, K. L.; Lambertucci, S. A.	2022	Flying wildlife may mask the loss of ecological functions due to terrestrial habitat fragmentation	Barrier effect, fragmentation	World	Bird, mammal, invertebrate

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6. Social and Cultural Aspects

Comparing high voltage overhead and underground transmission infrastructure (up to 500 kV)

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1.

Introduction

This study aims to investigate the benefits and trade-offs between overhead and underground transmission line infrastructure, specifically focusing on issues associated with under-grounding new transmission infrastructure. It seeks to establish a clear and consistent approach to the evaluation of overhead lines and underground cable transmission, including the consideration of community concerns around the need for new transmission infrastructure to connect large renewable energy generation projects. It does this through systematic reviews of the literature as well as incorporating experiences of Transmission Network Service Providers (TNSPs) in Australia and overseas. The study has a particular focus on 500kV transmission infrastructure which are projected to figure in most large projects in Australia going forward.

Historically, transmission networks in Australia developed from the need to transfer large amounts of power from large coal fired power stations, typically co-located near coal reserves, over long distances to major cities and industrial load centres. In contrast, the proposed large scale renewable generation facilities, mainly solar and wind farms, require greater land areas and are largely being located in greenfield areas with little or no existing transmission network infrastructure. These new developments are naturally creating community interest and concerns around a range of potential impacts, including but not limited to: visual amenity; environment; Traditional Owner lands; agricultural land use; and social licence to operate concerns. This has led to questions surrounding when it is appropriate to underground transmission infrastructure and the likely implications of doing so.

This chapter focuses on the social and cultural dimensions that influence the acceptance of overhead and underground transmission lines. It does this through consideration of individuals, communities and First Nations People in two parts. It first focuses on the factors that influence social acceptance and social licence that emerged from the peer reviewed literature in Scopus and Web of Science, using the PRISMA methodology to guide the process (refer Appendix A). Through this process, 102 papers were included in this review. Geographically, nearly 90% of the studies were conducted in Europe or the US, with only 4 studies being located in Australia (all of which took place in Queensland). The second section summarises an overview of considerations for ensuring culturally responsive engagement with First Nations People and details the principles for cross-cultural collaborative design with a detailed account provided in Appendix B. The key findings from the literature review were compared with the engagement principles of the 2017 CIGRE Greenbook. The findings from the literature review differ in that they have a stronger focus on normative aspects to ensure social justice considerations enhance collaboration with communities. Finally, the chapter presents some overall conclusions and key findings arising from the review and discusses their associated implications.

2.

Results

2.1 Frameworks in the literature

Since 1988, there have been a variety of social acceptance frameworks developed in the literature that investigate the key factors that influence the social acceptance of transmission lines. They mainly focus on overhead lines which, until recently, have been the predominant form of transmission infrastructure [1], [2]. The earliest study by Furby et al., (1988) [5] (Figure 1), details a number of factors that extend beyond the physical features of the technology. All have appeared in subsequent frameworks and are applicable today.

In addition to the physical factors these include: types of participation; information and knowledge; issues of procedural and distributive justice [2]; fairness and trust [3]; along with perceptions of risk; - all of which lead to the formation of an individual's attitude (positive, neutral or negative) towards a project. Many of these factors feature in Moffat and Zhang's [4] social licence to operate (SLO) framework and the term most often referred to in the co-design workshop that informed this project (refer Chapter 2). SLO refers "to the ongoing acceptance and approval of an industry's operations by local community members and other stakeholders that can affect its profitability" [4, p. 61] and is particularly relevant to the challenge of deploying transmission lines.

A more recent framework that has frequently been applied to studies investigating the acceptance of energy technologies is the *Technology Acceptance Framework*, developed by Huijts, Molin and Steg (2012) [6] (Figure 2). This model shows more detail of the range of factors that influence a person's willingness to accept or oppose a technology. These factors highlight the ways in which individuals will make trade-offs when

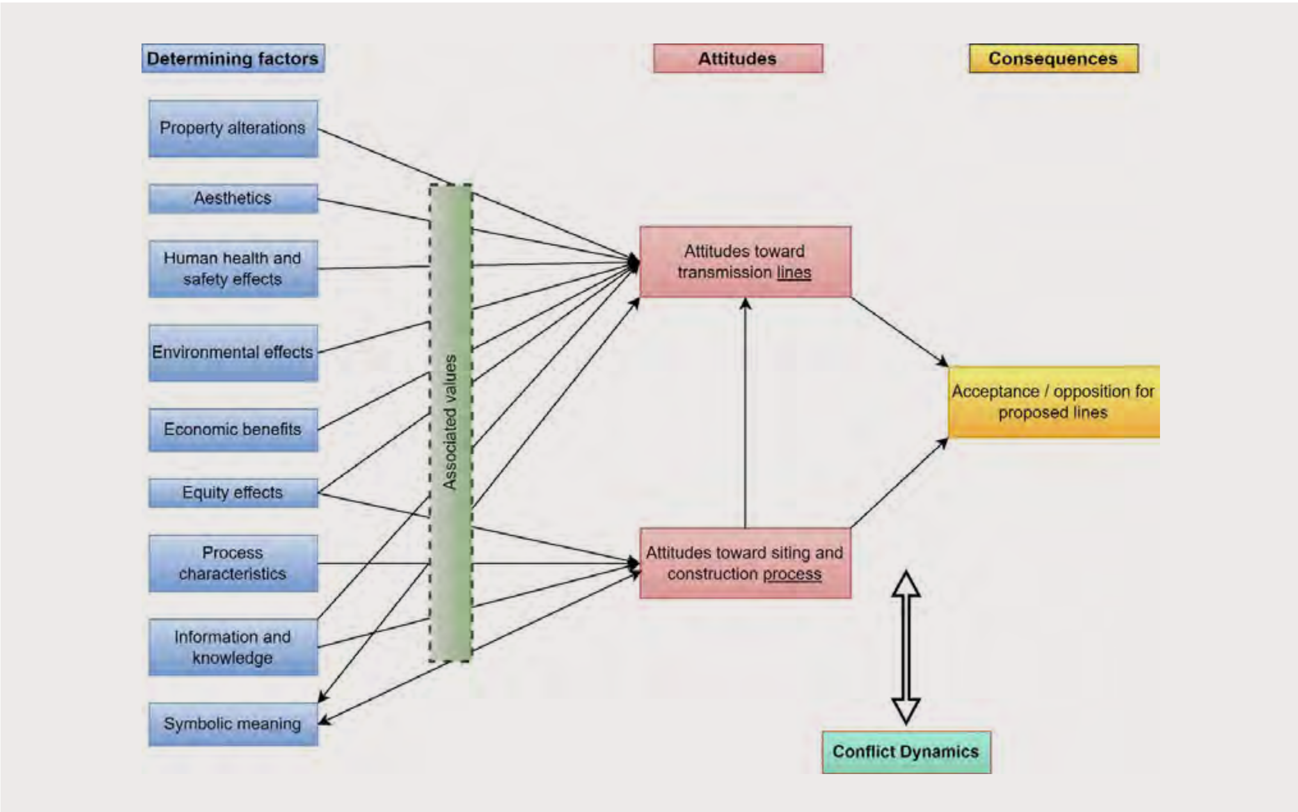

Figure 1 - Social Acceptance Conceptual Framework Adapted from - Social acceptance conceptual framework adapted from Furby et al. [5]

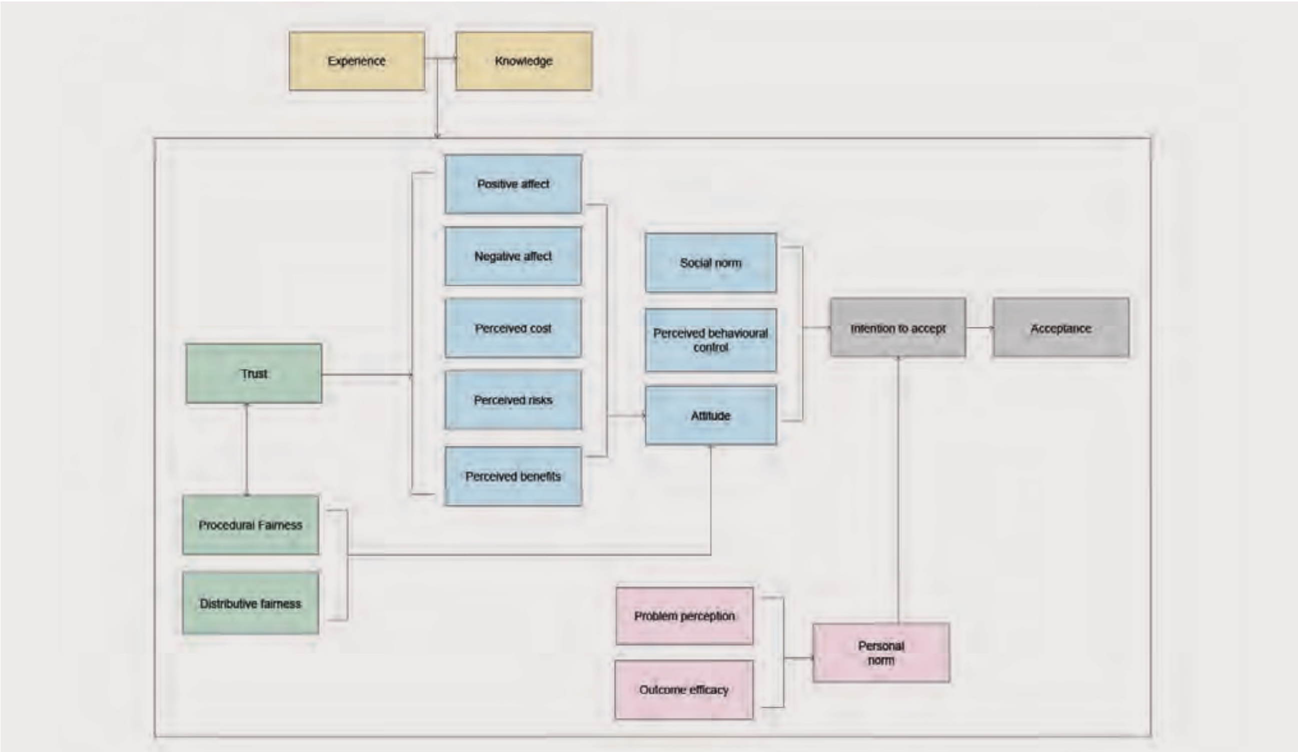

Figure 2 Technology Acceptance Framework (Huijts, Molin & Steg 2012) [6]

considering proposed transmission projects. It also highlights the influence of social norms and how local community, friends and families will influence how an individual might perceive a project and decide to accept or reject it [6]. This has been the case in Australia with groups of farmers and other stakeholders influencing their counterparts in their response to proposed transmission projects.

Other relevant and important considerations that have evolved in response to transmission lines (and other energy projects) and the earlier studies of NIMBYism (Not In My Back Yard), are the concepts of place attachment and place identity [7]. Devine-Wright (2009), summarises "place attachment" as a *"positive emotional connection with familiar locations such as the home or neighbourhood"* (p.417), which builds over time, while "place identity" describes how local characteristics, both *physical and symbolic*, contribute to an individual's sense of identity. For example, do they identify as a cattle farmer, a city dweller, or something else. When new projects are proposed, that may change or disrupt a local area, an individual's sense of place is likely to be challenged. How they respond to such disruption not only depends on their strength of attachment (i.e. length of time in the place), but similar to the *Technology Acceptance Framework*, the likely impacts of the change (positive or negative), trust in the developer and procedural justice considerations [8].

2.2 Factors influencing social licence and acceptance

2.2.1 Complexity, context and changing norms

The literature highlighted how the factors that influence social licence and acceptance can be difficult to understand. This is mainly due to the combination of: a) electricity system complexity, b) dynamic views (reflecting changing norms, identity and place attachment), and c) context dependency (each site has its own unique characteristics). The complexity of the electricity system from governance mechanisms to technology deployment, renders gaining a shared understanding and participation between stakeholders difficult, particularly for members of the general public [9]. Additionally, several papers showed that societal attitudes and acceptance of transmission line projects are dynamic [9]–[13]. That is, they will be influenced by project related events which can arise at any stage [14], [15], as well as broader *socioeconomic and political events* that have the potential to influence acceptance of a project [12]. However, Friedl and Reichl [16] showed that once a person's attitude solidifies, either for or against a project, they are less likely to change their mind.

Context dependency and the difficulties in generalising findings from one study to the next was mentioned in the majority of papers and highlighted in several reviews ([5], [13], [17]). The two quotes below reflect the dynamic and context dependent nature of social acceptance.

"...each transmission line siting presents a unique combination of characteristics, and it is unlikely that we will be able to predict exactly how the affected public will react with respect to all the relevant elements" [5, p. 39]

"Interventions that worked in 2008 would probably not have worked out in the same way in 2013. This suggests that there is no blueprint approach for organizing stakeholder participation in transmission grid planning, yet the France–Spain interconnection project shows that true dialogue can foster societal support." [18, p. 226]

This means that projects to date, whilst useful in understanding and identifying what has led to acceptance in the past, cannot be applied independently of the specific context in which the project is occurring.

2.2.2 Aesthetics and visual impact

In the studies reviewed, overhead transmission lines and towers were always viewed negatively because of their visual impact on the landscape [5], [19]. Unsurprisingly, this was not mentioned in relation to underground cables. When comparing other energy infrastructure projects, roads, or telephone towers with overhead transmission lines, transmission lines were ranked as being the worst when considering negative visual impacts [20]–[24]. Visual impacts were reported to have additional negative effects on the character of the place and property values, depending on the setting (i.e. rural or urban, farmland or wilderness). They were also inferred to have additional potential impacts on recreational activities, tourism, and local commerce.

A German study cited in Menges and Beyer [25] from the environmental non-government organisation Environment Action Germany (*Deutsche Umwelthilfe*) found that in 2010:

"over 70% of participants at least 'agree fully' to the statement 'overhead lines impair a landscape's character'. In contrast, 70% of respondents see no noteworthy landscape impairment in the case of underground cables". [25, p. 34]

To understand whether the negative response to visual impacts of transmission line towers could be reduced through improved design, Priestly and Evans [26] surveyed 236 US residents affected by the upgrade of an existing overhead transmission line in California. Their methodology used photographs of tubular and lattice overhead towers within different landscapes and with towers painted green to blend in more to the background. The authors reported that the tubular design was more attractive for some participants (47%) but less attractive for others (21%). The green paint fared similarly. However, the landscaping of easements received overall positive reviews. This concurred with the study by Brinkley and Leach [27] where landscaping of easements was found to overcome initial negative impacts on property values.

In Queensland, Australia, Elliott and Wadley [28] conducted focus groups with homeowners and found that single steel pole tower designs were preferred to lattice towers. Similarly, Devine-Wright and Batel [29] surveyed the preferences of UK citizens for three different designs of overhead transmission towers - t-shaped, totem, and traditional - and found that 77% of respondents ranked the t-shaped tower as their first preference, while the traditional lattice pylon came last. For the Hinkley Point transmission line in the UK, Cotton and Devine-Wright [14] also noted that during workshops with affected residents, they were most concerned about tower height, and of their own accord discussed alternative designs to lattice designs and their potential suitability.

Lienert et al.'s, [20] survey of Swiss citizens (n=248) showed that new transmission line projects and the use of larger sized towers, both led to lower acceptance. Interestingly, Wadley et al., [19] linked visual impacts with health impacts where it was felt that:

"visual factors might act as a proxy for, or reminder of, the alleged harm of EMFs. Both externalities constitute not shocks but stresses, the visual one overt, the health one covert." [19, p. 751]

In contrast to the above research, Keir et al., [30] reviewed citizen submissions to the Department of Energy (DOE) in the US in relation to a new overhead transmission line project - the 187-mile Northern Pass in New England. Concerns with visual impacts were only present in 11% (4th ranking) of the submissions and the dominant concerns were with the procedural and distributive justice elements of the project (refer section 2.2.9).

2.2.3 Human health

The literature shows that concerns relating to human health impacts arising from transmission lines mostly focus on the impact of electromagnetic fields (EMF) and to a much lower extent noise [19], [31], [32]. Additionally, the risk of electrocution and or accidents such as collision with equipment was mentioned in a few studies [5], [28], [33].

The strength to which EMF was reported to influence acceptance varied significantly between studies. The studies suggest that the depth and source of the information influenced an individual's response to the concept of EMF, with some individuals expressing considerable concern surrounding EMF while others were much less worried. It could be assumed that communicating the most up to date and factual information will be an important factor to minimise these concerns.

German, Swiss, and Australian research conducted with residents not directly affected by transmission line projects, showed that perceptions of EMF risk significantly undermined acceptance [1], [28], [31], [34]. These results align with studies conducted in transmission line host communities in the Netherlands [35], Denmark [10], Germany [36], and the UK [14] where overall, local residents expected negative EMF related health impacts. For the UK Hinkley Point transmission line, the most commonly discussed issue during focus groups involving local residents was EMF [14]. Some residents raised concerns about *"the 'contamination' of food systems or ecosystems and the release of 'gases' from HVOTLs"* illustrating some of the confusion regarding the impact of EMF. In addition, residents mentioned that they did not trust electricity utilities to provide accurate and unbiased information on the matter. In Denmark, local residents, interest organisations, and municipalities raised concerns with EMF which focused mainly on the quality of information provided and calculations in relation to the required safe distances from houses [10].

Conversely, Cotton and Devine-Wright [37] found, using a prioritisation method (Q sort) that EMF was not the main concern for professional stakeholders nor local residents. Similarly, EMF was only included in 8% of citizens' submissions to the DOE in the US for a new overhead transmission line project [30]. In Germany, Mueller [38] reported that residents' concerns over EMF was not a significant driver to take action against transmission lines. In another study they reported:

"residents living at the underground HVTL project site do not expect more or less harm from future power lines than people living in the overhead HVTL project area." [39, p. 462]

2.2.4 Proximity

Carley et al.'s [17] systematic review of survey-based studies, found no consistent findings on the impact of energy infrastructure proximity on resident acceptance. They concluded that proximity acceptance was a context dependent issue. It was also noted in large national surveys by Konisky et al., [40] of a representative sample of US citizens' attitudes (n=16,200) towards energy infrastructure - with some living in proximity of existing transmission line projects and others living near proposed transmission line projects - found that proximity played a limited role. However, Zaunbrecher et al.'s survey across Germany found that for a hypothetical project located 400m, 800m, and 1200m from their residence *"the highest possible distances from residential dwellings are preferred"* [34, p. 436]. Similarly, Stadelmann-Steffen's [31] survey of Swiss residents (n=1,129) found that negative perceptions was highest in those not living near transmission lines while those living closer were less likely to hold this perception. This suggests there is an element of normalisation for those living in proximity.

Several investigations targeted the effect of proximity on affected communities. For example, when Cotton and Devine-Wright [14] conducted focus groups with 38 residents affected by a proposed new transmission line project, the residents were most concerned with EMF in relation to the proximity of homes and schools, but their discussions suggested that those concerns could be mitigated by tower heights and undergrounding. Nelson et al., [41] showed that when residents (n=358) along the Tehachapi transmission line in the US had negative attitudes towards the transmission lines, they perceived the line as closer, and they were more likely to take action and oppose. While Mueller et al., in their survey (n=1,302) of people living along a proposed overhead transmission line in Germany, *"revealed that increasing spatial proximity significantly enhanced local residents' risk perceptions, reduced general public support for grid expansion, and triggered their information seeking and oppositional behaviour"* [42, p. 145].

However, it is important not to generalise, when trying to evaluate how close is too close for local residents. Giaccaria et al., [43] surveyed (n=1,410) residents in communities affected by existing overhead transmission lines in Italy and participants' perceptions of impact from the existing line were stratified according to their proximity. The perceived impacts cited were visual, health and property value. No impact was reported by 6.9% of residents living 0 to 50m from the line, 31.8% for those living between 50-200m from the line, and 60.8% for those living in the 200-1000m area.

Bertsch et al., [44] studied what the minimum acceptable distance might be for hypothetical overhead and underground transmission line projects in Ireland (n=1,044). The research revealed that less than one third of participants would accept an overhead line within 5km of their residence, while approximately 50% of participants would accept an underground line within 5km.

2.2.5 Familiarity

Building on proximity, Devine-Wright and Devine-Wright [45] theorised that when something new becomes familiar it "loses specificity and potentially threatening qualities" (p. 359). As such, this familiarisation could potentially lead to greater acceptance of new transmission lines where older transmission line projects are already in place. Bailey et al., [46] conducted interviews of local residents along a proposed overhead transmission line in the UK and found that long term residents of the area had higher acceptance of the new line and this acceptance was attributed to their familiarity with other powerlines in the area. Joe et al., reported that:

"people who can see existing HVOTLs from their homes also do not think the HVOTLs are intrusive; that they are not opposed to siting new HVOTLs near their home; and that they did not think new HVOTLs would decrease the property value of their homes". [47, p. 132]

Simora et al. [48] showed that for a convenience sample of 6,568 German citizens, existing transmission line towers in their area had no influence on acceptance of new transmission line infrastructure. However, Wadley et al. [19] surveying Queensland residents revealed that acquaintance with overhead lines was a reliable predictor of concern.

2.2.6 A strong preference for undergrounding

Recognising overhead transmission line acceptance issues, the German government "introduced more technology options, in particular the use of high-voltage direct-current (HVDC) power lines and extended the usage of underground cables" [36, p. 225], starting with pilot projects with the objective of assessing public acceptance. Zaunbrecher et al., [49] surveyed German residents (n=109) and reported that overhead HVDC did not significantly influence acceptance. Additionally, when information about HVDC powerlines was provided, it only mildly positively influenced preference.

In their assessment of several energy technologies including hypothetical overhead and underground transmission lines Bertsch et al., [44] showed there was a marked preference for underground transmission lines (Table 1). Similarly, surveys by Lienert et al., [50] in Switzerland and by Sharpton et al., [51] in the US found that undergrounding was preferred, although US responses were still neutral to positive towards overhead lines.

In the Cotton and Devine-Wright [14] focus group (n=38) study in the UK, the majority of participants supported undergrounding with a minority discussing EMF and environmental impacts of undergrounding [17]. A German study cited in Menges and Beyer in 2010 showed that 77% of participants *"would support construction works without any further conditions if underground cables were used"* [25, p. 34].

Table 1. Comparing Acceptance of Overhead and Underground Transmission Lines

Level of acceptance	OH (%)	UG (%)
Positive	5	43
Somewhat positive	18	32
Neutral	30	21
Somewhat negative	30	3
Negative	14	1

Data sourced from Bertsch et al., 2017 p. 477

For existing overhead transmission lines, Wuebben [24] conducted a survey of visitors (n=81) to a US arboretum specifically designed around an existing overhead transmission line and its associated substation, 46% of respondents indicated that powerlines should be removed or buried. Elliott and Wadley [28] facilitated focus groups (n=78), with mixed communities from across Queensland to assess overhead transmission line tower design preferences. They reported that undergrounding was preferred to any overhead transmission line tower design presented. However, participants acknowledged that cost might preclude undergrounding.

2.2.7 Economic considerations

Installation impacts

In advance of projects being deployed, economic impacts, such as the effects on tourism, were mentioned as a consequence of the loss of visual amenity through the use of overhead powerlines in a UK study [14].
In the US, local communities linked overhead lines with a number of economic impacts including lower productivity because of disruption, job losses and a reduction in community tax bases [30]. Conversely, in Delaware and New Jersey (US), Firestone et al., [52] found that the local population expected neutral or positive effects from a submarine cable in terms of local jobs and commercial fishing impacts.

Post project deployment, Sæpórsdóttir and Hall [53] investigated tourist views of overhead transmission lines in Iceland and found that 54% had a negative experience and they were amongst *"the least desirable infrastructure in natural areas"*[54]. Further research by Sæpórsdóttir and Hall [54] confirmed that tourism operators found tourism prospects were much better at creating jobs than energy projects. However, any economic effect of these perceptions was not quantified with other authors suggesting it may or may not translate in lower visitation and loss of revenue [55].

Property values

Elliott & Wadley defined the loss related to residential property value from nearby overhead transmission lines in two ways:

"a resident's perceived loss of utility in foregone views and compatibility of adjacent land uses, but also in a reduction of investment value if prospective purchasers perceive a place as stigmatized" [28, p. 198].

Perceptions surrounding the impact of overhead transmission lines on property values is mostly negative though its prevalence and magnitude varies. For example, Nelson et al., [41] surveyed residents along the Tehachapi power line project (California, US) and showed that health impacts and property values were their main concerns. Lienert et al.,[20] surveyed Swiss residents and showed that house owners were more likely to have low acceptance and attributed it to fear of property values losses. Similarly, Simora at al., [48] asked German citizens to vote on hypothetical local overhead line projects and found that homeowners are less likely to vote in favour of the projects.

Mueller [38] conducted a survey in German rural communities in the vicinity of proposed transmission lines (n=2,605). The author found that the expected decrease in property value was slightly greater for overhead compared to underground. This in turn was expected to increase participation in the planning process.

In contrast, Keir et al., [30] analysed citizen submissions for a new transmission line in US and showed that only 5% of submissions included property value concerns, so whilst an important factor to consider, it was not a major concern. Similarly, Wadley et al., [19] surveyed Queensland residents and showed that loss in property value was cited by less than 50% of participants and ranked last amongst concerns. Joe et al., [47] in the US showed that those who could see the lines were not concerned with decreasing property values, suggesting pre-existing experience with powerlines helps improve their acceptability, when it comes to property values.

Although Furby et al., [5] raised the importance of understanding property professionals' perception to reduce any rippling effect to buyers and sellers. More recently Wadley et al., [32] showed a difference in perception between homeowners, property valuers and real estate agents. The study revealed that all three participant groups ranked visual impacts and noise as their main concerns. For homeowners, the second-ranked concern was EMF, while for valuers and agents, it was property value. Regarding the quantifiable financial impact of transmission lines on property values, Brinkley and Leach [27] conducted a meta-analysis of various technology impacts on property values including overhead transmission lines. The meta-analysis focused on overhead distribution and transmission lines between 1960 and 2008. The authors established that the range of average value change was *"+ 10% if including improved access to greenspace to -30%"*(p63). This aligns with a review by Cain and Nelson [13] showing that studies on property value loss have revealed mixed results.

The relationship between price-distance was also demonstrated to be non-linear [27]. However, only two of the reviewed studies were conducted pre- and post-construction, offering few possibilities to compare value variation for specific properties. Thus, for the vast majority of studies the variation in property value is calculated according to the distance to the overhead line or its visibility from the house along with the property market value at the time. The decrease in value is attributed to visual and aesthetic impacts while an increase in value was observed with accessible landscaped easements and the possibility of recreational activities. It was also observed that the property value loss disappeared over time (e.g. after 5 to 14 years post construction) which confirms the concepts of familiarisation and normalisation occur [27].

While most property value studies focus on family homes, few have been found to focus on commercial and industrial or agricultural land [27]. Sardaro et al., [56] conducted a review of farmland depreciation in the Apulia region, Italy and calculated that it ranged from approximately 6% for wheat through to 14% for vineyards. This was mainly impacted by where the lines intersected the land and the area it occupied, along with the height of towers and distance from the property boundary. However, the study did not discuss that such loss of property value is offset by compensation, with the main consideration being whether the compensation is adequate enough to cover any such loss of value.

Use of cost benefit analysis

Cost benefit analysis (CBA) is used to justify projects ranging from whole of transition and a zero carbon economy for grid expansion (AEMO ISP) to individual transmission projects [57]. For individual projects, the analysis supports decision makers with technology selection, transmission line siting, and compensation schemes. CBA is used to evaluate the balance of a project's positive and negative effects and through an accounting exercise, decide if the project would, overall, have positive outcomes and therefore should go ahead. The CBA process includes calculations, estimations, or attribution of values, often numerical, within the decided boundary of the assessment. The numerical value most used for transmission line projects is financial value.

Based on this literature review, there are five fundamental issues arising from CBA:

- CBA assumes that everything valued can be monetised and that all stakeholders agree with the assigned amount. Some components of CBA, such as the cost of underground cable versus overhead lines, are objective and relatively fixed. However, the monetisation of environmental or human health impacts becomes contentious. Additionally, the values attributed are subjective, highly context dependent and dynamic [57].
- The boundaries of the assessment are often considered to be too narrow e.g. limited to economic impacts, and do not evaluate alternative options for the transition as a whole or the transmission corridor location, or transmission corridor technology [14], [33], [37], [57], [58].
- Transparency and communication are lacking. Multiple decisions and assumptions are made throughout the assessment which require transparent and adequate communication for all stakeholders, and even more so as the project grows in complexity [10].
- Regulated processes to conduct CBAs are either missing or unsatisfactory [10], [58]. This includes issues relating to discount rates [57].
- Citizen's participation and its influence on CBA process and outcomes are not clear and/or mandated [10], [57], [58].

Compensation

The research confirmed that local impacts and associated losses should be compensated to allow impacted stakeholders and communities to receive the same level of benefits from infrastructure projects as the wider community [5], [59]. In the case of land resumption or compulsory acquisition, established compensation measures are determined *"by assessing the fair market value [FMV] of the land. FMV is the theoretical market value a willing buyer and willing seller would reach in a voluntary transaction"* [5], [60, p. 541], [61]. However, this does not account for several factors including the fact that owners of the land may not be willing sellers, and that attachment to place and community, or the suitability of land for particular uses such as farming, is not accounted for in the calculations [5], [60].

Beyond land resumption, testing households' compensation amount below 1000 euros in the general German population, Zaunbrecher et al., [34] revealed that compensation had no influence on acceptance and Simora et al., [48] showed that such compensation amounts may diminish acceptance. They suggest that the notion of what compensation amounts should be tested in communities and opened up for discussion if it is to have a positive impact on acceptance.

Furthermore, the literature pointed to a tension between individual and collective compensation. Hyland and Bertsch [62] conducted a national survey (n=1,044) of Irish residents associated with new transmission lines and found higher acceptance for infrastructure when compensated via a collective community benefit scheme. Additionally, Koelman et al., [63] interviewed transmission project community engagement personnel involved in negotiations with landowners along a new underground line in the Netherlands. They found that the majority of landowners were less concerned by their individual financial compensation than its fair distribution according to benefits and burdens.

Devine-Wright and Sherry-Brennan [64] investigated the impact of a community fund associated with a new overhead transmission line in the Leinster province of Ireland to compensate for visual impacts. The fund of 360,000 euros related to 24km of the new line and was administered by local councils and a national NGO through grants. It was additional to any financial compensation provided to landowners within 200 m of the transmission line. The authors found stakeholders within the local community broadly viewed the community fund as positive. However, they contested its geographical boundaries and its foundation on visual impacts only. The authors suggested that a collaborative approach to boundary setting could lead to further positive outcomes.

Vega-Araujo and Heffron [65] conducted interviews with a mix of stakeholders along a new overhead transmission line in Colombia, including Indigenous stakeholders. Three compensation schemes were available for socio-cultural impacts, use of territory, and ecosystem losses. Socio-cultural and use of territory compensation were both one off payments, which Indigenous communities criticised for their narrow boundaries, the lack of continuous assessment of project and compensation effects through the lifespan of the project. Compensation for ecosystem losses was also criticised as being ineffective and not fully understanding Indigenous cultures.

Use of the willingness to pay (WTP) analysis.

Willingness to pay (WTP) analysis is used to quantify the potential gap between the cost to implement people's preferences for a product or service, or in the case of transmission lines, a technology or certain level of reliability, and the maximum amount they are prepared to pay for it. WTP for mitigation measures of local impacts is difficult to calculate as it was shown to be non-linearly affected by distance to the transmission lines and requires disaggregation according to its drivers (visual, health, property value) as they result in significantly different WTP values [43].

WTP itself is a contested measure [57]. WTP for mitigation measures of local impacts such as pylon design or undergrounding do not reflect local stakeholders' preferences as transmission line projects benefit the entire nation and as such the cost of their impact should not be expected to be borne locally [29]. This issue was also encountered in Navrud et al.'s, [66] study that found Norwegian households did not believe a scenario in which locally impacted households would have to pay for mitigation measures.

2.2.8 Environmental impacts

In 17 articles, impacts on the environment by transmission line projects were cited as contributing to low acceptance. This is also consistent with the social licence to operate (SLO) literature where minimisation of environmental impacts and having strong environmental regulations in place were critical for ensuring an SLO existed. Keir at al., [30] reported that environmental impact was cited in 18% of the submissions to the new Northern Pass overhead line project in the US. Additionally, Lienert et al., [50] cites a German survey showing a lack of awareness of impacts of underground transmission lines on landscape modification in 82% of participants.

Challenges here include the quality of the Environmental Impact Assessment process, ensuring a real financial value is attributed to the environment, and how it is monitored. Key considerations include environmental damage in general or more specifically vegetation clearance, habitat and wildlife loss (6 papers), soil degradation (2 papers), water and groundwater quality and flow (2 papers), noise (6 papers), fire (1 paper), weed dispersal (1 paper), waste (1 paper), impact on national park and conservation areas (1 paper) and impacts on agriculture (2 papers). In some studies, transmission projects were found to have a positive impact on the environmental quality perception through landscaping and specific design with the OHTL easement [23], [26].

2.2.9 Process

The process theme was by far the most significant of all themes that emerged in the literature, cited in 68 papers. Many of these studies were concerned with either: (i) distributive justice—concerned with the allocation of benefits (e.g. are revenues shared sufficiently) and burdens or costs (who suffers from the burden or environmental impacts of the siting of the infrastructure) or (ii) procedural justice—concerns about whether the process is fair, transparent and follows a due process with adequate governance and attenuation to any power imbalances; allows for participation and engagement; information sharing and so on (Vega-Araujo & Heffron [65]). These concepts are expanded upon in the following section.

Distributive justice

The electricity system and the services it distributes throughout the grid can represent equity ideals while at the same time, the system itself is an epitome of spatial injustice for the community affected by the infrastructure [45]. Batel and Devine-Wright [67] argue that the energy transition, as it is currently being implemented, perpetuates neoliberal and colonial models of development on local and global scales and increases inequalities. Furby et al., [5] reported that cost benefit analyses estimated overall positive outcomes for the broader community, while local communities carry most of the burden of the projects. As inequalities emerge between communities then so do the concerns of distributive justice [65].

According to Vega-Araujo and Heffron [65], Indigenous communities disputed the financial compensation procedure and calculation for the overhead transmission line projects taking place in La Guarija region of Colombia. They cited concerns from Indigenous communities across several areas including the proportionality of impacts and benefits, and the need for reparation for historical wrongdoings. Having the capacity to negotiate better outcomes is an important consideration for overcoming distributive justice concerns.

Financial compensation and land resumption are key areas where distributive justice issues emerge. Koelman et al., [63] showed that within an affected community, distributive justice and appropriate sharing of benefits, was considered more important than individual financial compensation. Another example of lack of distributive justice was highlighted by Porsius et al., (2016) who found that when land resumption takes place—in this example land was resumed for those within the 0.4m zone—those outside the zone were also concerned about the impacts of health and on property values but were without compensation [28].

The literature confirms that accelerated approval processes for transmission line projects are counter to ensuring considerations of distributive justice, as they often are not seen to give due consideration to community concerns [36]. Furby et al., [5] suggested that procedural justice could help to compensate for distributive justice issues and this view was widely shared across the literature, in particular the need for early citizen participation [37].

Procedural justice

A core component of procedural justice is ensuring adequate governance structures are in place that allow for transparency and public participation. This can be both formal and informal interactions, depending on the decision-making processes in place. Azarova et al., [68], confirmed that while the attributes of the technology are important, so too are the governance structures that surround its design, implementation and operation. Additionally, a lack of coordination and efficiency in the planning processes between jurisdictions can lead to project delays. An issue now being rectified in several European jurisdictions, with the potential for fines if projects take too long [18], [36], [69].

Regulated public engagement is common throughout Europe, the US and the UK. However, regulations can at times fall short. For example, there is a balance to be found relating to timing. That is, when to involve communities and end users. Involving communities in scenario and transition planning where a specific route may not have been settled upon can cause undue concern for communities who may end up not being impacted by it. This means at times, early engagement can be seen to be counterproductive. Moreover, the need for new transmission lines may need to be revisited (for every project in the area) and re-evaluated with community input causing engagement fatigue, delays and potential cancellation of projects [2], [36], [37], [58], [70].

As such, the goals of public engagement and participation require clarity for all stakeholders, including electric utilities [70]. Furthermore, adequate resources for engagement, including the use of independent experts or processes facilitated through research institutions, can help to facilitate more successful and fair project outcomes [5], [71], [72]. The latter due to a view of independence of the research institution. Lastly, acknowledging that full consensus is unlikely to be reached, even with best practice public engagement, having a clear picture of what constitutes “good enough” consensus and support, and communicating this upfront may improve transparency and fairness [16].

In some instances, a single cross-jurisdictional planning entity has also been seen to add value in transmission line project governance. Although again, such an entity may not always be able to deal with specific contexts. However, having a single point of contact for the public, providing access to a core group of experts, has been seen to improve perceptions of procedural justice [36], [69]. Coordination of spatial planning between electricity projects as well as between other economic development activities such as tourism, telecommunication or transport was also regarded as an important contributor to just and fair governance and reducing engagement fatigue [18], [54].

Information and knowledge

A lack of knowledge about the electricity system, coupled with a lack of information about projects has been identified as drivers of opposition amongst various transmission line projects [9], [73]. Quality information for building acceptance has multiple purposes including raising awareness, education, developing capacity, and relationship building. Filling knowledge gaps around governance structures and regulations of the electricity system, environmental and health impacts and risks, and alternative technologies and their trade-offs have all been seen to enhance acceptance of projects [5], [74], with a warning not to assume a knowledge deficit exists for all [14], [38], [70]. Regardless of the information, transparency was key. Stadelmann-Steffen [31] posited that because negative information can substantiate latent fears, opponents’ use of *“information about the negative consequences of a project will generally be more powerful on the debate compared to the arguments of the proponents of a project—rather independently of whether the arguments are appropriate or not”* [31, pp. 540–541].

However, when it comes to information provision, the literature shows there is no consistent message or information bundle that helps build confidence in the process. For example, Cohen et al., [75] found that messages including the economic and decarbonisation effects of transmission line projects were more likely to reduce opposition compared with local compensation information. Technical details and project maps were seen to be useful information to be shared by electric utilities [58]. However, it was found there were several misperceptions that were hard to overcome through engagement around transmission lines. For example:

- decentralisation renders grid expansion and transmission lines unnecessary
- the extent to which soil shields from EMF
- underground lines result in landscape alterations [20]
- why EMF safe distance calculations use average rather than peak load [10].

Similarly, who shares the information relating to EMF, was found to be important for building trust. There was some caution suggested with using regulators or those seen to have a vested interest in the outcomes of the project [5], [10], [14], but at the same time information from multiple sources that are contradictory can also be problematic [35]. These findings are in line with the SLO literature which talks about the need for quality not quantity of information and the importance of trusted experts as sources [4], [76]. These instances highlight the fine balance required by projects to contextualise and tailor information for the range of audiences to ensure perceptions of procedural justice and fairness are present [2].

Porsius et al. noted a *"mismatch between the information they* [residents] *wanted and the information they received"* [35, p. 1504] and that personalised information was desired (touching again on context sensitivity). For example, pylon height in comparison to local landmarks could allow local residents to picture the towers and their impacts on the landscape better [14], or maps with the transmission line location and the EMF sensitive zone marked out was deemed to be helpful [35]. Additionally, Moyer and Song [76] highlighted that narratives rooted in cultural identity are likely to be more effective.

Continuous access to information organised by various stakeholders through media, public meetings, press conferences, website containing transcripts of meetings and letters allowed all stakeholders to keep abreast of up to date information [18]. However, again according to the SLO literature this must concentrate on quality not quantity.

Collaborative engagement and participation forms

Public engagement can be thought of as the sum of the interactions between project related information, people, structures, organisations and the public and its representative organisations. Devine-Wright and Batel [7], [80], posited that those interactions would be the key determinants of acceptance.

According to Fiorino [81], participation exists in three forms that will lead to different outcomes:

- *Instrumental participation* aims to increase trust in, and social acceptance of, the process and outcomes, and stems from the question - how do we get this done [18]? It is associated with top-down approaches, later stage public engagement, and legitimisation of predetermined outcomes [14], [30], [65], [69].
- *Substantive participation* recognises that stakeholders, including non-experts (local or others), have value which leads to essential knowledge creation; it is described as constructive dialogue and enables collaboration that leads to two-way knowledge creation in which contextualised learning takes place, and shared understanding is developed, ultimately reflected in the design and construction of the project [2], [18], [29], [31], [58], [65], [72].
- *Normative participation* is concerned with citizens being ultimately in control of the decisions directly affecting them and focuses on how to enable meaningful and inclusive participation [18]. From a social justice perspective, it is concerned with inclusion and representation, legitimacy, transparency, accountability, agency, and power balance.

Who is being engaged by decision-makers plays a major role in the substantive considerations of procedural fairness and the perceptions of it. As such, the processes of identification of stakeholders to be engaged matters and requires a process that has a clear rationale, is transparent and inclusive, and ultimately enables adequate communication [70], [82].

Activism was overtly mentioned in 15 papers and depicted as being highly influential on community acceptance, conflict development, project delays and cancellations [13], [18]. However, it was not an actual focus of any studies. Furby et al., [5] cited a study that showed that organised activism can play a greater role than negative media coverage in the development of conflict. For some projects, activist groups were seen to provide value by local residents and electric utilities [18], however they could also lack legitimacy [14].

Activist groups can originate from, and be composed of, diverse groups of people. In the examples provided by the literature, sometimes the groups acted independently and at other times they formed networks or coalitions [13], [83], [84] and would often participate in actions both within and outside, the formal processes of engagement [13]. Some local action groups declined to participate in transmission line consultation because they did not believe the project was needed and did not trust the transmission line company to manage it properly [58].

Trust

Trust was often viewed and observed to be a key component of acceptance. It was seen to play an important role as a mediator of the perception of risks and benefits, and likelihood of contestation and activism [13], [30], [85]. Ceglarz et al., highlighted that trust is *"a complex, multidimensional and context-dependent concept"* [79, p. 571]. They identified three dimensions of trust relating to transmission line projects: interpersonal, institutional, and generalised or social trust. Institutional trust instilled confidence in the need for the energy transition as a whole and the requirement for the individual project within it. Social or generalised trust allowed for common good to take precedence over individual interests, as well as improving citizens' willingness to participate in a constructive manner. Finally, interpersonal trust was the most significant of all dimensions and is exemplified by transmission line project employees establishing open and respectful dialogue with citizens, where personal values are heard, taken seriously and well-integrated into the process to allow trust to develop.

Trust in all entities and individuals, involved formally or informally in the process, affected overall acceptance [1], [14], [16]–[18], [30], [37], [40], [58], [65]. Genuine integration of outcomes from participation into decision-making and project outcomes can increase trust. However, a participation process perceived as disingenuous, will reduce trust and impacts subsequent participation processes [30], [72]. Nelson et al. [41] showed how trust can influence perceptions of the project, where residents with low trust in the process, perceived the overhead lines to be closer and were more likely to oppose projects.

3.

Culturally-responsive Collaborative Design with First Peoples

3.1 Contextual considerations

Building on the co-design workshop it was recognised that the implementation of transmission line projects in Australia will bring proponents into contact with First Peoples that require specific personal, social and cultural considerations. A more detailed approach to enabling culturally-responsive collaborative design with First Peoples is found at Appendix B. However, some of the key considerations are detailed here.

Under the United Nations Declaration on the Rights of Indigenous Peoples [86], First Peoples are identified (rather than defined) via:

- Self-identification as Indigenous Peoples at the individual level and accepted by the community as their member
- Historical continuity with pre-colonial and/or pre-settler societies
- Strong links to territories and surrounding natural resources
- Distinct social, economic or political systems
- Distinct language, culture and beliefs
- Forming non-dominant groups of society
- Resolution to maintain and reproduce their ancestral environments and systems as distinctive Peoples and Communities

As such, First Peoples are fundamental rights-holders in many locations in Australia, with approximately 60% of mainland Australia expected to soon be managed, or jointly-managed, by First Peoples. The complex interplay with First Peoples between Culture, Country and Community manifests a suite of values, some of which align with Western colonial values and the institutions they have implemented, and several which are fundamentally different. In the past, these value differences have, in part, led to post-colonial disempowerment and dispossession of First Peoples in land management decision-making with foundational production sectors including pastoralism, irrigated and dryland cropping, mining and urban development.

The onset of energy transition initiatives, including transmission line projects, provide opportunities for exploring and implementing new approaches for sharing the benefits provided by these projects across stakeholder groups, including First Peoples as rights-holders. However, the general absence of a history of collaboration between production sectors and First Peoples manifests uncertainty in new and emerging projects. Such a lack of understanding between First Peoples and proponents of development limits the effectiveness of assessment, planning, management and adaptation of projects. The opportunity to build respectful relationships – not simply transactional engagements – between First Peoples Communities and proponents can promote delivery of more effective, cost-efficient and ethical transmission line projects. However, there is little empirical evidence to support the adoption of methods and methodologies for building respectful relationships by proponents with First Peoples. As evidenced in this review, only one article was identified that focussed on First Peoples Communities as stakeholders, and none as rights-holders. That said, pockets of expertise founded upon experiential learning are exhibited by individuals and groups in many locations. The development of evidence-based guidelines that synthesise empirical evidence with experiential knowledge to identify the values, knowledge, skills and attributes of individuals, teams and organisations that support the building of effective, cost-efficient, ethical and resilient professional relationships offered by transmission line projects will contribute directly to their success.

3.2 Impacts of Transmission Lines on First Peoples

It is likely that transmission lines will impact First Peoples as rights-holders, in ways similar to other groups of stakeholders. However, based on the situation-specific character of their connections to Country, combined with the substantial knowledge gap in understanding the broader impacts of transmission infrastructure projects on First Peoples' Country, Culture and Community, there is a need for proponents to authentically invest time and resources to develop a deep, pragmatic, working understanding of First Peoples, values, aspirations, protocols, responsibilities and history as they interact with the design and implementation of projects (including pre-project discussions). This will ensure that the Cultural Safety and Cultural Security of individuals and groups is secured, and promotes the Cultural Proficiency of all participants in transmission infrastructure projects.

Some fundamental differences in the perspectives, attitudes, responsibilities and behaviours of First Peoples individuals, groups and Communities to the wider Australian community may result in different responses to transmission infrastructure projects. These may include: i) Loss of species of cultural significance and/or important for subsistence; ii) Compromising intangible sites of cultural significance; iii) Degradation or destruction of tangible sites of cultural significance; iv) Visual disruption of the night sky; v) Ecological impacts associated with these losses rendering First Peoples unable to meet their cultural, social and personal responsibilities; vi) Community and personal health and wellbeing impacts and costs associated with individual and collective losses that leave First Peoples unable to meet the social and personal cultural responsibilities; vii) The weaving of transmission lines into contemporary stories and Songlines; and viii) Declining opportunities for self-determination, which exacerbate existing marginalisation of First Peoples as individuals and Communities.

Accordingly, the ‘Prudent Avoidance Policy’ (i.e., the Precautionary Principle) needs to be enacted to ensure the values of First Peoples are not compromised as a result of new transmission infrastructure projects. Current guidelines create a situation where the prudent avoidance policy adopted by TNSPs only requires proponents to, for example, implement no cost and very low-cost measures that reduce exposure of individuals and Communities to transmission lines and the potential health impacts, while not unduly compromising (from a proponent’s perspective) other issues. Unlike planning to avoid health impacts, where in most cases the application of prudent avoidance can be implemented without the need for a specific assessment, cases where First Peoples are potentially impacted requires a more comprehensive assessment of the tangible and intangible aspects of Country than historically has been enacted. This can be achieved by investing time and resources to levels sufficient to ensure authentic, meaningful working relationships are established with Communities prior to initiating new transmission projects.

4.

Collaboration and Engagement Principles

To ensure a comprehensive review of engagement principles for all stakeholders, including First Peoples as rights-holders, the principles and guidelines for electric utilities from the 2017 CIGRE Green Book [87] were reviewed and contrasted with the findings from the systematic review. The CIGRE engagement principles cover instrumental and substantive aspects. However, they do not engage with normative aspects and social justice considerations which, while it might be expected from an engineering and technical standpoint, would likely have consequences in how genuine the public perceive the engagement to be in its process and outcomes. Table 2 highlights the differences and details enhancements to the principles from the literature.

Table 2. Merging CIGRE Engagement Principles and Systematic Review Findings

Principles from CIGRE, 2017	Principles as per CIGRE Green Book [87]	Enhanced Principles	Additional contribution from PRISMA review
Approach to stakeholder relationships	Stakeholder engagement processes should be consistent and aim to build trust.	**Approach to developing relationships**	Highlights that consistency in collaborative protocols and processes across industry and economic sectors, combined with coordinated and efficient processes, can help to reduce engagement fatigue and frustration. Thus improving the quality of the process for host communities, rights-holders, and the broader public.
Project scoping (Proportional approach)	The scope of stakeholder engagement for each project stage must be defined including its objectives, constraints and limitations.	**Project scoping (Proportional approach)**	In order to minimise the contestation of the need for new OHTL and avoid compromising First Peoples' and other stakeholders' rights, early collaboration and engagement at the electricity system planning level is required.
Stakeholder identification	The stakeholder mapping and selection process needs to be consistent. Local stakeholders, including those with specific community interests and those difficult to reach, need to be specifically targeted. The engagement also needs to reflect an understanding of stakeholders' requirements and preferences.	**Rights-holder and stakeholder identification**	Culturally-appropriate dialogue and clear communication of stakeholder and rights-holder mapping and selection processes is an integral part of the relationship building and engagement processes.
Start engagement early	Early engagement, i.e. during the formative stage, is valuable for knowledge creation including for subsequent engagement and for establishing the integration of stakeholders' input into routing and design.	**Start collaboration and engagement early**	The literature goes further and advocates for rights-holder and stakeholder collaboration at electricity system level planning and potentially even earlier when planning the transition to a low carbon economy. However this is (currently) outside the scope of transmission company remits. Collaboration should ideally begin prior to the conceptualisation of a project.

Principles from CIGRE, 2017	Principles as per CIGRE Green Book [87]	Enhanced Principles	Additional contribution from PRISMA review
Targeted mix of consultation/engagement methods	Engagement methods need to be tailored to their targets and allow for regular engagement. A dedicated community liaison representative is suggested.	**Targeted mix of methods for building relationships and engagement**	Amongst other challenges, collaboration and engagement processes need to account for individual and community willingness and capacity to engage with the complexity of the electricity system and its governance, as well as the process more broadly. The literature emphasises the value of a single point of contact for rights-holders and stakeholders which can contribute to a more fair and just process.
Create an open and transparent process	The scope of the engagement is transparent at each stage of the project and broadly communicated.	**Create an open and transparent process**	Transparency of the collaborative process and quality information provision contributes to procedural fairness and building trust.
Provide feedback to stakeholders (Monitor and evaluate)	A clear and transparent process is established to demonstrate and communicate how stakeholders' input was integrated into the project and provide rationale for inclusion and exclusion.	**Provide feedback to rights-holders and stakeholders (Monitor and evaluate)**	The literature shows that this step is amongst the most important, if not the most important, for building trust and fostering subsequent constructive engagement and participation.
Engagement should be proactive and meaningful	For engagement to be meaningful, it needs to have influence on the project outcomes. As such the scope of influence need to be clear and clearly communicated. Engagement should be proactive, accessible and inclusive.	**Collaboration and engagement should be proactive and meaningful**	Meaningful relationship building is paramount. Acknowledging that full consensus is unlikely to be reached even with best practice public engagement. Having a clear picture of "good enough" consensus and communicating it upfront improves transparency and perceptions of fairness.

Consideration of normative aspects and social justice issues also apply for First Peoples. The First Nations Clean Energy Network developed *Best Practice Principles for Clean Energy Projects* to help address this issue. The 10 Principles aim to guide projects to provide economic and social benefits as well as ensure Free, Prior and Informed Consent (FPIC) is secured by First Peoples, as rights-holders, for energy projects. The Principles include: "Engage respectfully; Prioritise clear, accessible and accurate information; Ensure cultural heritage is preserved and protected; Protect Country and environment; Be a good neighbour; Ensure economic benefits are shared; Provide social benefits for Community; Embed land stewardship; Ensure cultural competency; and Implement, monitor and report back." Combined with the principles outlined in Table 2 these can help to inform how to engage proactively with First Nations representatives.

5.

Discussion

5.1 Social Licence and Acceptance

It is evident from the literature that social acceptance and social licence of either overhead or underground transmission lines is not straight forward. Based on the more recent transmission projects that were able to progress with either hybrid overhead and underground, or fully underground outcomes, undergrounding may appear as the sole route for gaining acceptance. However, the picture is far more complex. The impacts and trade-offs between the two require high levels of contextualised understanding (what does this mean and look like here), and collaborative engagement and deliberation with all rights-holders and stakeholders.

While the review systematically highlighted the different factors influencing social licence and acceptance, they are extremely interrelated. Therefore, they need to be considered in a systemic way. For example, when considering visual impacts, issues relating to health, property values, proximity and compensation will also need to be considered. Furthermore, when attending to context sensitivity, a recognition of the various trade-offs is necessary as rights-holders and stakeholders are often weighing up multiple factors and thus making relative rather than absolute judgements. Understanding the individual context, in particular, the history of what projects have occurred previously in an area - that may not be related to transmission lines - is critical. Whether previous local experiences have been negative or positive is particularly important to know.

In terms of process, whether overhead or underground, whole of economy transition - including transmission line planning and design— that is based on human rights and social justice principles is fundamental. This involves deep contextual understanding and integration from the national to the local level, inclusive of cultural, social and political landscapes. While this is outside the scope of transmission line entities it does highlight the need for a whole of government approach to collaboration and engagement over the need for the energy transition and what it entails. While community responses often exhibit a preference for undergrounding, the review shows that it is not a one size fits all approach and there is a need to provide all of the information on the benefits, costs and consequences that will emerge as a result of such choices. Regardless of the outcome, transparency in project decision making and the ability to listen and reflect community concerns in the planning process may help to alleviate some of their concerns.

Constraint mapping is an essential tool for transmission experts when route planning. Common constraint considerations include cultural heritage, threatened species, areas of environmental significance, population density, and existing land use. These are well documented in the CIGRE Report 147 [88]. A mix of qualitative and quantitative assessment is then undertaken to identify the most preferred routes. The list of constraints are usually shared with communities to build transparency in the siting process but also to identify if there are any additional local constraints that may have been overlooked by the proponent and need to be included in the constraint mapping exercise. To help build support for the final outcome, an essential step has been to undertake a weighting exercise that brings together community and proponent preferences to reach agreement on the preferred priorities for siting transmission routes, including representatives from First Peoples. While such processes can be exacerbated by individual preferences and values, such rigor goes some way in helping to gain broad community support for the final route selection (CIGRE 147 [88] p.26).

Cross-cultural collaboration has historically been viewed by proponents as a hinderance to extractive industry activities and this has manifested in numerous and consistent breaches of the human rights of First Peoples. Opportunities exist for deriving substantial benefits from cross-cultural collaboration to enhance the resilience, sustainability, profitability and ethical delivery of transmission line projects. Promoting the connection of First Peoples to Country, Culture and Community can minimise and avoid ecological, economic and social risks to proponents, developers, companies, the wider public, as well as First Peoples Communities. Such activities include investing in developing sector-leading practices to drive investment and, more broadly, a national values-led economy (Chalmers 2023 [89]) to promote the interest of all Australians, inclusive of First Peoples, through the emerging clean energy economy and transmission line projects.

5.2 Limitations

Considering how much context matters in enabling social acceptance, the literature offers few Australian examples. The Australian context was only explored through four publications directly addressing transmission lines. Additionally, only one article focussed on First Peoples as stakeholders, and not as rights-holders. As part of this literature review no articles were found where the research design was to test an actual intervention and measure its influence on acceptance. The literature comprised predominantly of hypothetical projects or project observations without a purposely designed intervention method. Both Carley et al. [98], and Brinkley and Leach [27] highlighted a dearth of pre- and post-studies and a lack of control groups. As such, the efficacy of specific measures thought to contribute to acceptance cannot be evaluated. However, this does create an opportunity as the projects in Australia continue and the latest observations from the Australian and international cases are documented in this report.

6.

Conclusions

The emergence of transmission line projects in Australia to support the nation's transition to clean and sustainable energy provides a bright opportunity for collaborating in authentic, meaningful and just ways that share genuine benefits across all groups inclusive of First Peoples' Communities, proponents, developers, companies, and other rights-holders and stakeholders. This includes fundamentally maintaining and promoting the connection of First Peoples with Country, Culture and Community which is most effectively and sustainably achieved through the implementation of culturally-responsive cross-cultural collaborative design.

The co-design workshop, conducted to inform this review, also spoke of the need to be inclusive of all stakeholders and highlighted the importance of process, including distributive and procedural justice considerations, the requirement for good governance for gaining a social licence. While the literature provided overarching principles for engagement it did not provide a practical guide.

Illustrating the importance of gaining social licence and acceptance, there are a multitude of guidelines that exist in Australia for engaging with communities on transmission and energy projects, with many more emerging. For example, the Queensland Farmers' Federation recently released their Renewable Energy Toolkit; The Energy Charter, The Landholder and Community Better Practice Engagement Guide which underpins their *Better Practice Social Licence Guideline;* and the Energy Grid Alliance, Acquiring Social Licence for Electricity Transmission: A Best Practice Approach to Electricity Transmission Infrastructure Development; and the First Nations Clean Energy Network. Internationally, the Renewables Grid Initiative provides a wealth of resources (videos, fact sheets etc.) and publications that explain impacts and trade-offs for transmission infrastructure projects.

In August, the findings from the NSW Parliamentary Inquiry were published stating that *the current plan for constructing HumeLink as a 500 kV overhead transmission line is the correct approach* (p.34)[1]. However, on the 13 September 2023 a further Inquiry by a Select Committee was announced to report back their findings by 31 March 2024. The Australian Energy Market Commission (AEMC) also published a draft determination and rule change for *enhancing community engagement in transmission building* with the intention to fast track its release by December, 2023. At the same time the Australian Energy Infrastructure Commissioner is also undertaking a review to *enhance community support and ensure that electricity transmission and renewable energy developments deliver for communities, landholders and Traditional Owners*. Their website also provides a comprehensive list of best practice guidelines that relate to energy projects. So there are a multitude of resources for proponents and community to draw upon. Critical is ensuring the procedural and distributive considerations underpin any approaches to communities to ensure fairness for all who are likely to be impacted.

6.1 Key Findings

1. In addition to the physical factors of the technology there are a range of factors that will influence the public's willingness to accept transmission lines which include issues of procedural and distributive justice, fairness and trust in the process, along with how individuals assess the trade-offs between the cost, risks and benefits.
2. Place based engagement using two-way engagement that focuses on local values, aspiration, needs, concerns and histories can help to ameliorate negative reactions to new projects but requires adequate time and reflexive processes to ensure feedback from communities is incorporated into the final project plans.
3. Such context specific considerations also includes First Peoples and ensuring adequate engagement and collaboration with them is in place from the start – the First Nations Clean Energy Network have published principles for engagement which provide a basis for informing these processes.
4. Constraint mapping has been used by TNSPs to inform their route selection and this includes checking in with communities for local constraints. Involving the community in weighting the importance

[1] https://www.parliament.nsw.gov.au/committees/inquiries/Pages/inquiry-details.aspx?pk=2966#tab-reportsandgovernmentresponses

of each of the constraints at the early planning stages to create agreement for prioritisation of the various constraints will help to build support and buy-in for the final route.

5. Compensation for local impacts and associated losses is important and approaches to compensation also need to be fair and consistent, including recognising beyond just the local host to near neighbours. Understanding the interaction of the project on suitability of the land for other uses will also influence the final outcome, but compensation alone does not guarantee project success.
6. Engaging with communities for energy infrastructure projects is not new and there are a number of best practice principles that have been developed for engagement which can help to guide more successful outcomes.
7. There is a need for more consistent public education that explains in plain language: (1) Why we need to build more transmission infrastructure; (2) What HVAC and HVDC transmission infrastructure is; and (3) How transmission costs will be reflected in state capital borrowings and electricity bills – more transparent conversations around this at both the federal and state level should help increase the public's understanding of the trade-offs required.

6.2 Comparison Table – Social Aspects of HV Transmission Infrastructure

A summary comparing the social and community factors of overhead and underground infrastructure is presented in Table 3 below.

Table 3. Comparison of HV Overhead and Underground Cable Transmission- Social and Community Factors

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Under-ground
			Social Acceptance Factors		
1	**Overall social licence and acceptance**	Context dependent and dynamic. *Potentially reduced in host communities because of the perceived burden of the project. *Influenced by the factors described in this table.	Context dependent and dynamic. Potentially improved in hosting communities. Influenced by the factors described in this table.	Only one study. Similar to overhead AC.	
2	**Aesthetic and visual**	Visual impacts negatively influence acceptance. Expected flow on impacts include diminished recreational activities, tourism, local commerce, and health stress. Tower design, paint, and landscaping of the corridor may positively influence acceptance.	Undergrounding can positively influence visual impacts, but clearing is required (which is a negative impact).	No data.	
3	**Human health**	EMF concerns' influence on acceptance is neutral to negative. *Information provision from independent, trusted sources, and transparency in decision-making process can contribute to mitigating concerns.	Limited data in the literature. An awareness gap was identified for underground EMF effects.	Only one study. No influence on acceptance compared to overhead AC.	
4	**Proximity**	Proximity influence is neutral to negative on acceptance. Concerns relate mostly to EMF and effects on property value. Acceptance does not follow a linear rule with distance from the transmission line.	Similar to OHTL, however acceptable distance appears to be reduced compared to OHTL.	No data.	
5	**Familiarity**	Familiarity is linked to proximity of an existing OHTL and may positive influence acceptance.	No data.	No data.	

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Under-ground
6	**Financial compensation**	Geographic boundaries, calculation, and administration of compensation are the subject of contestation and may be mitigated with engagement and participation. Individual compensation for land and homeowners is expected. *Beyond property value loss, it needs to account for attachment to place and community (in the case of resumption) and land use. Community benefits positively influence acceptance. For Indigenous communities compensation needs to account for cultural values.	No data.	No data.	
7	**Environmental impacts**	Environmental impacts negatively influence acceptance. Concerns are focussed on vegetation clearance, habitat and wildlife loss, soil degradation, water and groundwater quality and flow, noise, fire, weed dispersal, waste, national park and conservation areas, and impacts on agriculture.	Often seen as a mitigation measure of impact on significant landscape and biospheres, however lack of awareness of UGTL environmental impacts was highlighted.	No data.	
8	**Distributive justice: equity**	If the distribution of benefit and burden is unequal it negatively influences acceptance. This may be mitigated with community benefits and sound environmental measures in place. Capacity to negotiate better outcomes is often unequal between communities. This may be mitigated with capacity building and use of independent experts. Accelerated processes negatively influence acceptance.	Undergrounding might be seen as a mitigation of unequal distribution of burdens.	No data.	
9	**Procedural justice: Governance**	Fair and transparent governance influence acceptance positively. Coordination and efficiency in the planning processes between jurisdictions and economic sectors alleviate engagement frustration and fatigue compared to multiple, confusing and, at times, contradictory processes. Participation in national transition planning through to regional transmission line planning may influence positive acceptance. Clear goals and outcomes for all processes, including participation, may contribute to alleviating lack of trust issues.			
10	**Procedural justice: Information**	Quality, contextualised, timely and transparent information about available technologies, risks, trade-offs, and governance positively influences acceptance. Trusted sources and easy access also positively influence acceptance.	Similar to overhead AC. An awareness and knowledge gap was identified about EMF and environmental impacts from undergrounding.	Only one study. An awareness and knowledge gap was identified about HVDC. Information provision can be helpful towards improving acceptance.	

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Under-ground
11	**Procedural justice: Engagement & Participation**	There is a need to have a clear and transparent stakeholder identification process. Engagement is the sum of all interactions between all stakeholders of TLs and can influence acceptance. Participation is an essential component of engagement and requires clear goals and expected outcomes. A goal to solely increasing acceptance tends to negatively influence acceptance. Contextualised knowledge creation and relationship building based on shared understanding, transparently incorporated into project design and construction positively influences acceptance. Participation processes that are inclusive and ensure adequate local representation, provide agency and power balance positively influence acceptance. Accountability in the process is key.			
12	**Procedural justice: Trust**	High levels of trust in the process and the institution positively influences acceptance. Lack of trust hinders participatory processes and ultimately acceptance. The elements highlighted in this summary are critical to building trust in the proponent and their associated activities.			
13	**First Nations' Engagement Principles**	"Engage respectfully; Prioritise clear, accessible and accurate information; Ensure cultural heritage is preserved and protected; Protect Country and environment; Be a good neighbour; Ensure economic benefits are shared; Provide social benefits for Community; Embed land stewardship; Ensure cultural competency; Implement, monitor and report back" Source: https://www.firstnationscleanenergy.org.au/network_guides.			

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Appendix A: PRISMA Methodology for Social Licence and Acceptance

1. Eligibility Criteria (Inclusion & Exclusion)

The major criteria that were used to decide what information was included or not are detailed below.

Inclusion criteria

- Studies which cover social acceptance of overhead transmission line and underground cables
- Voltage level is not cited in the social science literature but is referred to as "transmission line"
- There was no limitation placed on date of publication

Exclusion criteria

- Publications or studies that were duplicated
- Studies that were irrelevant to the scope of this review. For example, technology other than transmission lines
- Language other than English

2. Information Sources

Both Scopus and Web of Science databases were the selected databases for peer reviewed articles.

3. Search Strategy

Both databases were searched for Title, Abstract and Keywords. However, the original search terms returned too many irrelevant papers. However, some of the words were related and therefore needed to be part of the same sentence. To search in this way, we used the proximity search function which increase the likelihood of those words appearing in the same sentence. This resulted in the final search terms being:

To establish the domain of enquiry: (electric* OR energy) AND

To narrow the domain to transmission lines: (power OR transmission OR "high voltage") within 2 words of (line OR cable OR wire))

To target social acceptance: (social OR public OR *owner OR community OR resident* OR local* OR indigenous OR farmer*) within 4 words of (licen* OR acceptance OR perception OR attitude OR willingness OR support OR opposition OR benefit* OR resistance OR cost* OR compensation)

4. Data Collection Process

Based on the above eligibility criteria, information sources and search strategy, publications were identified as per the procedures presented in the flow chart in Figure 3. According to the search strategy, 1,209 publications were found through Web of Science and Scopus, after removal of duplicates and papers outside the inclusion criteria, 591 were determined to be potentially contributing to the scope of this study. The papers were then screened by reading all publications' titles and abstracts and 169 were deemed within scope. These shortlisted publications were read in detail resulting in 102 publications being selected for further consideration and analysis.

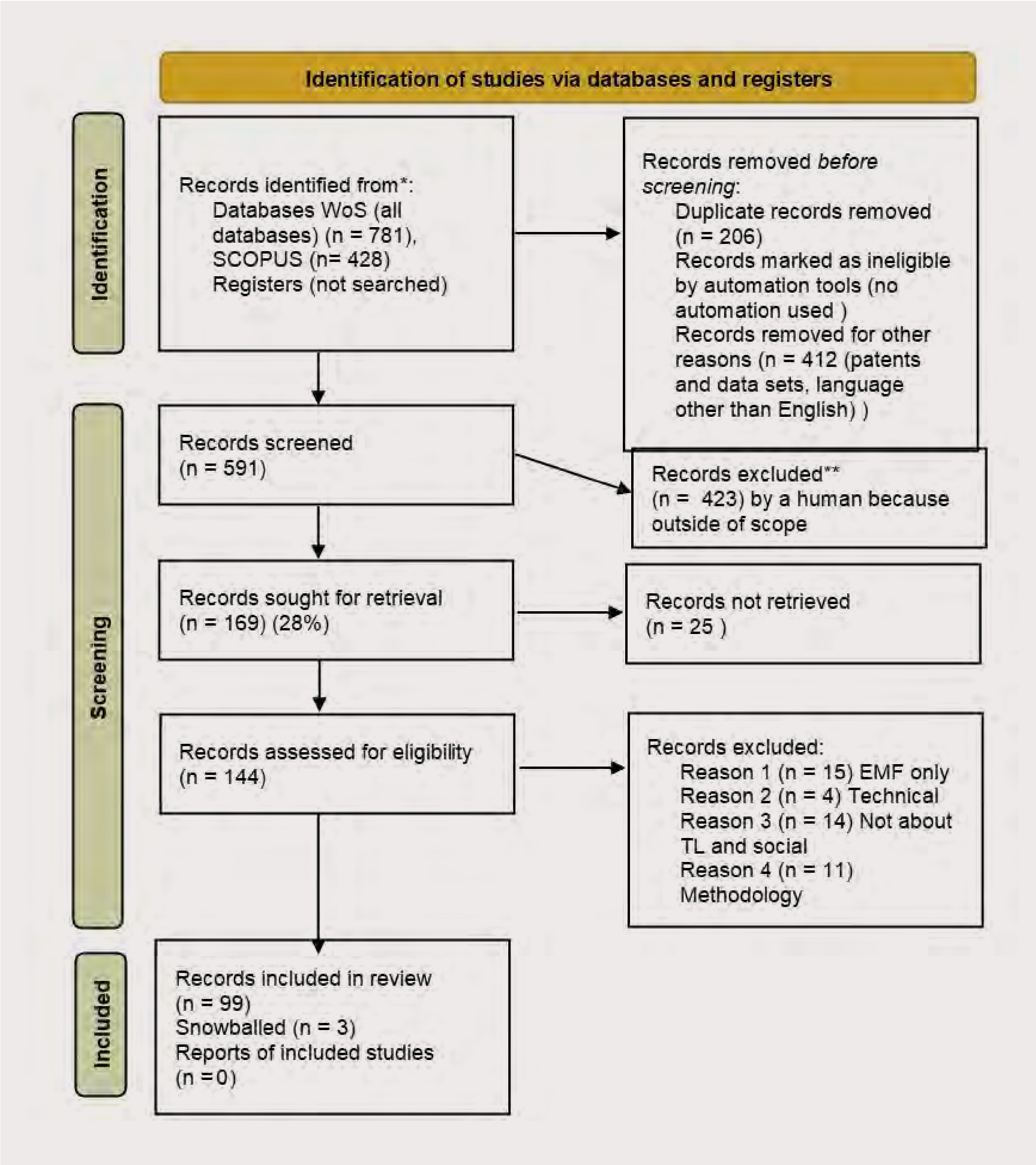

Figure 3 - Prisma flow diagram of studies to be included in the systematic literature review

5. Thematic Analysis

Data analysis of the 102 articles was undertaken using the software NVivo 12, a software package used to organise and help analyse the data through the following methods. This first stage is a thematic analysis through which the main themes are identified (refer Appendix C for the further details of the 102 papers). The second stage consisted of categorising extracts from the articles further and organising the findings into a cohesive argument.

Literature characteristics

Geographically, nearly 90% of the 102 studies were conducted in Europe or the US (Table 4) with only 4 studies being located in Australia. All four Australian studies took place in Queensland.

There was no date restriction applied to the search. The first paper available in Scopus and Web of Science was published in 1988 and was a review of the literature to that point in time. Between 1988 and 2013, one to two papers were published each year with a focus on social acceptance. The field then developed and peaked to 13 publications in 2020 but has reduced since, as seen in Figure 4. The lower publication rates in the earlier years possibly reflects the lack of transmission infrastructure built during that time, with recent focus likely to be related to the increased renewable energy projects being developed and the need to integrate them into the grid.

The data collection methods used in the reviewed studies are presented in Figure 5. A large number used a survey (50%) as the method of investigation, followed by interviews (17%) and focus groups (9%). There were 4 papers based on the literature review method but only one was a systematic review. Some studies used a combination of methods e.g. interviews and focus groups or interviews and reviews.

Notably, 53 studies targeted a specific project, 14 studies were based on hypothetical projects, and 35 were not applied to any project at all. For those studies that investigated people's views and acceptance, over 30 focussed on local or hosting communities that were directly affected by a proposed or current transmission line development (Figure 6). Whereas 27 studies recruited participants at the national level. In total 16 studies targeted professionals, namely electric utilities' employees, policy makers or property agents. Three studies targeted visitors to a specific area.

Table 4. Studies' Target Population Location

Country	Number of papers
USA	22
Germany	22
UK	18
International	8
Norway	7
Switzerland	5
Italy	5
Ireland	4
France	4
Iceland	3
Europe	2
Australia	4
Netherlands	2
Austria	2
Colombia	1
Denmark	1
Finland	1
Sweden	1

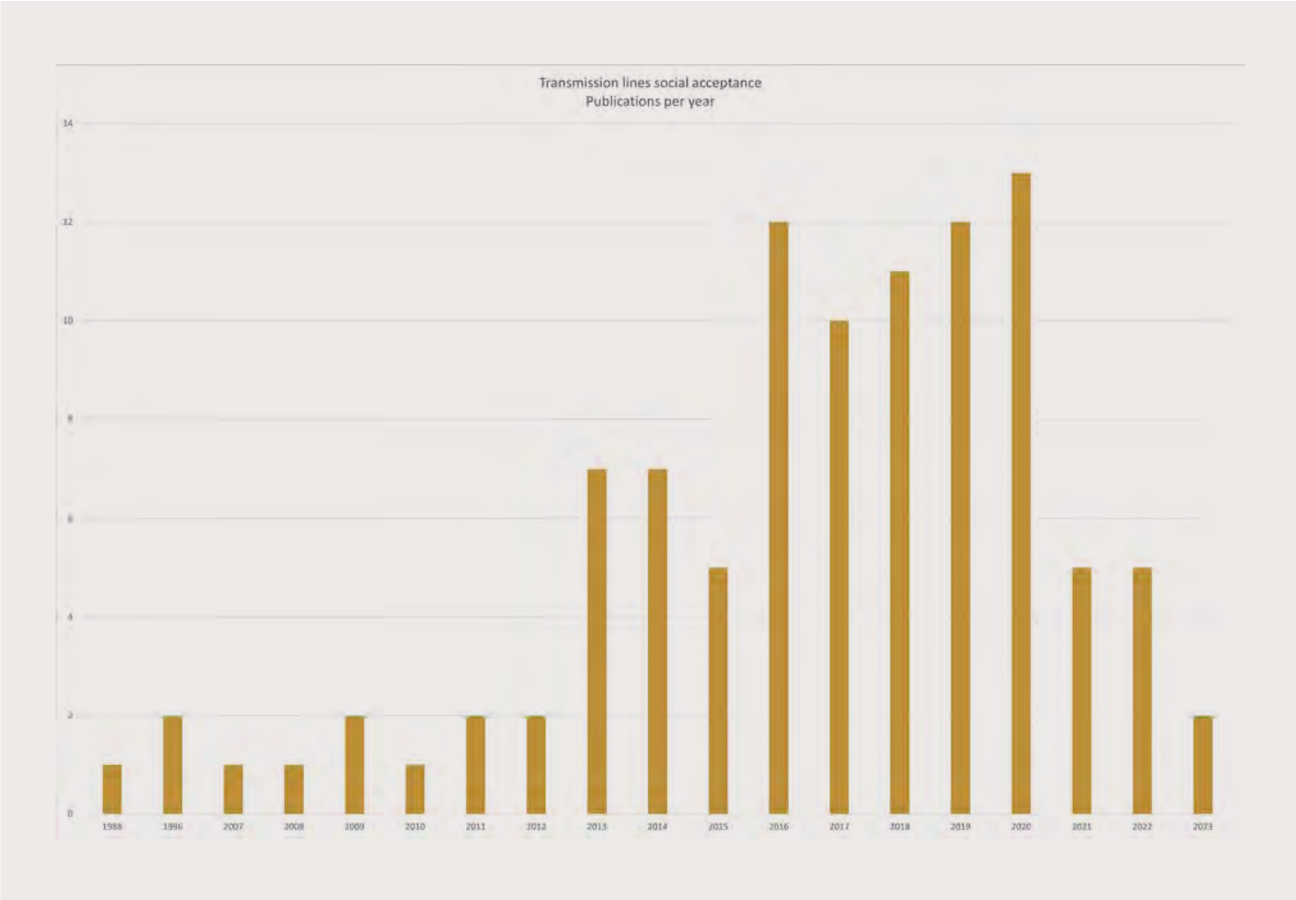

Figure 4. Number of Publications

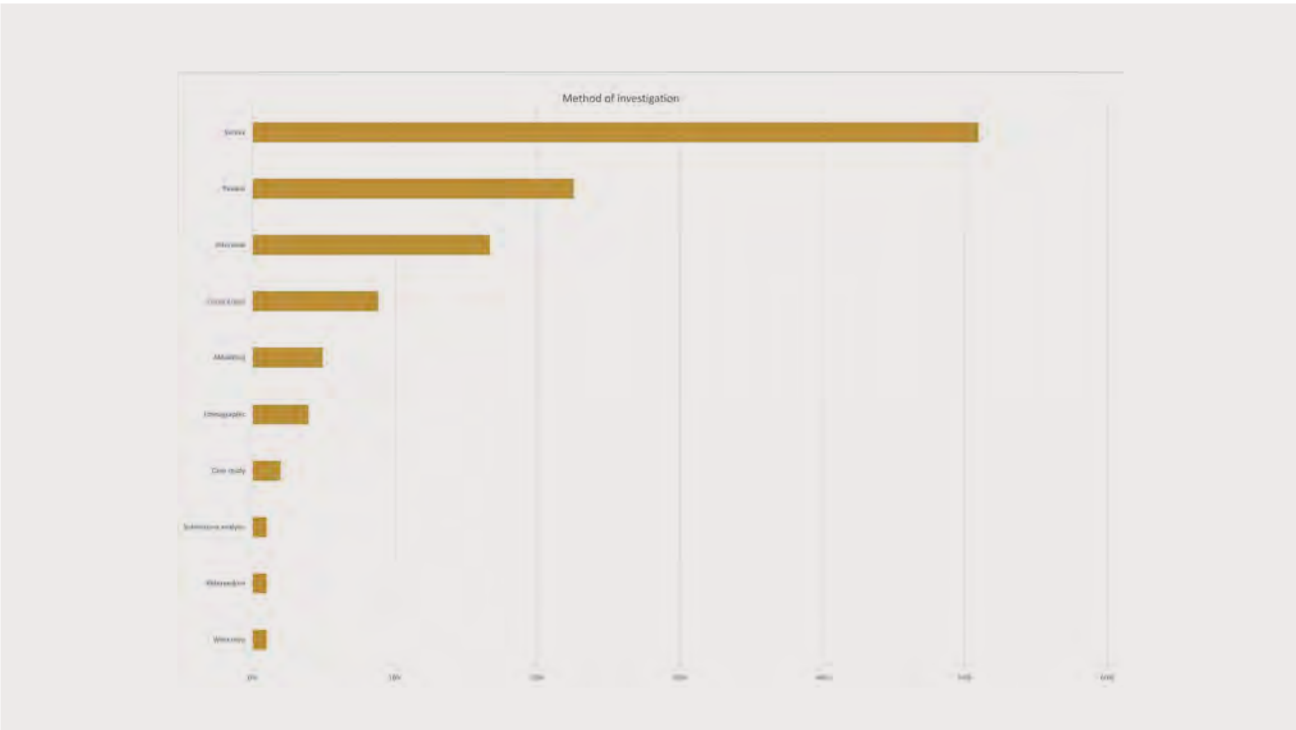

Figure 5. Method of Investigation

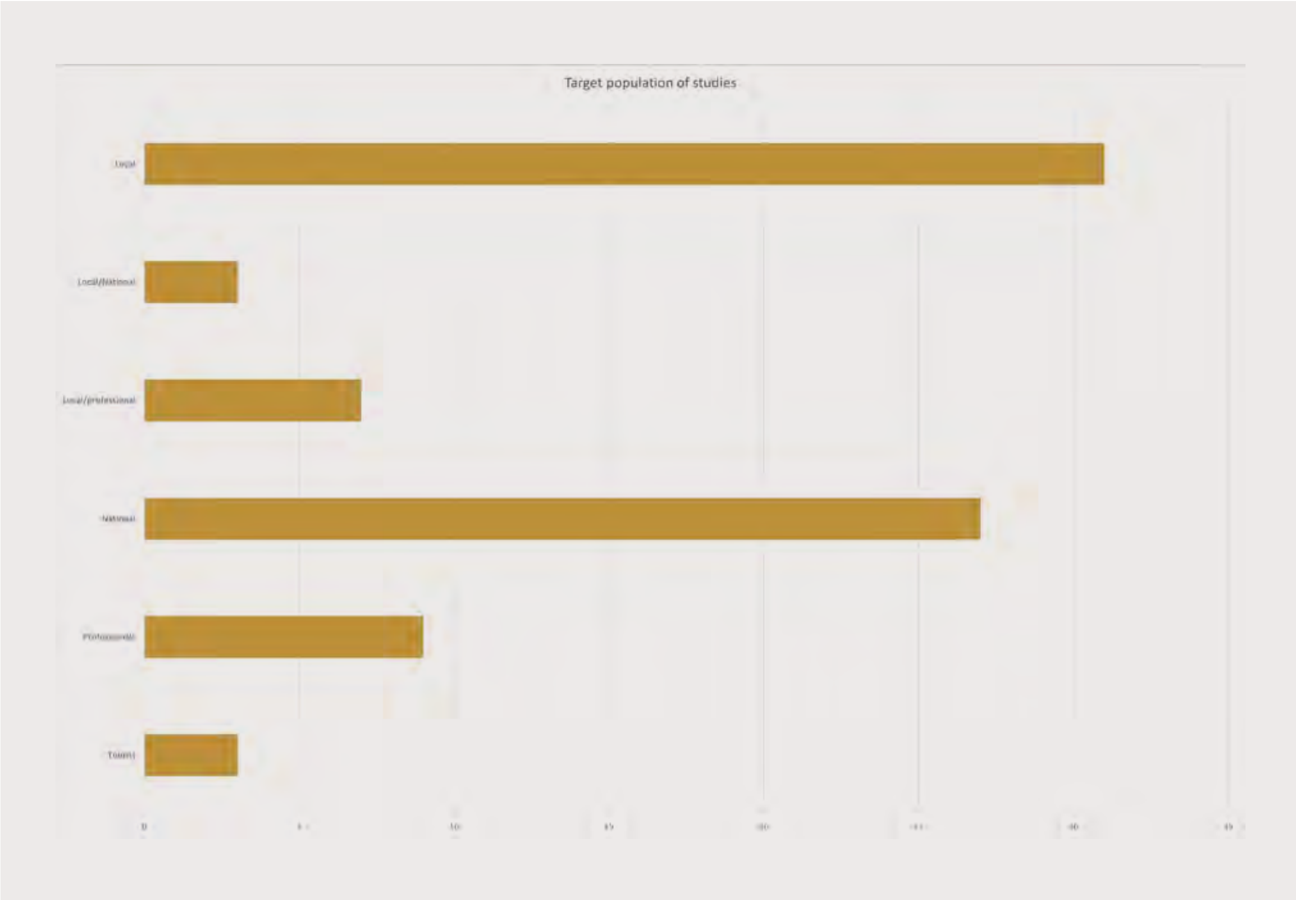

Figure 6. Target Population of Studies

Appendix B: Culturally-responsive Cross-cultural Collaborative Design with First Peoples

By: Assoc. Prof. Andrew Knight, ARC Industrial Training Centre for Healing Country

1. Introduction

The implementation of transmission line projects in Australia will bring proponents and government, and in some locations other stakeholders, into contact with First Peoples. Under the United Nations Declaration on the Rights of Indigenous Peoples [86], First Peoples are identified (rather than defined) via:

- Self-identification as indigenous peoples at the individual level and accepted by the community as their member.
- Historical continuity with pre-colonial and/or pre-settler societies
- Strong links to territories and surrounding natural resources
- Distinct social, economic or political systems
- Distinct language, culture and beliefs
- Forming non-dominant groups of society
- Resolution to maintain and reproduce their ancestral environments and systems as distinctive peoples and communities

As such, First Peoples are fundamental rights-holders in many locations in Australia. Approximately 60% of mainland Australia is expected to soon be managed or jointly-managed by First Peoples. The complex interplay with First Peoples between Culture, Country and Community manifest a suite of values, some of which align with Western colonial values and the institutions they have implemented, and several which are fundamentally different. In the past, these value differences have, in part, lead to post-colonial disempowerment and dispossession of First Peoples in land management decision-making with foundational production sectors, including pastoralism, mining and urban development. Energy transition initiatives, including transmission line projects, provide opportunities for exploring and implementing new approaches for sharing the benefits provided by these projects across stakeholder groups, inclusive of First Peoples.

The general absence of a history of collaboration between production sectors and First Peoples, the divergence in values of land, sea and sky, coupled with the manifestation of some of these values in intangible ways (e.g., Songlines) manifests uncertainty in new and emerging projects. For example, recent research in the mining sector has revealed that most managers believe social and environmental uncertainties pose the most significant risks to mining ventures (Ernst & Young 2022 [90]). The lack of understanding between First Peoples and proponents of development limits the effectiveness of assessment, planning, management, and adaptation of projects. Building relationships – not simply transactional engagement - First Peoples Communities can deliver effective and ethical transmission line projects.

Little empirical evidence exists to support the adoption of effective methods and methodologies for building relationships between First Peoples and proponents. For example, the review of social aspects of transmission lines presented in this report found only one article focussed on First Peoples as stakeholders (p.158). That said, pockets of expertise founded upon experiential learning are to be found in many locations. The development of evidence-based guidelines that synthesise empirical evidence to identify the values, knowledge, skills and attributes of individuals, teams and organisations that support the building of ethical and resilient professional relationships offered by transmission line projects will contribute directly to their success.

2. Impacts of Transmission Lines on First Peoples

The design, planning, implementation, maintenance and decommissioning of transmission lines may impact First Peoples in ways similar to other groups of rights-holders and stakeholders. These impacts may include: health impacts such as effects on the rate of specific chemical reactions, minor compromising of hand-eye coordination and visual contrast, vertigo and nausea; economic impacts such as forgone current and future income and degradation or loss of ecosystem services; environmental impacts such as the loss of valued genes, species, habitats and ecosystems; and social impacts such as the loss of ecosystem services such as the provisioning of experiential and intellectual interactions.

Whilst investments have been made into understanding the broader impacts of transmission line developments, very little time and effort has been invested in understanding the impacts upon First Peoples. This is a substantial and unsatisfactory knowledge gap, given the typically marginalised status of First Peoples, and the situation-specific character of their connections to the world around them. Proponents need to invest time and resources in collaborating with First Peoples if developments are to be effective and ethical.

First Peoples may be impacted by transmission line projects in ways that differ to other rights-holders and stakeholder groups. These result from fundamental differences in the perspectives, attitudes, responsibilities and behaviours of First Peoples individuals, groups and Communities to the wider Australian community. These may include:

Loss of species of cultural significance, including terrestrial, aquatic, marine and subterranean species of plant and animals, which may have spiritual, totemic, ceremonial and/or medicinal importance;

Loss of species important for subsistence, as some Communities harvest directly from Country in subsistence or partly-subsistence livelihoods, for example, foodstuffs such as kangaroo, goanna, native yams;

Compromising of intangible sites of cultural significance, for example, transmission lines may align with Songlines and other important routes used by First Peoples, as these were commonly adopted in some locations as they represent pathways of least effort for traversing land- and seascapes.

Degradation or destruction of tangible sites of cultural significance, for example, physical destruction of landforms, waterholes and wetlands, and/or specific types of ecosystems or habitats, inclusive of underground sites;

Visual disruption of the night sky, for example, for sighting constellations necessary for navigation or for undertaking cultural ceremonies and story-telling, is a specific impact of overhead transmission lines;

The *ecological impacts* associated with these losses rendering First Peoples unable to meet the cultural, social and personal responsibilities that ensure their connection with Country, Culture and Community, and hence the active management of, for example, fire;

The social and personal health and wellbeing impacts associated with these individual and collective losses that leave First Peoples unable to meet the social and personal cultural responsibilities to Country, Culture and Community;

The *social and personal health and wellbeing costs* associated with the need to practice 'code-switching' when communicating with individuals outside their Community regarding the design, planning, implementation, monitoring and evaluation of transmission line projects;

The weaving of transmission lines into contemporary stories and Songlines, which requires maintaining infrastructure that may have been scheduled for decommissioning;

Declining opportunities for self-determination, which exacerbate existing marginalisation of First Peoples as individuals and Communities.

Accordingly, the 'Prudent Avoidance Policy' (i.e., the Precautionary Principle) should be enacted to ensure that knowledge gaps (i.e., low cultural competence) do not result in the values of First Peoples being compromised and recognises the potential for health risks and aims to minimise exposure as a precautionary measure. Current guidelines create a situation where the prudent avoidance policy adopted by TNSPs only requires proponents to, for example, implement no cost and very low-cost measures that reduce exposure of individuals and Communities to transmission lines and the potential health impacts while not unduly compromising other issues. Unlike planning to avoid health impacts where in most cases the application of prudent avoidance can be implemented without the need for a specific assessment, cases where First Peoples are potentially impacted will require comprehensive assessment of the tangible and intangible aspects of Country.

3. Keeping Connected: Culturally-responsive Transmission Line Projects

Transmission lines connect places for a specific purpose – to provide electricity. Without connections that are robust and genuine, the integrity and functioning of a transmission line system is compromised. In much the same way, First Peoples can be compromised when their connection to Country, Culture and Community is compromised. Proponents and First Peoples both require connection. When connections are lost between First Peoples and Country, Culture and/or Community, individual and Community rights, health and wellbeing are compromised. First Peoples 'connections' are complex and should be explicitly identified, mapped and incorporated in decision-making processes (where culturally-appropriate) (Figure 7).

Figure 7. A conceptualisation of the Social and Emotional Wellbeing Framework depicting the interplay of social and historical determinates on the wellbeing of First Peoples (Dudgeon et al. 2020 [96], as adapted from Gee et al. 2014 [91])

The values, perspectives, attitudes and behaviours of First Peoples differ fundamentally from those of colonial and post-colonial settlers in Australia. This divergence places First Peoples in situations in their day-to-day lives where their view of themselves, their mental and physical health, their responsibilities to Country, Culture and Community, and hence their willingness and capacity to navigate work and life in a Western world is compromised.

An understanding of the concepts of Cultural Safety, Cultural Security, Cultural Proficiency and Code-Switching is essential for reducing the uncertainty surrounding cross-cultural relationships, and hence increases the probability of success for transmission line projects. This understanding allows proponents to design, implement, evaluate and refine approaches to building relationships that are trusting and resilient. These concepts apply equally to those who do, and who do not, identify as First Peoples. For example, the concept of ‘Cultural Safety’ is analogous to the concept of ‘psychological safety’ commonly used in the organisational and management sciences (Edmondson 1999 [92]). These concepts manifest across individuals, teams and organisations (Figure 8). This conceptualisation allows for the identification, assessment and actioning of thinking and practices

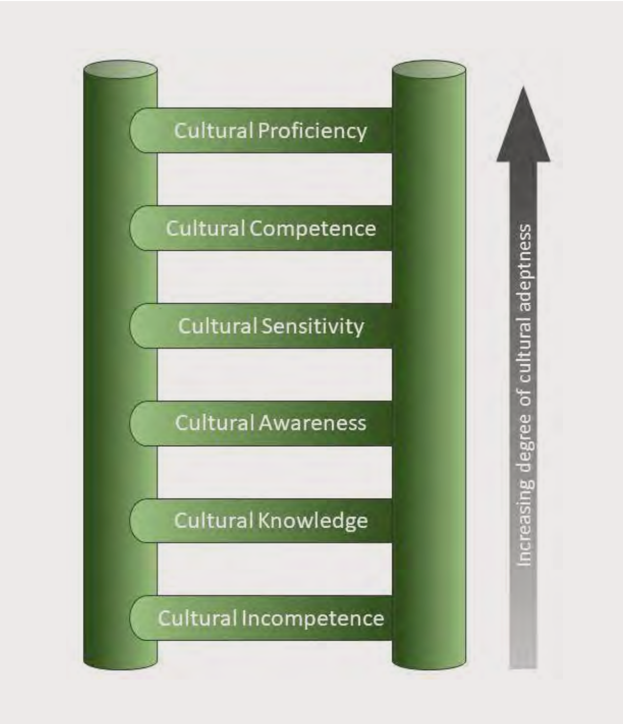

Figure 8. A representation of the stages of progression towards cultural proficiency that can be actively fostered by individuals and teams (adapted from Wells 2000 [93]).

that promote an agreed and appropriate degree of participant proficiency for situation-specific cross-cultural collaborative design activities for transmission line projects.

Cultural Safety is a situation-specific *state of mind* experienced by an individual where she or he feels themselves sheltered from exposure to some form of risk. Risks might include the compromising of personal psychological wellbeing, physical harm, and/or their rights, cultural expectations and responsibilities to their cultural or social situation. Individuals perceive risks differently and idiosyncratically, meaning one team member may feel culturally safe in a specific situation whilst another may not. An example of cultural safety being promoted could be the arranging of special leave entitlements for First Peoples to attend extended periods of time away from work for cultural reasons, such a 'sorry business'.

In contrast, Cultural Security is a situation-specific *state of participation* where respect for cultural differences is intrinsically embedded within the thinking and practices developed, adopted, implemented, evaluated and refined by an institution. This may include activities such as acknowledging the historical causes of inequity and inequality; ensuring Indigenous leadership and participation; and recognising Country, Culture and Community as foundational to effectiveness. The principle of cultural security includes not only cultural differences between First Peoples and other Australians, but also differences between, and within, Indigenous groups. For example, providing working parents with facilities for changing and feeding infants in the workplace.

The knowledge deficit that exists between First Peoples and other Australians in transmission line projects is best overcome by learning about the foundations of effective professional relationships. Reflective practice is a foundation to learning in professional contexts (Schon 1983 [94]). Cultural Proficiency is a dynamic, situation-specific and continuous process through which an individual, and the team, organisation and community of practice of which they are a part, strives and evolves towards a state where Cultural Security is able to be effectively sought and secured through ongoing personal and group learning and adaptation. It is distinct from cultural competence in that competence denotes a willingness and ready capacity for the routine application of culturally-appropriate thinking (e.g., attitudes) and practices (e.g., individual behaviours, institutional systems). Cultural proficiency is not an end unto itself, but rather an evolving state responding to change in the situation of an individual and the 'space' in which they operate (e.g., the uptake of Community responsibilities following the passing of a Community Elder, a change in legislation) and cultural change (the natural evolution of social norms and practices).

The cultural differences between First Peoples and the groups within wider Australian society in which they live and work prompts several responses from First Peoples as individuals. One of these is known as code-switching. Code-switching can be broadly defined as the adjusting of one's style of speech, appearance, behaviour, and/or expression in ways that will optimize the comfort of others in exchange for some type of benefit, or to avoid some form of risk, such as fair treatment, quality service, and employment opportunities (McCluney et al. 2019 [95]). Practicing code-switching can impact First Peoples through hostility from members of their Community for conforming to another cultural or social group's expectations; depletes cognitive resources through the need to be vigilant to maintain a preferred persona; contributes to burnout; undermines the building of trusting relationships; and generally hinders performance.

Recognising the costs and benefits to cross-cultural relationships between First Peoples and others regarding code-switching, Cultural Safety, Cultural Security and Cultural Proficiency will facilitate resilient relationships and thereby promote successful projects.

4. Principles of Culturally-responsive Collaborative Design

A significant number of approaches to collaborative design (sometimes known as 'co-design') involving First Peoples have been developed in Australia. The land management and healthcare sectors are notable for their contributions. The scope and level of detail providing direction for the implementation of individual projects and programs across these approaches varies substantially, with some providing a philosophy or conceptual foundation of collaborative design, whilst other publications provide information on which, and how, specific activities can be implemented. Several commonalities exist across many of these approaches, which reflect the need for generic advice and basic foundational elements of collaborative design projects and programs. One common component is the inclusion of principles for guiding collaborative design activities.

The First Peoples Clean Energy Network Best Practice Principles for Clean Energy Projects provides useful guidance for transmission line project proponents. The 10 Principles are intended to help ensure projects provide economic and social benefits such as business development and employment opportunities; ensure mutual respect, clear communication and cultural and environmental protection; promote sustainable land management; and ensure Free, Prior and Informed Consent (FPIC) is secured for First Peoples, as rights-holders, for the activities conducted. The 10 Principles (in no priority order) are:

1. Engage respectfully

The *United Nations Declaration on the Rights of Indigenous Peoples* states that the principle of "Free, Prior and Informed Consent" (FPIC) must apply when engaging with First Peoples communities. Putting in place mechanisms for building respectful relationships must be prioritised, established and maintained (inclusive of funding for independent expert legal, scientific, business, commercial and other advice) from the commencement of scoping a project in culturally-responsive ways. The agenda, character and timelines must be negotiated jointly by Community, the project developer and other rights-holders and stakeholder.

2. Prioritise clear, accessible and accurate information

Accessible, timely, accurate and detailed information on the character, design, construction, impact, ongoing life and decommissioning of transmission line projects on or near their land is fundamental to ethical and effective decision-making by First Peoples. This includes transparent processes for Community feedback with insights, concerns and advice to be received and acted on in actionable and respectful ways. Opportunities must be provided for Communities to have agreements reviewed (before they are finalised) by expert advisors to ensure that terms and conditions are fair, binding and provide avenues for benefit-sharing.

3. Ensure cultural heritage is preserved and protected

Proponents, industry and investors must commit to avoiding damage to cultural sites and ensuring First Peoples connection to Country. First Peoples should be able to choose assesses, plans and manages cultural heritage. Companies should fund First Peoples to undertake cultural heritage assessment protection work. Regular and ongoing cultural competency training should be prioritised by companies for their employees. The cultural rights and obligations to care for Country, including cultural sites, requires access to project sites, which should be provided respectfully, proactively and in a timely manner.

4. Protect Country and environment

First Peoples have occupied Country for thousands of years and their rights to Country were never ceded. Companies should respect a Community's authority and responsibility to preserve and actively manage areas of environmental value. First Peoples must have representatives with Cultural decision-making authority on environmental protection decision-making bodies. Procedures should be implemented for the collaborative design of culturally-responsive land and environmental protection plans, inclusive of the design, operation, transition, closure (including remediation, rehabilitation and restoration) and restitution phases of a project. Companies should adequately resource the ongoing management, implementation and enforcement of the plan.

5. Be a good neighbour

Solutions to a project's potential visual, noise, traffic and other impacts should be sought through collaborative design of transmission line projects. Impacts to manage and mitigate may include the use of shared water resources and disposal of waste. Regular monitoring and evaluation of impacts should be funded, undertaken and reported to Community and the wider public.

6. Ensure economic benefits are shared

Companies must explore and provide a range of culturally-responsive opportunities for First Peoples Communities to share the benefits provided by projects. These may include priority for employment opportunities; owning a stake in a project and its assets; and/or rental payments for the disturbance, use and occupation of land or sea. Prioritising, setting employment targets, and reporting on First Peoples employment should be undertaken through joint culturally-responsive procedures, with accountability assigned to senior executive company personnel. Clear career pathways, that ensure a workplace conducive to the recruitment and retention of First Peoples through ongoing mentoring and training, can assist companies to enhance delivery of their objectives by producing a highly competent First Peoples workforce. First Peoples goods and services must be prioritised for use over those brought in from outside Country.

7. Provide social benefits for Community

Projects should proactively work to provide social benefits for local Communities. The types of community benefits should be discussed during the design stage of a project, and their delivery built into a project's governance and accountability structures and procedures. Providing renewable energy to communities will help to ensure energy security positively contributes to improving community outcomes and well-being.

8. Embed land stewardship

Transmission line projects have opportunities for demonstrating models of greater sustainability, equity and resilience than past extractive projects. Companies can explore and implement Nature Positive activities, moving beyond simply securing a 'no net loss' of ecological, cultural and agricultural values of land and sea. This could include funding First Peoples Ranger programs to manage feral animals and invasive weeds and restore important local wildlife habitats.

9. Ensure cultural competency

A company must develop, mainstream and evaluate ways – guided by a Reconciliation Action Plan – in which staff, at all levels, and particularly senior personnel, can experience and learn about local Country, Culture and Community, inclusive of (where culturally appropriate) cultural heritage sites and stories. Cultural competency training, provided by the local community, should be part of the company's governance structures, with explicit targets to drive the continual improvement of cultural competency across all levels of the organisation.

10. Implement, monitor and report back

A project's development life-cycle should include personnel, structures and procedures detailing and mobilising explicit and trackable company commitments to local First Peoples Communities. These must ensure future project owners and operators are bound by them. Company commitments to First Peoples communities should be linked to the performance executive personnel. Commitments must also be adequately resourced to ensure effective, ethical and equitable delivery and should be regularly monitored, evaluated and reported to Communities, shareholders and the wider public, inclusive of feedback provided by Communities, promote continuous improvement of company operations.

5. Opportunities for Delivering Multiple Benefits Through Cross-cultural Collaboration

Culturally-responsive cross-cultural collaboration has historically often been viewed as a hinderance to extractive industry activities. This view manifests in the numerous and consistent breaches of the human rights of First Peoples. Opportunities exist for deriving substantial benefits from cross-cultural collaboration which enhance the resilience, sustainability, profitability and ethical delivery of transmission line projects. Promoting the connection of First Peoples to Country, Culture and Community minimises or avoids ecological, economic and social risks to proponents, developers, companies, the wider public, as well as First Peoples Communities. Such activities include:

Proponents, developers, companies, First Peoples Communities, and other rights-holders and stakeholders where appropriate, invest in developing sector-leading practices to drive investment and, more broadly, a national values-led economy (Chalmers 2023 [89]) to promote the interest of all Australians, inclusive of First Peoples, through the emerging clean energy economy, and transmission line projects specifically;

Proponents, developers, companies, First Peoples Communities, and other rights-holders and stakeholders where appropriate exploring *'biocultural' perspectives*, mechanisms and tools that avoid the current limitations of reductionist approaches to the assessment, planning, management and evaluation of the land and sea on which transmission lines projects are located. For example, biocultural mapping of First Peoples values may optimise the securing of cultural, ecological and economic benefits simultaneously;

Seek multiple benefits on sites occupied by transmission lines through the implementation of 'onsets' (sometimes known as 'insets'), as opposed to offsets, which can optimise delivery of project objectives. For example, rehabilitating or restoring transmission line locations can employ plant species valued for the medicinal, totemic and food values of First Peoples; soil binding properties and carbon sequestration potential.

Framing company cross-cultural collaboration thinking and practices so as to align with the United Nation's *Sustainable Development Goals* (SDGs) so that activities for maintaining First Peoples connection to Country, Culture and Community simultaneously promotes global reporting responsibilities and Environmental, Social, and Governance (ESG) expectations of investors and shareholders;

Exploring and developing novel and situation-specific authentic, culturally-responsive and collaboratively-designed mindsets, methods and methodologies for land and sea management which deliver more effective, cost-efficient, equitable and resilient. For example, the collaborative design of 'traditional burning' fire management policies and procedures.

Exploring and developing new culturally-responsive policies, procedures, structures and activities involving First Peoples, especially local Communities, and proponents, developers and companies to enhance the delivery of the values, priorities, profitability and expectations of a company, its investors and shareholders, and their targets markets.

Development, testing and implementation of innovative methods and methodologies for monitoring, evaluating and improving the Cultural Safety, Cultural Security and Cultural Proficiency of all stakeholders, including First Peoples, to ensure accountability, defensibility, reliability and confidence in transmission line projects.

6. Conclusion

First Peoples have not only been marginalised, but have also suffered directly from activities in all land-use sectors in Australia. The emergence of transmission line projects in Australia to support the nation's transition to clean and sustainable energy provides a bright opportunity for collaborating in authentic, meaningful and just ways that share genuine benefits across all groups inclusive of First People's Communities, proponents, developers, companies, and other rights-holders and stakeholders. This fundamentally requires maintaining and promoting the connection of First Peoples with Country, Culture and Community. This is most effectively, cost-efficiently and sustainably achieved through the implementation of culturally-responsive cross-cultural collaborative design.

Appendix C: Summary of References from the Literature R eview

Authors	Year	Country	Method	Target population	Number of Participants
Aaen, Sara Bjørn; Kerndrup, Søren; Lyhne, Ivar	2016	Denmark	Interview/ Ethnographic	Local	4
Aas, Øystein; Devine-Wright, Patrick; Tangeland, Torvald; Batel, Susana; Ruud, Audun	2014	Norway Sweden UK	Survey	National	5,107
Aas, Øystein; Qvenild, Marte; Wold, Line Camilla; Jacobsen, Gerd Blindheim; Ruud, Audun	2017	Norway	Interview/focus group	Local	75
Azarova, Valeriya; Cohen, Jed; Friedl, Christina; Reichl, Johannes	2019	Austria Germany Italy Switzerland	Survey	National	2,000
Bailey, Etienne; Devine-Wright, Patrick; Batel, Susana	2016	UK	Interview narrative	Local	25
Batel, Susana	2018	International	Review	Not Applicable	Not Applicable
Batel, Susana	2020	International	Review	Not Applicable	Not Applicable
Batel, Susana; Devine-Wright, Patrick	2015	UK	Survey	Local/National	2,021
Batel, Susana; Devine-Wright, Patrick	2017	UK	Focus group	Local	Not specified
Batel, Susana; Devine-Wright, Patrick	2018	UK	Survey	National	2,560
Batel, Susana; Devine-Wright, Patrick	2020	UK	Focus group	Local	50
Batel, Susana; Devine-Wright, Patrick; Tangeland, Torvald	2013	UK Norway	Survey	National	2,123
Batel, Susana; Devine-Wright, Patrick; Wold, Line Camilla; Egeland, H.; Jacobsen, Gerd Blindheim; Aas, Øystein	2015	UK Norway	Focus group	Local	83
Bertsch, Valentin; Hyland, Marie; Mahony, Michael	2017	Ireland	Survey	National	1,044
Brinkley, Catherine; Leach, Andrew	2019	International	Review	Not Applicable	Not Applicable
Cain, Nicholas L.; Nelson, Hal T.	2013	USA	Review	Not Applicable	Not Applicable
Carley, Sanya; Ansolabehere, Stephen; Konisky, David M.	2019	USA	Survey	National	2,000
Carley, Sanya; Konisky, David M; Atiq, Zoya; Land, Nick	2020	International	Review	Not Applicable	Not Applicable
Ceglarz, Andrzej; Beneking, Andreas; Ellenbeck, Saskia; Battaglini, Antonella	2017	Norway	Interview/ focus group	Local	17
Ciupuliga, A.R.; Cuppen, E.	2013	France	Case study	Local	Not Applicable

Authors	Year	Country	Method	Target population	Number of Participants
Cohen, Jed J.; Reichl, Johannes; Schmidthaler, Michael	2014	International	Review	Not Applicable	Not Applicable
Cohen, Jed; Moeltner, Klaus; Reichl, Johannes; Schmidthaler, Michael	2016	Europe	Survey	National	7,659
Cotton, M.; Devine-Wright, P.	2011	UK	Interview/ survey	Local/ professional	25
Cotton, Matthew; Devine-Wright, Patrick	2012	UK	Interview	Professionals	22
Cotton, Matthew; Devine-Wright, Patrick	2013	UK	Focus group	Local	38
Devine-Wright, Hannah; Devine-Wright, Patrick	2009	UK	Focus group	Local	62
Devine-Wright, Patrick	2009	UK	Review	Not Applicable	Not Applicable
Devine-Wright, Patrick	2013	UK	Survey	Local	503
Devine-Wright, Patrick; Batel, Susana	2013	UK	Survey	National	1,519
Devine-Wright, Patrick; Batel, Susana	2017	UK	Survey	National	1,519
Devine-Wright, Patrick; Devine-Wright, Hannah; Sherry-Brennan, Fionnguala	2010	UK	Survey	National	1,041
Devine-Wright, Patrick; Sherry-Brennan, Fionnguala	2019	Ireland	Interview/ Ethnographic	Local/ professional	13
Di Angelo, Luca; Gherardini, Francesco; Di Stefano, Paolo; Leali, Francesco	2020	Italy	Model	Not Applicable	Not Applicable
Elliott, P.; Wadley, D.; Han, J.H.	2016	Australia	Survey	Local/National	600
Elliott, Peter; Wadley, David	2012	Australia	Focus group	National	78
Escribano, Gonzalo; Gonzalez-Enriquez, Carmen; Lazaro-Touza, Lara; Paredes-Gazquez, Juandiego	2023	France Germany Italy Spain	Survey	National	4,000
Firestone, Jeremy; Bates, Alison W.; Prefer, Adam	2018	USA	Interview/ survey	Local	443
Flachsbarth, Franziska; Wingenbach, Marion; Koch, Matthias	2021	Germany	Model	Not Applicable	Not Applicable
Friedl, Christina; Reichl, Johannes	2016	Austria Germany	Interview/ workshop	Local/ professional	16
Furby, L; Slovic, P; Fischhoff, B; Gregory, R	1988	USA	Review	Not Applicable	Not Applicable
Gerstle, B.	2014	USA	Review	Not Applicable	Not Applicable
Giaccaria, S.; Frontuto, V.; Dalmazzone, S.	2016	Italy	Survey	Local	1,410
Giron, R.	2014	USA	Review	Not Applicable	Not Applicable
Gölz, Sebastian; Wedderhoff, Oliver	2018	Germany	Survey	National	2,009
Henry, Sebastien; Panciatici, Patrick; Parisot, Alexandre	2014	France	Review	Not Applicable	Not Applicable
Hyland, Marie; Bertsch, Valentin	2018	Ireland	Survey	National	1,044
Joalland, Olivier; Pereau, Jean-Christophe; Rambonilaza, Tina	2019	France	Model	Not Applicable	Not Applicable

Authors	Year	Country	Method	Target population	Number of Participants
Joe, Jeffrey C.; Hendrickson, Kelsie; Wong, Maria; Kane, Stephanie L.; Solan, David; Carlisle, Juliet E.; Koehler, David; Ames, Daniel P.; Beazer, Robert	2016	USA	Survey	Local	695
Kamlage, Jan-Hendrik; Drewing, Emily; Reinermann, Julia Lena; de Vries, Nicole; Flores, Marissa	2020	Germany	Case study	Local	Not Applicable
Keir, L.; Watts, R.; Inwood, S.	2014	USA	Submission analysis	Local	Not Applicable
Knudsen, Jørgen K.; Wold, Line Camilla; Aas, Øystein; Kielland Haug, Jens Jacob; Batel, Susana; Devine-Wright, Patrick; Qvenild, Marte; Jacobsen, Gerd Blindheim	2015	UK Norway	Focus group	Local	Not specified
Koecklin, Manuel Tong; Longoria, Genaro; Fitiwi, Desta Z.; DeCarolis, Joseph F.; Curtis, John	2021	Ireland	Survey/ modelling	National	1,057
Koelman, Mark; Hartmann, Thomas; Spit, Tejo J. M.	2022	Netherlands	Interview	Professionals	15
Komendantova, Nadejda; Battaglini, Antonella	2016	Germany	Survey/ Ethnographic	Local/ professional	Not specified
Konisky, David M.; Ansolabehere, Stephen; Carley, Sanya	2020	USA	Survey	Local/National	16,200
Lienert, Pascal; Suetterlin, Bernadette; Siegrist, Michael	2015	Switzerland	Survey	National	248
Lienert, Pascal; Sütterlin, Bernadette; Siegrist, Michael	2018	Switzerland	Survey	National	515
Linzenich, Anika; Zaunbrecher, Barbara Sophie; Ziefle, Martina	2020	Germany	Survey	National	147
Linzenich, Anika; Ziefle, Martina	2018	Germany	Survey	National	70
Maney, CT	1996	USA	Review	Not Applicable	Not Applicable
Martiskainen, Mari; Sovacool, Benjamin K.	2021	International	Review	Not Applicable	Not Applicable
Menges, R.; Beyer, G.	2014	Germany	Survey	Local	1,003
Moyer, R.M.; Song, G.	2016	USA	Survey	Professionals	420
Moyer, R.M.; Song, G.	2019	USA	Survey	Professionals	420
Mueller, Christoph Emanuel	2019	Germany	Survey	Local	1,300
Mueller, Christoph Emanuel	2020	Germany	Survey	Local	1,303
Mueller, Christoph Emanuel	2020	Germany	Survey	Local	2,605
Mueller, Christoph Emanuel; Keil, S.I.	2020	Germany	Survey	Local	859
Mueller, Christoph Emanuel; Keil, S.I.; Bauer, C.	2017	Germany	Survey	Local	1,302
Mueller, Christoph Emanuel; Keil, S.I.; Bauer, C.	2019	Germany	Survey	Local	2,605
Navrud, Ståle; Ready, Richard C.; Magnussen, Kristin; Bergland, Olvar	2008	Norway	Survey	Local	604

Authors	Year	Country	Method	Target population	Number of Participants
Nelson, Hal T.; Swanson, Brian; Cain, Nicholas L.	2018	USA	Survey	Local	358
Neukirch, Mario	2020	Germany	Interview	Professionals	12
Porsius, Jarry T.; Claassen, Liesbeth; Weijland, Patricia E.; Timmermans, Danielle R. M.	2016	Netherlands	Interview	Local	15
Priestley, T.; Evans, G.W.	1996	USA	Survey	Local	236
Sæþórsdóttir, A.D.; Hall, C.M.	2018	Iceland	Survey	Tourist	1,078
Saethorsdottir, Anna Dora; Hall, C. Michael	2019	Iceland	Interview/ survey	Professionals	221
Salak, B.; Lindberg, K.; Kienast, F.; Hunziker, M.	2021	Switzerland	Survey/ modelling	National	1,062
Sardaro, Ruggiero; Bozzo, Francesco; Fucilli, Vincenzo	2018	Italy	Review	Local	Not Applicable
Schmidt, Peter; Lilliestam, Johan	2015	Europe	Review	Not Applicable	Not Applicable
Sharpton, Tara; Lawrence, Thomas; Hall, Margeret	2020	USA	Survey	National	2,550
Simora, Michael; Frondel, Manuel; Vance, Colin	2020	Germany	Referendum	National	6,568
Soini, K.; Pouta, E.; Salmiovirta, M.; Uusitalo, M.; Kivinen, T.	2011	Finland	Survey	Local	630
Stadelmann-Steffen, Isabelle	2019	Switzerland	Interview	National	1,129
Stefansson, Þorkell; Saeporsdottir, Anna Dora; Hall, C. Michael	2017	Iceland	Survey	Tourist	2,075
Steinbach, Armin	2013	Germany	Review	Not Applicable	Not Applicable
Tate, R.D.	2021	USA	Review	Local	Not Applicable
Thomas, Heiko; Marian, Adela; Chervyakov, Alexander; Stueckrad, Stefan; Salmieri, Delia; Rubbia, Carlo	2016	Germany	Review	Not Applicable	Not Applicable
Tumlison, C.; Moyer, R.M.; Song, G.	2017	USA	Survey	Professionals	420
Vajjhala, Shalini P.; Fischbeck, Paul S.	2007	USA	Survey	Professionals	56
van de Grift, Elisabeth; Cuppen, Eefje	2022	International	Review	Not Applicable	Not Applicable
Vega-Araujo, Jose; Heffron, Raphael J.	2022	Colombia	Interview	Local/ professional	10
Wadley, D.; Han, J.H.; Elliott, P.	2019	Queensland, Australia	Survey	National	780
Wadley, D.A.; Han, J.H.; Elliott, P.G.	2019	Australia	Survey	National	780
Wolsink, Maarten	2018	International	Review	Not Applicable	Not Applicable
Wuebben, Daniel	2017	USA	Ethnographic/ survey	Tourist	81

Authors	Year	Country	Method	Target population	Number of Participants
You, Jongeun; Heikkila, Tanya; Weible, Christopher M.; Kim, Serena; Park, Kyudong; Yordy, Jill; Smolinski, Sharon L.	2022	USA	Interview/ review	Local/ professional	43
You, Jongeun; Weible, Christopher M.; Heikkila, Tanya	2022	USA	Review	Local/ professional	Not Applicable
You, Jongeun; Yordy, Jill; Weible, Christopher M.; Park, Kyudong; Heikkila, Tanya; Gilchrist, Duncan	2023	USA	Interview/ review	Professionals	7
Zaunbrecher, Barbara S.; Linzenich, Anika; Ziefle, Martina	2017	Germany	Survey	National	149
Zaunbrecher, Barbara S.; Stieneker, Marco; De Doncker, Rik W.; Ziefle, Martina	2016	Germany	Survey	National	109

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7.

Case Studies

Comparing high voltage overhead and underground transmission infrastructure (up to 500 kV)

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Abbreviations and Acronyms

Abbreviation	Description
AC	Alternating Current
ACSR	Aluminium conductor steel-reinforced cable (or conductor)
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AVP	AEMO Victorian Planning
CBA	Cost Benefit Analysis
CIGRE	International Council on Large Energy Systems
DC	Direct Current
EHV	Extra High Voltage—consensus for AC Transmission lines is 345kV and above
EIS	Environmental Impact Assessment
EIR	Environmental Impact Review
EIS	Environmental Impact Statement
ELF	Extremely low frequency
EMF	Electromagnetic Fields
ENA	Electricity Networks Australia
EPR	Ethylene propylene cable
EPRI	Electrical Power Research Institute
GIL	Gas Insulated Line
GC	Gas cable
HDD	Horizontal Directional Drilling
HPOF	High-pressure oil-filled cable

Abbreviation	Description
HTLS	High Temperature Low Sag Conductors
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ISP	AEMO's Integrated System Plan
NEM	National Electricity Market
OH	Overhead
OHTL	Overhead transmission line
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
REZ	Renewable Energy Zone
RIT-T	Regulatory Investment Test—Transmission
ROW	Right of Way (e.g. easement)
SCOF	Self-contained oil-filled cable
SLO	Social Licence to Operate
UG	Underground
UGC	Underground cable
UGTL	Underground transmission line
XLPE	Cross-linked polyethylene

1.

Introduction

This study aims to investigate the benefits and trade-offs between overhead and underground transmission line infrastructure, specifically focusing on issues associated with undergrounding new transmission infrastructure. It seeks to establish a clear and consistent approach to the evaluation of overhead lines and underground cable transmission, including the consideration of community concerns around the need for new transmission infrastructure to connect large renewable energy generation projects. It does this through systematic reviews of the literature as well as incorporating experiences of Transmission Network Service Providers (TNSPs) in Australia and overseas. The study has a particular focus on 500kV infrastructure which is expected to be the system voltage for high-capacity transmission lines in Australia going forward.

Historically, transmission networks in Australia developed from the need to transfer large amounts of power from large coal fired power stations, typically co-located near coal reserves, over long distances to major cities and industrial load centres. In contrast, the proposed large scale renewable generation facilities, mainly solar and wind farms, require greater land areas and are largely being located in greenfield areas with little or no existing transmission network infrastructure. These new developments are naturally creating community interest and concerns around a range of potential impacts, including but not limited to: visual amenity; environment; Traditional Owner lands; agricultural land use; and social licence to operate concerns. This has led to questions surrounding when it is appropriate to underground transmission infrastructure and the likely implications of doing so.

This chapter provides a review of case studies, both Australian and international, in considering technical, cost, environmental, social and community information for transmission projects in the range of 330kV to 500kV.

2.

Review of Current Developments in the Australian NEM

2.1 Overview of NEM

The National Electricity Market (NEM) is comprised of five physically connected regions on the east coast of Australia: Queensland, New South Wales (which includes the ACT), Victoria, Tasmania, and South Australia. Western Australia and the Northern Territory are not connected to the NEM. They have their own electricity systems and separate regulatory arrangements, although the AEMC does have a role in the Northern Territory.

The Australian Energy Market Agreement sets out the legislative and regulatory framework for Australia's energy markets. It provides for national legislation that is implemented in each participating state and territory. There are four key market bodies governing the NEM:

- The Australian Energy Market Commission (AEMC) develops the rules by which the market must operate.
- The Australian Energy Market Operator (AEMO) handles the day-to-day operations of the electricity and gas markets.
- The Australian Energy Regulator (AER) enforces the national electricity market rules and makes judgements on the regulatory proposals of monopoly network operators.

While Energy Consumers Australia are the national voice for residential and small business energy consumers.

National Electricity Law, establishes obligations in the NEM, including transmission networks. The Law is supported by the National Electricity Rules. The requirements for planning and operation of transmission networks are set in the National Electricity rules and supported by guidelines and processes administered by the AER and AEMO. The objectives are to ensure the safe, reliable, and efficient operation of the transmission system. These requirements cover a wide range of issues including design and construction; maintenance and repair; environmental; and social impacts of the transmission lines.

2.2 NEM Transmission Network Planning and Approval Processes

Transmission Network Service Providers (TNSPs) must undertake the AER's Regulatory Investment Test for Transmission (RIT-T) when potential solutions to reinvest in network assets or increase the capacity of high voltage transmission network are over a $7 million threshold—as defined in the National Electricity Rules.

The RIT-T is a consultation process which has 3 stages:

1. Project Specification Consultation Report (PSCR) is published. Stage 1 is not required for projects that have been identified as actionable under AEMO's Integrated System Plan (ISP).
2. Project Assessment Draft Report (PADR) is published.
3. Project Assessment Conclusions Report (PACR) is published.

State governments or their jurisdictional bodies also develop projects, including those related to renewable energy zones. These projects are not necessarily subject to the RIT-T process. The RIT-T is specifically designed to assess transmission investments proposed by TNSPs within the NEM in Australia.

There is coordination and collaboration between state government projects and the regulatory processes conducted by the AER and AEMO with its ISP. This collaboration ensures that the state projects align with the broader requirements of the NEM and consider system security and efficiency. However, the specific processes for state government projects differ from the formal RIT-T process that applies to TNSPs.

2.3 AEMO's Integrated System Plan (ISP)

AEMO developed the first ISP in 2018 to provide an actionable roadmap for eastern Australia's power system. The plan is updated every 2 years, with the current published plan being the 2022 ISP. Consultation for the 2024 ISP is currently in progress. The ISP has drawn on extensive stakeholder engagement and internal and external industry and power system expertise to develop a blueprint that maximises consumer benefits through a transition period of great complexity and uncertainty.

As part of the 2024 ISP consultation process, AEMO recently released the 2023 Transmission Expansion Options Report [1]. This report lists projects currently being assessed and reviewed for the 2024 ISP and summarised in Table 1, Table 2 and Table 3.

In addition to the projects listed above, the ISP provides an overview of network development options related to flow paths linking existing network and renewable energy zones (REZs). An overview is provided in the map in Figure 1.

Table 1. Committed and Anticipated Projects (from AEMO 2023 Transmission Expansion Options Report [1])

Project	Status	Responsible TNSP(s) or jurisdictional bodies
Central-West Orana REZ Transmission Link	Anticipated	EnergyCo
Eyre Peninsula Link	Committed	ElectraNet
VNI Minor (also named VNI East Upgrade)	Committed	AEMO (Victorian Planning), Transgrid
QNI Minor (Queensland—New South Wales Interconnector)	Committed	Transgrid
Northern QREZ	Committed	Powerlink
Project EnergyConnect—Stage 1	Committed	ElectraNet, Transgrid
Project EnergyConnect—Stage 2	Committed	ElectraNet, Transgrid
Murray River REZ and Western Victoria REZ minor augmentations	Committed	AEMO (Victorian Planning)
Victoria Central North REZ minor augmentations	Committed	AEMO (Victorian Planning)
Mortlake Turn-In	Committed	AEMO (Victorian Planning)
Waratah Super Battery Network Augmentations and SIPS Control	Committed	EnergyCo
Ararat synchronous condenser	Committed	AEMO (Victorian Planning)
Western Renewables Link	Anticipated	AEMO (Victorian Planning)

Table 2. RIT-T Projects in 2024 ISP (from AEMO 2023 Transmission Expansion Options Report [1])

Project	Responsible TNSP(s) or jurisdictional bodies
HumeLink	Transgrid
VNI West	Transgrid and AEMO (Victorian Planning)
Marinus Link	TasNetworks, Marinus Link

Table 3. Future ISP Projects with Preparatory (from AEMO 2023 Transmission Expansion Options Report [1])

Project	2022 ISP Timing	Responsible TNSP(s)
South East SA REZ expansion (Stage 1)	2025-26 to 2045-49	ElectraNet
Darling Downs REZ Expansion (Stage 1)	2025-26 to 2047-48	Powerlink
Mid-North SA REZ Expansion	≥ 2028-29	ElectraNet
QNI Connect (500 kV option)	2029-30 to 2036-37	Powerlink and Transgrid
QNI Connect (330 kV option – NSW scope)	2029-30 to 2036-37	Transgrid
South West Victoria REZ Expansion	≥ 2033-34	AEMO (Victorian Planning)

These projects are generally in planning phase by TNSP's and State jurisdictional bodies. The Queensland Energy and Jobs Plan [2] provides details and an overview of the roadmap for Queensland's proposed REZ expansion. Similar plans are available in the other states.

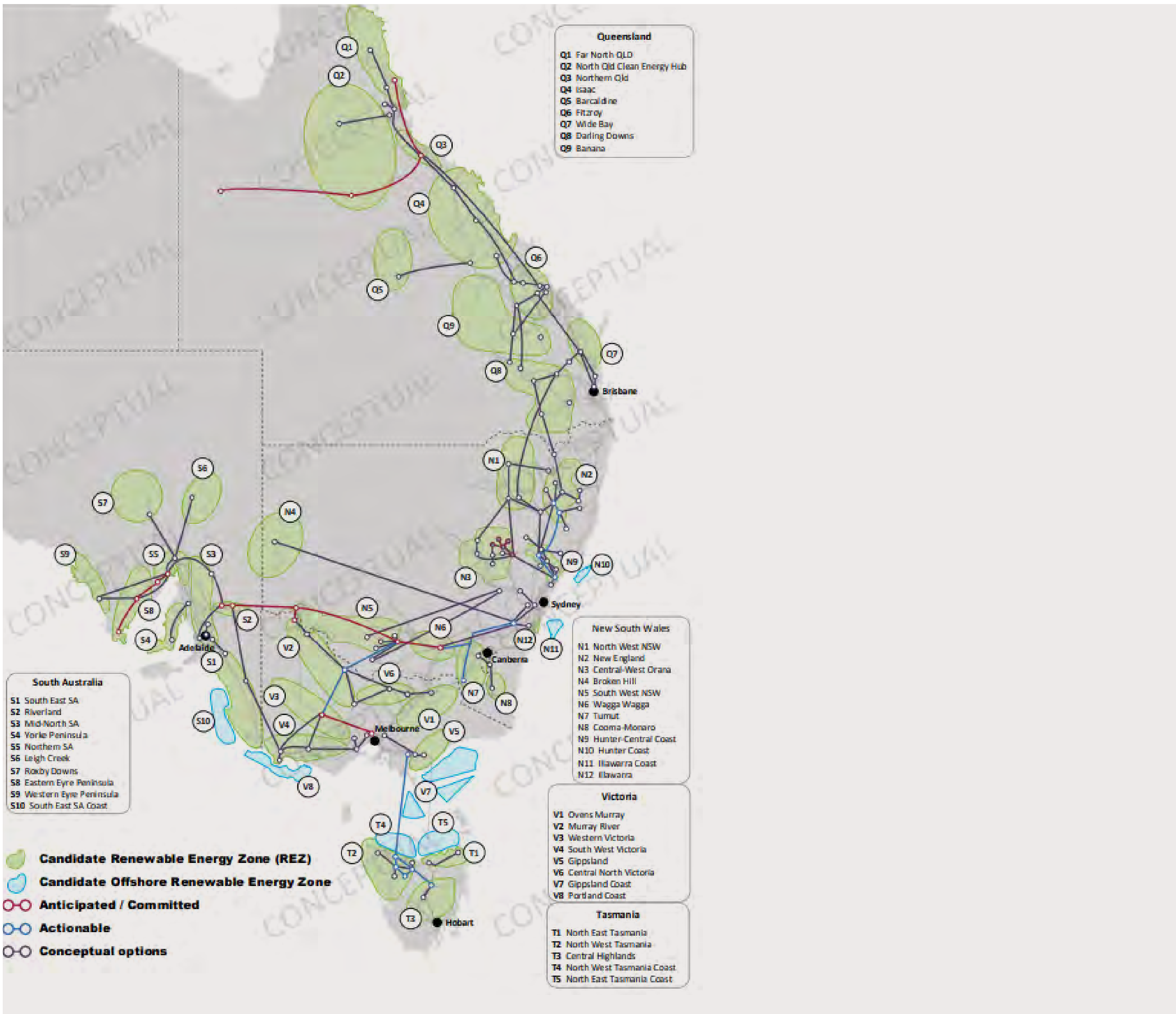

Figure 1. MAP of REZs and Flow Path Options (AEMO 2023 Transmission Expansion Options Report [1])

2.4 Current NEM Engagements involving Significant Transmission Line Projects

This section of the report focusses on three significant case studies where planning, consultation and engagement is in progress: (a) Humelink in NSW; (b) Western Renewables Link; (c) VNI West in Victoria. The review of these cases took place in July before the findings of the NSW Senate Inquiry in August, although the results are detailed in the chapter. However, we note the announcement of a subsequent Inquiry by a Select Committee in NSW in September, with the findings expected to be handed down in March 2024. While Powerlink Queensland is progressing the Borumba Pumped Hydro Connection and Copperstring 2032 projects, given the infancy of these projects they were not included as case studies for this research.

2.4.1 Humelink (NSW)

The HumeLink project involves a 500 kV transmission upgrade connecting Project EnergyConnect and the Snowy Mountains Hydroelectric Scheme to the existing Bannaby substation.

During stakeholder consultation for the HumeLink project, the community raised concerns regarding transparency and community engagement processes from Transgrid. They expressed dissatisfaction with a lack of clarity around what were negotiable and non-negotiable elements of the project, how decisions will be notified, and opportunities for community input. Notably, only landowners within the project corridor were consulted, while adjacent landowners felt excluded from the process. These landowners also reported feeling misunderstood, being treated disrespectfully, and believed that alternative options for the transmission corridor proposed were not given sufficient consideration.

In response to these concerns, Transgrid has initiated a series of measures aimed at improving community relations and delivering improved outcomes for impacted communities. This includes the establishment of Community Consultant Groups, which aim to involve a diverse range of stakeholders at every stage of the proposal, allowing them to provide valuable input and feedback. Transgrid has also actively sought expressions of interest from the community to assess the cultural significance of Aboriginal objects and places within the project area. HumeLink spans the lands of the Wiradjuri, Ngunnawal, Ngarigo, and Gundungurra people. In collaboration with Registered Aboriginal Parties, cultural heritage surveys have been conducted, providing valuable insights for assessing impacts and implementing appropriate mitigation measures.

The community raised several concerns regarding the potential disturbances caused by the HumeLink project to farming operations. These concerns include impacts that limit the use of drones and GPS systems, which were deemed essential tools for modern farming practices. Worries were also expressed around the risk of introducing and spreading weeds and pathogens from construction movements, which could have detrimental effects on agricultural productivity. Increased traffic associated with the project was also a concern, with its potential to disrupt road networks and lead to the deterioration of road conditions. Community members have also expressed concerns about air quality, particularly the dust generated by construction trucks, and its potential impact on human health and agricultural activities. Noise and vibration concerns have been raised, with landowners and livestock expected to experience disturbances from construction activities. Additionally, there are worries about the obstruction of natural landscapes and its potential impact on tourism in the area.

Through community consultation, environmental field studies and site assessments to identify regional constraints and investigate local considerations, Transgrid refined the route to minimise these impacts to the community. These included:

- Tumut Area Route Refinement Decision: Traverses a longer distance on private land and affects seven residences within a 500-meter radius (compared to 24 or 26 in other route options). However, the route has lower environmental and social impacts, and it passes a shorter distance through high to very high bushfire risk areas. Provides diversification in supply, improved network resilience, and reduced adverse effects on the community.
- Bannaby Route Refinement Decision: Prioritises lower environmental impact as a smaller area of impacted Plant Community Types and lower biodiversity offset costs. Shorter distance through high bushfire risk areas and better network resilience.
- Green Hills Route Refinement Decision: Despite having higher costs and poorer network resilience, the route reduces impact on private landowners by removing five residences within 500 meters of the line.
- Pejar Dam Route Refinement Decision: Considers amenity impact on Pejar Dam for recreational users. There are higher impacts on Plant Community Types and biodiversity offset costs along the alternate route, but it avoids crossing the middle of the recreational dam.

Throughout all stages of the project, the community has expressed a preference for undergrounding as a route option for the HumeLink project due to various concerns associated with overhead towers. These concerns include the potential for the towers to cause bushfires, hinder firefighting efforts, create electromagnetic fields with potential health impacts, render farmland unusable, industrialise the landscape, decrease land and property values, destroy native habitats, and be susceptible to collapse during storms and high winds. However, an Undergrounding Report conducted by Transgrid found that the technical feasibility of the undergrounding being limited to 70km and the excessive cost of undergrounding the transmission lines was deemed unsustainable. The cost would ultimately be borne by commercial, industrial, and private electricity consumers, and it would also result in a significant project completion delay. Stakeholders criticised the Undergrounding Study for its focus on highlighting negative impacts while lacking representation of potential positive benefits. They also highlighted the discrepancies in cost estimates for underground cable components, technical inaccuracies in installation and operation, excessive commissioning schedules, and constraints based on studies focused on the overhead route. Transgrid maintain undergrounding is not a viable option.

2.4.2 Victoria to New South Wales Interconnector West (VNI West)

This project consists of a new high capacity 500kV double-circuit transmission line to connect Western Renewables Link located north of Ballarat with Project EnergyConnect at Dinawan via a new terminal station near Kerang.

Some members of the community have expressed dissatisfaction with the stakeholder engagement process, citing several issues. These include late communication to potentially impacted communities about project decisions, which limited their ability to prepare and provide informed submissions. It was felt that the six-week consultation period was insufficient time for the community to thoroughly understand the project details and make meaningful contributions. Additionally, there were concerns about the adequacy of information provided, as some community members and landowners found it challenging to comprehend the technical and complex project details.

The AEMO's Project Assessment Draft Report (PADR) has also caused community concerns regarding the project. Stakeholders have emphasised the need to consider various social license issues, including visual amenity, biodiversity, land use, culture, heritage, tourism, and bushfire risk. Of particular concern is the impact on regional agriculture, as the installation of transmission lines was felt to impede the use of large tractors, irrigation systems, and modern agricultural technologies such as GPS-enabled tractors, auto steer, and drones. Property access issues have also been raised, including inadequate notice, undisclosed chemical usage, weed spread, failures in gate closures, crop and machinery damage, and soil impacts. Mental health concerns have been raised and attributed to the project, alongside worries about the potential impact of electromagnetic fields, including cancer and overall health risks for both humans and animals. Some stakeholders have suggested moving the corridor further west along a Bulgana to Kerang corridor, which offers lower density dwellings, increased wind resources to harness more renewable generation, larger agricultural properties, fewer constraints related to native vegetation and ecology, less sensitivity to cultural heritage, and reduced flood risk. Additionally, there have been questions regarding the accuracy of cost estimates and recorded benefits associated with VNI West's interaction with the Western Renewables Link and other projects within the NEM.

In response to the recommendations, AVP and Transgrid have taken the following actions:

- Considered five new options connecting VNI West to WRL further west, which they claim consider more factors that may impact social license than previous options.
- Extended the modelling horizon until 2049–50 as PADR submitters questioned the short duration of the NPV analysis, which ended in 2047–48. They noted that VNI West (via Kerang) has a longer economic life of 16 years, making the analysis period insufficient.
- Updated cost estimates for the New South Wales portion of investment based on the Strategic Benefits Payment Scheme as the estimated km length underpinning these payments has been updated.
- Improved alignment with RIT-T and AER's guidelines, aligning with the 2022 Integrated System Plan parameters.
- The market modelling undertaken for the PADR assumed that the Dinawan to Wagga Wagga portion of EnergyConnect is built to 500kV but operated at 330kV under both the base case and the option cases. Transgrid and AVP updated the modelling as being built and operated at 330kV under the base case to estimate the expected benefits of the project more accurately for consumers.
- Interaction with the Victorian Government's offshore wind policy was not included in the core scenarios for this cost benefit analysis, but due to increased stakeholder and government support for Victorian offshore wind, AVP and Transgrid expanded the sensitivity analysis to include assessing changes in transmission costs and the Victorian Government's offshore wind policy which assumes significant Victorian offshore wind development going forward.
- Increased transparency in cost estimates and terminal value calculation in their Project Assessment Consultation Report.

Transgrid published an additional Consultation Report in response to community feedback, identifying Option 5 (connects from Dinawan, via the new terminal station near Kerang, directly to WRL at a new terminal station near Bulgana) as the proposed preferred option for further development. However, stakeholders raised concerns about the study's lack of comprehensive engagement and accurate consideration of social constraints. They felt that agricultural impacts, mental health, and community opposition to Option 5 were not adequately addressed. The justification for Multi Criteria Analysis ratings was found lacking, with economic factors being prioritised over social, cultural, and environmental aspects, as is currently required by the RIT-T process. Regional plans and development directions were also not given sufficient consideration and it was suggested that the modelling overlooked impacts on land value, agriculture, tourism and lacked modelling disclosing the WRL and VNI West projects' carbon footprints.

In response to the concerns raised, Transgrid and AVP explored a variant of Option 5 called Option 5A, which involved selecting a different crossing point over the Murray River (north of Kerang rather than near Echuca) and allowing for higher hosting limits for renewable generation in the Murray River Renewable Energy Zone. Furthermore, Transgrid and AVP actively explored opportunities to increase the capacity for renewable generation within the VNI West project. To ensure accurate cost estimation that reflect the current market and labour trends, Transgrid and AVP updated their cost estimates to reflect latest market and labour trends. This update incorporated the latest information and insights from AEMO's 2023 Transmission Cost Database which highlights material and labour price inflation, as well as the recently announced additional landholder payments by the Victorian Government. This involves payments to landowners for a typical area of transmission easement at a standard rate of $8,000 per year per kilometre of transmission hosted for 25 years. The refined route option, considering stakeholder feedback, includes fewer environmental constraints and avoids intercepting the Patho Plains, an area of significant grassland habitat known to support the endangered Plains-wanderer bird. It also avoids passing near Ghow Swamp, a place of national cultural significance.

Undergrounding is once again a preferred transmission method advocated for by the community due to its perceived lower impact on flora, fauna, landscape, and visual aesthetics, reduced bushfire risk and lower impact on agricultural productivity including inability to operate tractors, drones, and airborne pesticide distribution. Specific requests were made for undergrounding in urbanised areas, areas of high landscape value, and around habitats of endangered species. AVP and Transgrid are considering partial undergrounding in areas where severe impacts cannot be avoided, but state that full undergrounding is not feasible because of the technical feasibility for undergrounding being limited to 70km. However, cost effective alternatives such as route diversion, screening, and line tower design will be prioritised.

2.4.3 Western Renewable Link Victoria (WRL)

The Western Renewables Link projects consists of a proposed 190km long transmission line extending from Bulgana near Stawell in Western Victoria to Sydenham in Melbourne's North-West via a new terminal station to the North of Ballarat.

Figure 2 Local farmers' protests of AusNet's Renewables West project

The community has expressed several concerns regarding the stakeholder engagement process. They have highlighted inadequate advertisement of community meetings, resulting in limited awareness and participation. Additionally, there is dissatisfaction with the limited notice provided for project updates (such as March 2021 session with announcement of the single corridor, scheduled for mid-year 2021), as well as long waiting times for community drop-in sessions that impede in-depth discussions on important matters. Stakeholders have also reported unsatisfactory or inadequate answers from AusNet representatives, leading to concerns about the effectiveness of the communication process. The community has expressed dissatisfaction with the phone services, noting that they were not effective in providing immediate assistance. Furthermore, there are concerns about the lack of empathy demonstrated by staff members during interactions. Stakeholders have felt that their concerns and feedback were not fully understood or addressed and levels of concern are illustrated in the signs of protest across various local farms (Figure 2).

The community has raised significant concerns regarding threats to biodiversity in relation to the proposed project. They have emphasised the importance of preserving habitat provided by hollow-bearing trees and riparian corridors along waterways. Observations of diverse fauna, including kangaroos, wombats, bats, brolgas, and raptors, have highlighted the ecological value of the area.

Stakeholders have also highlighted the presence of rare species such as Grevillea Steiglitziana and Braid Moss, underscoring the need for conservation efforts. Concerns extend beyond terrestrial wildlife, with stakeholders identifying important nesting sites for some bird species. The presence of platypi and Rakali around Clunes has also been noted. In addition to biodiversity, stakeholders have expressed worries about visual amenity and the potential loss of land value. Landscape impacts on volcanic cones, tourist spots, and night sky views are significant concerns. Furthermore, stakeholders have raised issues regarding electromagnetic force and its potential health risks, particularly in relation to pacemakers. The possibility of lightning strikes and flashovers has also been mentioned.

There have been additional concerns regarding bushfires in relation to the project. These concerns include fears of fires starting due to project infrastructure, potential impacts on bushfire management activities such as planned burning and aerial firefighting, difficulties in escaping forest areas during a bushfire event, coupled with the worsening of fire weather conditions and fire risk due to climate change. The community has proposed undergrounding as a potential solution to mitigate these concerns. However, AusNet has argued that while overhead transmission lines may cause less ground disturbance and provide cost-effective connections for renewable energy generators, they also meet the necessary requirements for electricity system availability and reliability. AusNet maintains that overhead construction is the most feasible option for the entire project.

The proposed route for AusNet's transmission line has been informed by community and stakeholder feedback, as well as technical studies, field surveys, and investigations. The key refinements for each area include:

- Bolwarrah: The new route minimises impacts on heavily vegetated areas while maximising the use of cleared land. It avoids a large cluster of endangered Brooker's gums but still impacts other clusters. The wetland adjacent to the Moorabool River West Branch, a potential habitat for growling grass frogs, is avoided. The route also maximises distance from houses in the Tooheys Close area and reduces visual impact through screening.
- Mt Steiglitz to Korjamnunnip Creek: The refinement increases the distance from houses and minimises land use impacts in this area.
- Myrniong: The route reduces the visual scale of towers from the Myrniong township by increasing the distance between the transmission line and the town. It is set against the backdrop of forested hills and ridges of the Lerderderg State Park, minimising visual impacts on adjacent houses. Efforts are made to minimise impacts on the area of cultural sensitivity associated with Myrniong Creek.
- Darley military camp area: Refinements are made to further reduce impacts on the military camp site and Grey Box Grassy Woodlands.
- Merrimu Reservoir: The route avoids impacts on the significant ecological values of Long Forest and Aboriginal cultural heritage sites. It maximises distance from residential properties and avoids potential impacts on any future dam wall upgrade works. The route also minimises impacts on existing quarry operations.
- Melton –– MacPherson Park: The route avoids threatened ecological communities and areas of Aboriginal cultural heritage sensitivity. It does not directly impact the sporting fields at MacPherson Park and follows property boundaries to minimise impacts on landholders. The current operations at Melton Aerodrome are also considered to minimise disruption.

A common theme observed across all three projects was the topic of undergrounding and its dismissal by project coordinators, as well as sentiments regarding the long-term advantages of underground transmission. Stakeholders argued that the initial cost and time investment of undergrounding (and the technical limit to short distances) would be outweighed by the significant benefits it offers. These benefits include enhanced safety and reduced health risks associated with electromagnetic fields, preservation of visual amenity and landscapes, safeguarding property values, minimising biosecurity threats where concerns were raised in relation to construction risks, preserving productive farming operations, and mitigating the risks of bushfires. Stakeholders also highlighted the importance of meaningful community engagement throughout the decision-making process for all three projects. They highlighted the need for transparent and inclusive dialogue that considers the perspectives and concerns of all stakeholders. By fostering a collaborative approach, stakeholders believed that a more balanced and equitable outcome could be achieved, considering the interests of the community to achieve long-term sustainability in transmission projects.

2.4.4 New South Wales Undergrounding Inquiry

A NSW Parliamentary Inquiry was conducted into the feasibility of undergrounding the transmission infrastructure for renewable energy projects[1]. The Committee inquired into (a) the costs and benefits of undergrounding; (b) existing case studies and current projects regarding similar undergrounding of transmission lines in both domestic and international contexts; (c) any impact on delivery timeframes of undergrounding; (d) any environmental impacts of undergrounding.

The inquiry's report was released in late August 2023. Its key findings and recommendations are:

> ***Finding 1***
>
> *That, in considering all the evidence, the current plan for constructing HumeLink as a 500 kV*
>
> *overhead transmission line is the correct approach especially given the applicable regulatory*
>
> *environment and the lack of any action to date in progressing the undergrounding option.*
>
> ***Recommendation 1***
>
> *That the NSW Government consider the viability of changing the New South Wales planning framework to require:*
>
> - *a comprehensive cumulative impact study to be undertaken before any renewable energy zone (REZ) is declared; and*
> - *community consultation on any proposed REZ to start at the scoping stage to allow adequate consideration of viable alternatives.*
>
> ***Recommendation 2***
>
> *That the NSW Government consider the creation of an independent ombudsman to oversee consultation upon, and rollout of, renewable energy projects and transmission infrastructure in New South Wales and to receive and handle complaints about these processes.*

Based on a negative response to the findings and recommendations, with some politicians and community questioning the integrity of the first Parliamentary Inquiry, on September 13, a subsequent Select Committee Inquiry has been announced. The Term of Reference include:

"1. That a select committee be established to inquire into and report on the feasibility of undergrounding the transmission infrastructure for renewable energy projects, and in particular:

> *(a) the costs, benefits and risks of underground versus overhead transmission lines, particularly with regard to bushfire and other weather-related events, ongoing environmental impacts, and community mental health and welfare*
>
> *(b) existing case studies and current projects regarding similar undergrounding of transmission lines in both domestic and international contexts*
>
> *(c) any impact on delivery timeframes of undergrounding with broad community consensus versus overhead transmission with large scale opposition*
>
> *(d) any* other related matters.

2. That the committee report by 31 March 2024."[2]

[1] Feasibility of undergrounding the transmission infrastructure for renewable energy projects (nsw.gov.au).
[2] https://www.parliament.nsw.gov.au/committees/listofcommittees/Pages/committee-details.aspx?pk=320#tab-termsofreference

3.

International Case Studies

3.1 Summary of Case Studies

Six case studies involving projects that have either recently been completed or have commenced design and construction phase were reviewed for this research considering technical, economic, environment and social aspects. The Powering Sydney's Future project was also included in these case studies as it provides a very recent example of a large underground transmission project. A summary of the projects is provided in Table 4 followed by a discussion on each case study.

Table 4. Case Studies for up to 500kV OHTL or UGTL Projects

Project Name	Year Completed or to be Completed	Location	Voltage (kV)	Capacity	Approximate Capital Costs	Features of Project
Southern California Edison	2016	California, USA	220 and 500 kV AC OHTL 500 kV AC UGTL	OHTL & UGTL 1732 MVA (normal) 3031 MVA (emergency)	Total project cost: $2.7B USD (2019) UGTL Cost: $224M USD (2013)	272 km OHTL (lattice tower design), 5.6 km UGTL (2 cables per phase with 2500 mm2 Cu cable in ducts)
West Coast Interconnector - Idomlund to German border	2022 to 2023	Denmark	400 kV AC OHTL and 400 kV AC UGTL	OHTL 2494 MVA (normal) 2771 MVA (maximum) UGTL 1663 MVA (continuous) 2494 MVA (40 hr short term rating)	Total project cost: €512M EUR (2023) UGTL Cost: €147M EUR (2023)	146 km OHTL (aesthetic low tubular tower design with triple bundles), 26 km UGTL (comprising 9 sections of XLPE 2500 mm2 AL cable)
Balen to Mapai	2021 to 2025	Sarawak Malaysia	500 kV AC OHTL	2200 MVA	Not Available	177 km OHTL (62 to 70 m lattice towers with quad bundled conductors) Comprehensive EIAS
Powering Sydney	2023	Sydney Australia	330 kV AC	2 x 750 MVA	$235M AUD (2022)	20 km UGTL (2500 mm2 Cu cables - laid in trefoil in duct banks and on bridges)
Hinkley Point Connection— National Grid UK	2022 to 2026	United Kingdom	400 kV AC OHTL and UGTL	2 x 2404 MVA continuous rating	£655.7 UK (2022)	48.5 km OHTL (new T-Pylon structures replacing existing 132 kV) and 8.5 km UGTL (in area of ONB) Comprehensive PEIS
Suedlink DC3 and DC4 HVDC Transmission Link	2026	Germany	+ 525kV HVDC UGTL	2 x 2000 MW	€11B EUR (2022)	700km 4GW 525kV HVDC underground transmission link with VSC converter stations.

3.2 Case Study 1 - Tehachapi Renewable Transmission Project, California USA

Overview

The Tehachapi Renewable Transmission Project (TRTP) is a series of new and upgraded high-voltage electric transmission lines and substations capable of carrying 4,500 megawatts of electricity from renewable and other generators in Kern County south to San Bernardino County, California, USA.[3]

One of the main reasons for the project was the urgent need to decarbonise the SCE grid, mainly through connections to several large wind farms. The project comprises 278km of transmission lines which replaced many of Southern California Edison's (SCE's) existing 220-kV lines with 500kV. They were all overhead lines except for 5.6km where the line passed through the city of Chino Hills.

The undergrounding was a result of the California Public Utilities Commission (CPUC) granting a request by the City of Chino Hills to underground the 5.6km segment of the project. This was a reversal of an earlier decision in 2009 where they had approved the project in spite of public opposition (Nelson, Swanson & Cain, 2018). Their subsequent finding was that the design of the above ground line effectively ignored community values and placed an unfair and unreasonable burden on residents. The cost estimate of the undergrounding in Chino Hills was approximately $224 million. This included an offset for Chino Hills' financial contribution of real property, which was valued at approximately $17 million USD. [4] From a technical point of view, Bucco et al. (2017) have reported that as a consequence of the inclusion of underground cables it:

"...causes the line to draw significant charging current, resulting in severe overvoltage conditions when the line is open circuited or lightly loaded".

This case study focuses on the underground cable section and the public opposition and process that led to the undergrounding outcome, with the project being completed in 2016.

Project Details

A summary of the project technical details is provided in Table 5.

The inclusion of underground cable necessitated the installation of reactive compensation in the network at Mira-Loma substation. A single line diagram of the 500kV network containing the underground cable is shown in Figure 3.

Construction Aspects

A map showing the overall scope of Tehachapi Renewable Transmission Project is provided in Figure 4 and a map showing location of the underground cable section in Figure 5.

Table 5. Project details—Tehachapi Renewable Transmission Project

Project owner:	Southern California Edison (SCE)
Overhead Lines:	
Voltage	220kV and 500kV AC
Circuit configuration	Double circuit and Single Circuit
Construction type	Double circuit and single circuit steel poles and lattice towers
Route length - overhead	272km
Underground Cable:	
Voltage	500kV AC
Circuit configuration	500-kV XLPE cable system consisting of one circuit with two cables per phase of 5000 kcmil (2500mm^2) copper conductor.
Construction type	Cables in concrete duct, banks grounded at a single point.
Route length - underground	5.6km
Transfer Capacity	1732 MVA (2000A) normal operation 3031 MVA (3500A) emergency operation There are spare conduit provisions to install a third cable per phase.
Cable manufacturer	Taihan Electric Wires (South Korea)
Project Costs:	
Total Cost—Lines and substations	$2.7B USD (2019) [5]
Estimated cost - Underground	$224M USD (2013) [4]
Project Construction Duration:	Overall project: 2010 to 2016 Underground section: 2014 to 2016
Project status:	Completed 2016

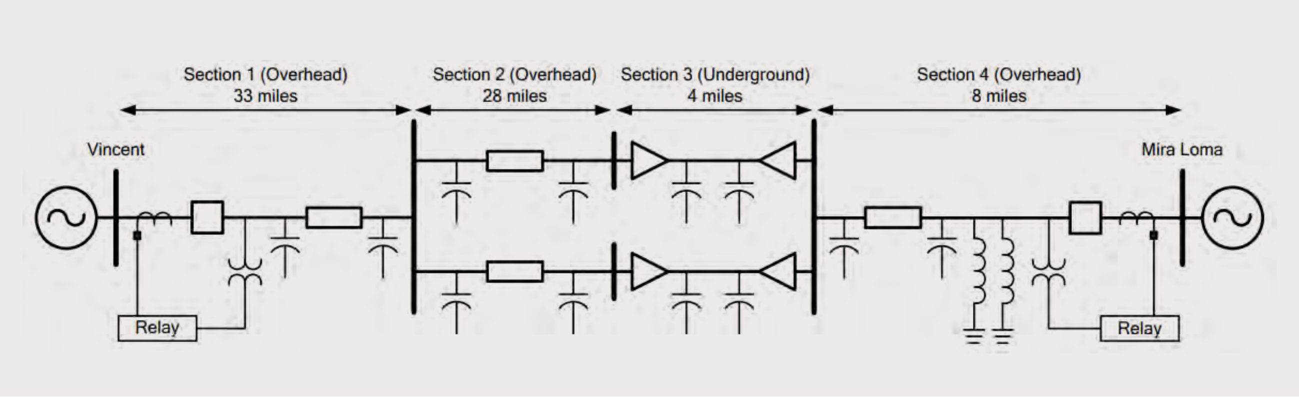

Figure 3. Single Line Diagram—500kV overhead and underground circuits (D. Bucco et al. [6])

Seg	Description
4	Single-circuit 500kV transmission line between Whirlwind and Antelope Substations
5	Replacement of two 220kV lines with one 500kV line between Antelope and Vincent Substations
6	32 miles of 500kV line from Vincent Substation through the Angeles National Forest
7	Replacement of 220kV line with 500kV line between Angeles National Forest and Mesa Substation
8	Replacement of 220kV line with 500kV line between Mesa and Mira Loma Substations. New and replacement double-circuit 220 kV lines between Chino and Mira Loma Substations
9	New Whirlwind Substation and upgrades to Antelope, Vincent, Windhub, Mesa, Gould, Mira Loma Substations
10	New 500kV line between Windhub and Whirlwind Substations
11	Replacement 500kV line between Vincent and Gould Substations. New 220kV circuit on existing structures between Gould and Mesa Substations

Figure 4. Project Overview Map—Tehachapi Renewable Transmission Project (Southern California Edison)

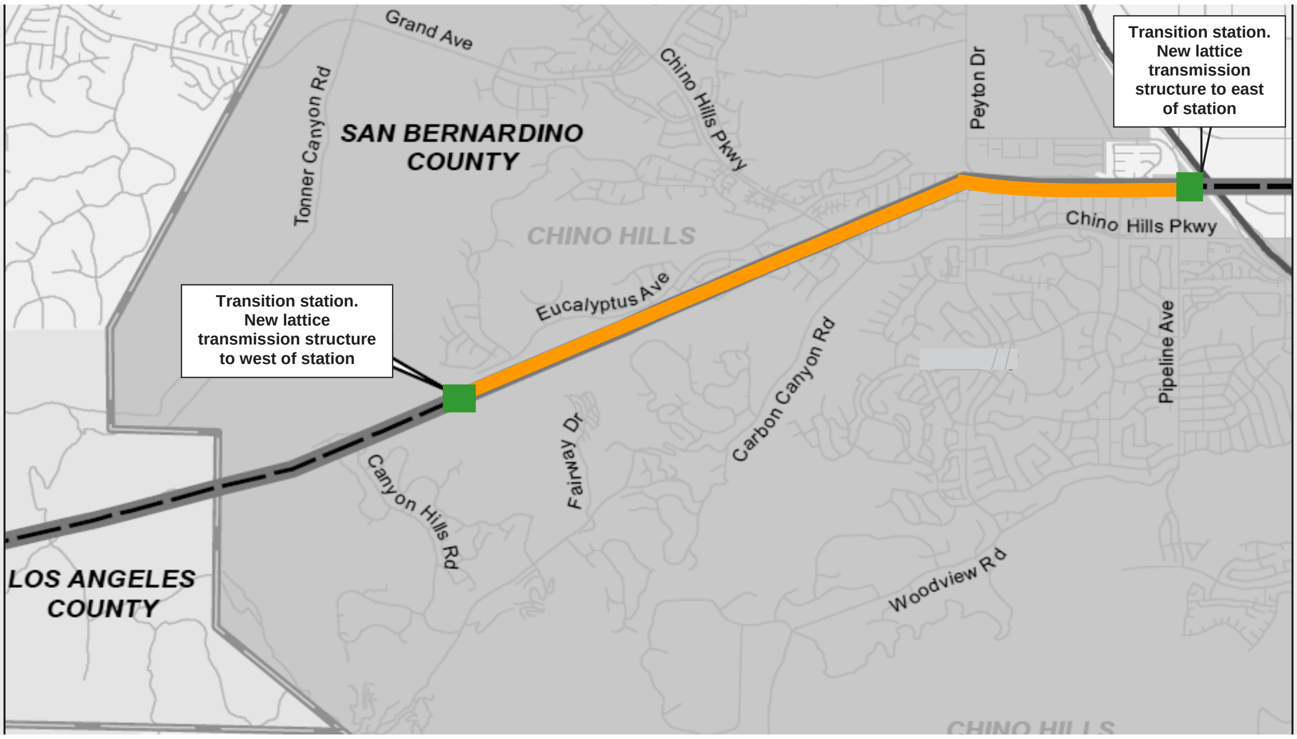

Figure 5. Undergrounding route map—Tehachapi Renewable Transmission Project (Southern California Edison)

Although the underground section of the project represented only 1.5% of the transmission line route it presented engineering and construction challenges because of the hilly terrain and location of transition stations. Figure 6 and Figure 7 illustrate the type of terrain [7].

Figure 6. 500kV Underground Cable Trench Installation at Chino Hills (T&D World)

Figure 7. Tehachapi 500kV Underground Cable Installation (dailybulletin.com)

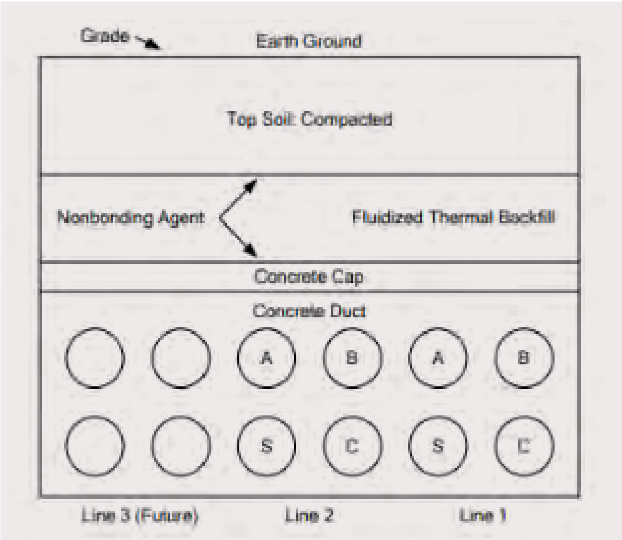

Figure 8. Underground Cable Trench Configuration (D. Bucco et al. [6])

Figure 9. 500kV Transition Station, Chino Hills (Southern California Edison)

The general configuration of the cable installation Trench is shown in Figure 8.

Restraining the cables along the route where they traversed steep hills also required special attention. Because of the flexible restraint systems in the vaults, the splices were not capable of restraining cables to fight gravity and prevent them from sliding downhill. Therefore, at six locations along the route, purposely built restraint vaults were designed to anchor the cables to prevent them from moving.

The two transition stations, each about 3 acres (1.2 hectares) in size, constituted major civil engineering work on their own. Because of the hilly terrain, the Western Transition Station required approximately 170,000 cubic yards (130,000 cubic m) of cut and 60,000 cubic yards (45,000 cubic m) of fill. The Eastern Transition Station involved the demolition of old buildings and hazardous contamination remediation. Key features of both stations are the cast-in-place concrete cable trenches, which were designed to relieve mechanical stress in the cable terminations by providing a space that would enable the cables to expand freely into the trenches.

Environmental Aspects

The California Public Utilities Commission was responsible for managing environmental impact assessment. Project configuration and route options were evaluated in an extensive EIS—Tehachapi Renewable Transmission Project Environmental Impact Report/Environmental Impact Statement. [8] The environment analysis in the report covered the following aspects:

- Aesthetics
- Agriculture
- Air Quality
- Biological Resources
- Cultural and Paleontological Resources
- Geology and Soils
- Hazards and Hazardous Materials
- Hydrology and Water Quality
- Land Use and Planning
- Mineral Resources
- Noise
- Population and Housing
- Public Services
- Public Utilities
- Traffic and Transportation
- Wilderness and Recreation

Social licence and impacts on landholders and communities

There was a large degree of public opposition to the project with a number of appeals through the courts. These caused multiple delays in the construction process and resulted in the undergrounding of the 5.6km segment through the built-up area. In short, the City of Chino Hills and their residents were not happy with the size of the transmission infrastructures being built, even though it was along an existing easement. In the protest document it was outlined that:

"...approximately 1046 homes will be located less than 500 feet from the proposed line. Currently these

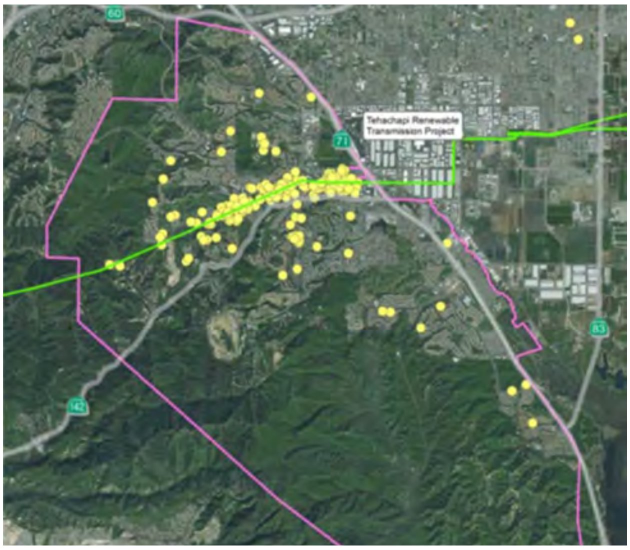

Figure 10. Aerial Image Showing image showing the boundary of Chino Hills, California (purple Line), the route of the power line project (green line), and location of Citizens who commented on the EIR (yellow dots).

(Esri, Digitalglobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AerGrid, IGN, and the GIS User Community)

neighbourhoods are dissected by a 150-foot-wide SCE easement on which there is a de-energized 220kV transmission line."

Figure 10 clearly shows location of those who commented on the Environmental Impact Review as well as the park areas nearby. Objections were around the size of the proposed towers "towering over the 'backyards'" and negatively impacting the "safety and welfare of the residents".

While considerable effort was spent investigating alternate routes. For example, at one point a proposed alternative involved the transmission line being re-routed through a state park. While a less populated area, the Recreation and Parks opposed the idea based on environmental and visual impacts. While the project progressed the City Council continued to lobby against the project with a renewed focus on undergrounding, which at the time had not really been done before in the US at that voltage [9]. With some controversy in its decision, in 2013 the CPUC overturned its original decision and moved the project towards undergrounding. The CPUC was responsible for regulatory approvals which included the environmental impact assessment phase.

In their 2007, protest application document, lawyers Day and Armstrong, on behalf of the City of Chino Hills, outlined pragmatic concerns about the SCE's planning process. They referred to the lack of effort by the SCE to consider viable alternatives, based on various project objectives that had been set. For example, Objective 8: Selection of the shortest feasible route and Objective 9: Meeting project needs in a timely manner. However, as was witnessed these objectives ultimately delayed the overall project delivery and resulted in additional costs and delays being incurred. Concerns around the safety considerations of electromagnetic fields were also raised at the time by many as a reason to object to the large infrastructure.

Minimising environmental impact

Examining the objections that were documented, size of laydown areas and marshalling yards for assembly and storage of poles and equipment and uncertainty about the vehicle and construction machinery requirements (i.e. cranes) and movements were items of concern. Particularly, ground disturbance and visual impact of such large infrastructures. Bushfire potential was also cited as reasons for seeking alternative routes but also recognition that the route choice by SCE in some instances was justified because of bushfire potential in some areas. Finally, a number of geological concerns centred around the existence of active faults, the potential for landslides and some potential for liquefaction were all raised as further environmental and safety reasons for seeking alternative routes. Vegetation management plans were required to ensure biodiversity considerations we well managed as part of the process.

Community consultation and engagement

SCE, as the project owner, was responsible for the stakeholder communication during the construction phase. Their website contains example Questions and Answers which consolidate many of the concerns that have arisen in the literature. While extensive community and stakeholder engagement occurred throughout the project (with the types of communications materials also available on the website), it is clear, from this case study, that any concerns about such a project, will need to be overcome with fair and transparent processes, fact-based information and strong leadership by the project proponent and communities they are working with.

3.3 Case Study 2 - West Coast 400kV AC Interconnector, Idomlund Denmark to German border

Overview

The project [10] is the part of a 400kV AC interconnector between Idomlund to the German border in Denmark. The transmission line comprises two 400kV AC circuits of with 146km of overhead line with 9 short sections totalling 26km of underground cable through socially and environmentally sensitive areas.

German TenneT and Danish Energinet [11]are working together to, plan and build this high-voltage transmission line connecting the German and the Danish electricity transmission systems. It is part of a so-called European "project of common interest" (PCI). To become a PCI, a project must have a significant impact on energy markets and market integration in at least two EU countries, boost competition on energy markets and help the EU's energy security by diversifying sources and contribute to the EU's climate and energy goals by integrating renewables.

The interconnection consists of a German section from a new-build substation in Klixbüll near Niebüll in Schleswig-Holstein to the Danish border, and a Danish section starting from the German border and ending at the Endrup substation near Esbjerg in Denmark.

The project is currently in progress and due for completion 2023.

Project Details

A summary of the project technical details is provided in Table 6.

Table 6. Project details—West Coast 400kV AC Interconnector, Idolum to German Border, Denmark

Project owner:	Energinet
Overhead Lines:	
Voltage	400kV AC
Circuit configuration	Double circuit
Construction type	The towers for the overhead line are in a new design called Thor-gi. It is a lattice tower with galvanised steel tubes. Because of the tubes instead of angle bars, the tower is more open with larger distance between the members. All phase conductors are placed in one level and there is only one crossarm. This means a relatively low tower. The phase conductors are 945 mm^2 AAAC in a triple configuration.
Transfer capacity	2771 MVA (4000A) maximum 2494 MVA (3600A) normal operating
Underground Cable:	
Voltage	400kV AC
Circuit configuration	Double circuit - 400-kV XLPE cable system consisting of two circuits each with two cables per phase of 2500mm^2 aluminium conductor. Cross bonded system.
Construction type	Cable installation method—direct buried into the soil. Backfill is sand with max thermal resistivity 0.8 Km/W. Under roads, streams etc. - horizontal directional drilling with one tube for each single phase cable.
Route length - underground	Total of 9 sections = 26 km
Transfer Capacity	1663 MVA (2400A) continuous 2494 MVA (3600A) 40-hour short term rating
Cable manufacturer	LS Cable (Korea) and Taihan Electric Wires (Korea)
Project Costs:	
Total Cost—Lines and substations	Endrup-Idomlund: €294M EUR (2023) Endrup-German border: €218M EUR (2023)
Estimated cost - Underground	€147M EUR (2023)
Project Construction Duration:	2022 to 2023
Project status:	In progress, expected commissioning in 2024

Undergrounding Investigation

An investigation and report on undergrounding options for the project was undertaken [12].

In December 2015, Energinet sought the permission of the Minister of Energy, Utilities and Climate to establish 400kV overhead lines between Endrup and Idomlund, and between Endrup and the Danish–German border.

In October 2017, the Minister approved the two projects, and Energinet notified the Danish Environmental Protection Agency of the projects in March 2018. The first public hearing phase of the EIA process ran from 9 April to 9 May 2018, and a series of public meetings were held at which the projects were presented as was the political agreement from November 2016 which states that, in general, 400kV transmission lines are to be established as overhead lines.

Based on feedback from local residents in the affected areas along the route of the proposed transmission line, the Minister requested Energinet in June 2018, to prepare a technical report detailing, for example the share of underground cabling that can be utilised for the new transmission line. The aim is to find a solution that limits the environmental impact and alleviate any public concerns as much as possible. The Minister requested that Energinet discuss various undergrounding options.

Figure 11. Overview Map of West Coast 400kV AC Interconnector Idomlund Denmark to Germany (Energinet)

Figure 12. Existing 150kV OHTL (left) and Proposed 400kv Structures (right) (Energinet)

HVAC and HVDC options were investigated.

The report concluded:

> *The possibility of increased 400kV underground cabling has been examined for the defined alternatives A, B, C and D. The conclusion is that it is possible to underground up to 15% of the total distance, corresponding to alternative B. Further underground cabling will result in significant and unacceptable risks to the electricity grid due to system wide amplification of harmonics. Maintaining harmonic distortion within utilized planning levels is extremely important for asset lifetime and a compatible operation. Deviation from planning levels will eventually cause miss-operation to a level that may possibly compromise the security of supply.*

Construction Aspects

A map showing the overall scope of the Transmission Project on the Denmark side is provided in Figure 11. The line is currently designed to have 9 sections of underground cable totalling 26km in route length.

The towers for the overhead line are in a new design called Thor-gi. It is a lattice tower with galvanised steel tubes. Because of the use of tubes instead of angle bars, the tower is more open with larger distance between the members. All phase conductors are placed in one level and there is only one crossarm. This results in a relatively low tower. There is one 400kV circuit on each side. Illustrations are provided in Figure 12, Figure 13 and Figure 14.

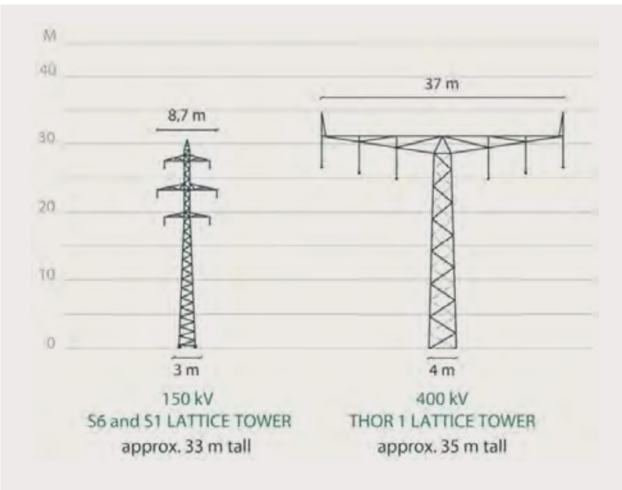

Figure 13. Dimensional Comparison of 150kV and 400kV Structures (Energinet)

Figure 14. 400kV Double Circuit Thor-gi Tubular Steel Structures (Energinet)

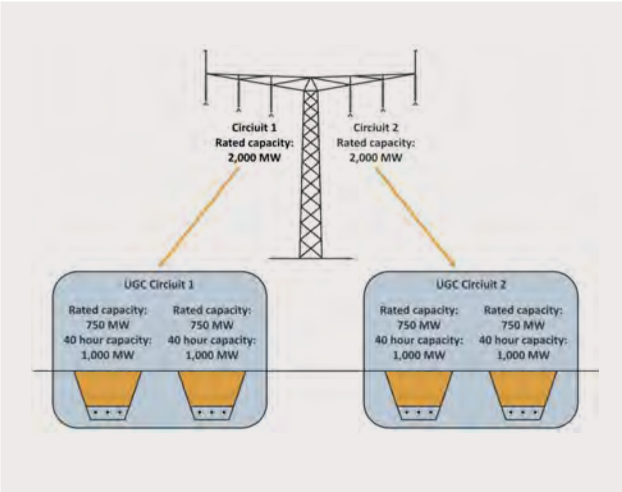

Figure 15. Comparison between Capacity of OHTL and UGTL (Energinet)

To match the rated capacity of a 400kV double circuit OHTL, 12 separate single- core cables in four separate trenches are needed as depicted in Figure 15. This results in a work zone of up to 36 metres wide as indicated in Figure 16. UGTLs with a capacity requirement comparable to OHTLs will have significant environmental impacts and restrictions along the route. In this declaration area, the construction of buildings or roads or terrain changes is only permissible in exceptional circumstances. Compared to OHTLs, cables allow for minor adjustments of the right of way for mitigating local land problems.

The inclusion of underground cable sections in the transmission line requires reactive power compensation plant. For this project this will be achieved with variable reactors on the line—partly directly connected to the line in the substations and partly switchable in the substations.

Environmental Aspects

Energinet obtained overall permission from the Climate and Energy Ministry in October 2017 and started the Environmental Impact Assessment process in spring 2018. The first public hearing in April–May 2018 triggered much community concern. There was initially political support to expand the 400kV grid with overhead lines however Politicians became involved with the community concerns about overhead lines. This resulted in undergrounding investigation referred to above. The conclusion was that Energinet could underground up to 26km (route length) of the lines without causing unacceptable risk with respect to quality, reliability, and security of supply.

Environmental Assessments are published on Danish Environmental Protection Agency's website [13]

The main factors influencing the decision to underground some sections of the line were:

- Short distance to towns or villages—visual impact, proximity to residential properties
- Protected nature and restricted areas because of birds
- Public access to beauty landscape and nature

Following negotiations between Energinet and the Environmental Protection Agency final approvals for the project were obtained in 2023.

Community and Stakeholder Engagement

Energinet commenced negotiations with the landowners and neighbouring property owners. In Denmark Energinet has reached an agreement with the farmers' organisation on how to compensate farmers and landowners. When overhead lines or underground cables are on their property there are payments between 7700 and 11600 Euros for each

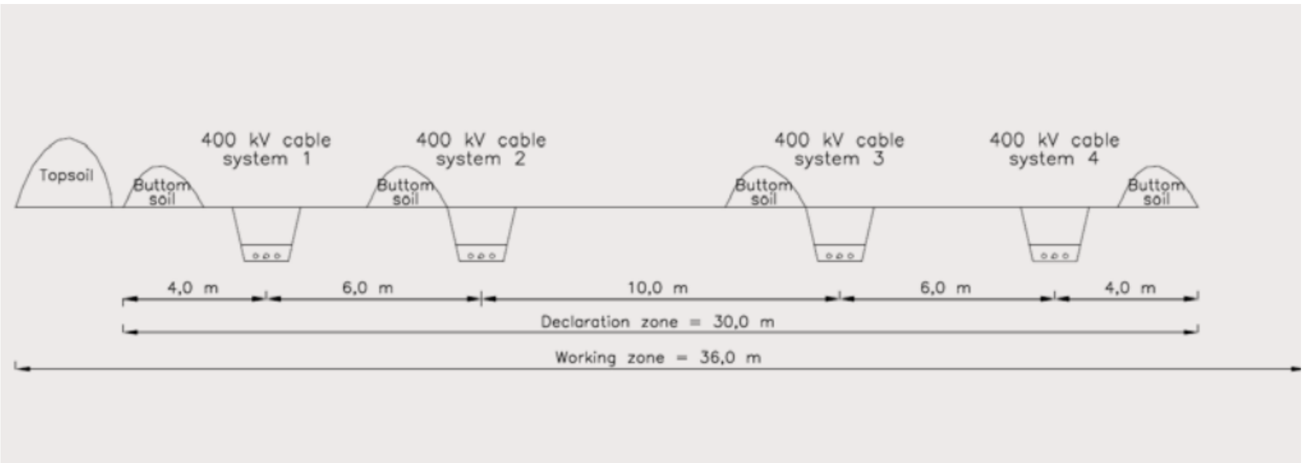

Figure 16. Typical Construction and Declaration Area with Two Cable Systems per OHTL System (Energinet)

400 kV tower and about 0.5 Euros/m2 for the area subject to easement. If the overhead line is placed near a residence (living-house), the compensation is a percentage of the market value for the house. The percentage depends on the distance between the house and the overhead line. The graph below shows how this is calculated (Figure 17).

For example, at 80m from the line, the compensation will be 50% of the market value of the house. At 280 m or more there will be no compensation. If there is less than 80m between the overhead line (nearest part) and house (nearest part), Energinet may offer to buy the whole property. If the owner doesn't want to sell (and there is enough space for it), they can be compensated with 50% or more of the market value.

Energinet does not provide any form of community benefit funding for the project. The only compensation is as described above i.e., to the directly impacted landowners and to neighbouring property owners close to the overhead line.

Outside of the formal processes for community consultation and impact assessments cited in the report, the online research has found very little protests or concerns raised or reported on the Endrup - Idomlund Line. It is possible that as concerns about overhead transmission lines near towns and sensitive environmental areas during public consultation were addressed with the underground installations, that the public were satisfied with the process.

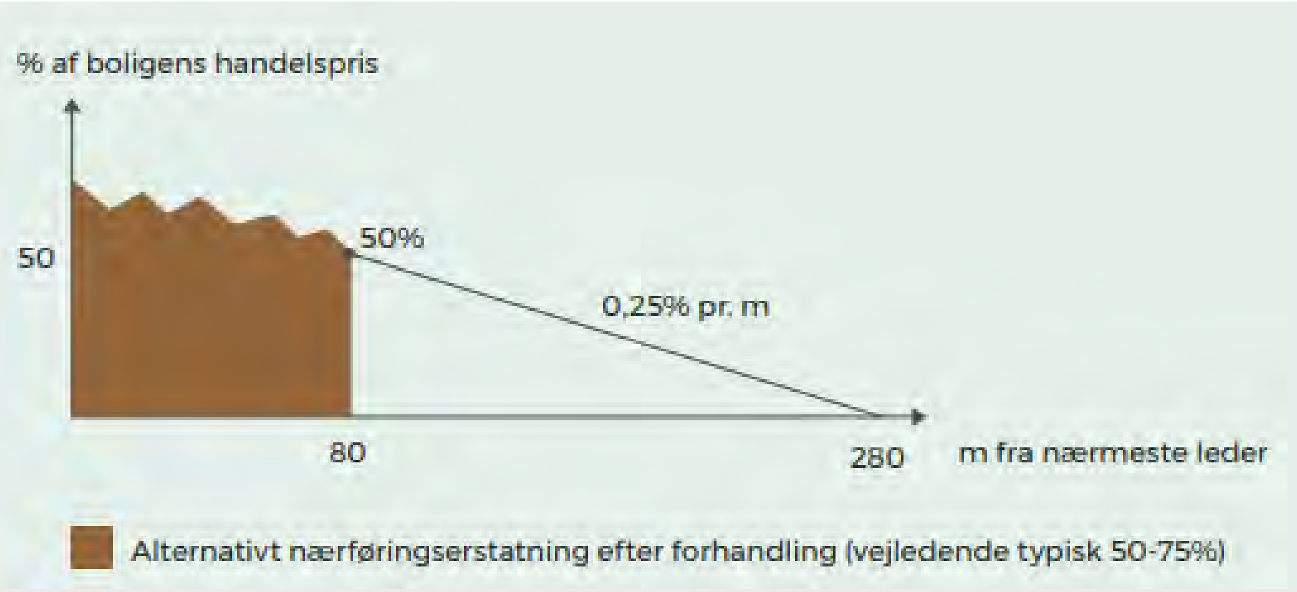

Figure 17. Compensation Values for Neighbouring Properties near Transmission Lines (Energinet)

Translations:

% af boligens handelspris = % of market price for the residence

m fra nærmeste leder = m from nearest conductor

Alternativt nærføringserstatning efter forhandling (vejledende typisk 50-75%) = Alternative compensation after negotiation (consultative typically 50–75%)

3.4 Case Study 3—Baleh–Mapai 500kV Transmission Line, Sarawak

Overview

Sarawak Energy Berhad (SEB) is establishing a 500kV overhead transmission line between 1285MW Baleh hydroelectric project (HEP) and Mapai substation in Sarawak [14].

The primary objective of the project is to contribute to the State of Sarawak's agenda of sustainable development. The State aims to eliminate the use of diesel-powered electricity supply and allow the affected areas of the proposed project to benefit from hydropower development in Sarawak. The electricity evacuation is aligned with the State and Malaysian Government's fuel diversification policy, which promotes greater use of renewable energy for power generation.

The main component of the project is a 177km, 2 x Quad conductor Drake 500kV transmission line. The line involves the construction of 413 towers in total—35 are angle towers and 378 are intermediate transmission towers.

The project is currently in progress and due for completion 2024.

Project Details

A summary of the project technical details is provided in Table 7.

Table 7. Project Details—Baleh–Mapai 500kV Overhead Transmission Line

Project owner:	Sarawak Energy
Overhead Lines:	
Voltage	500kV AC
Circuit configuration	Double circuit—2 x Quad conductor Drake 500 kV transmission line
Construction type	There are five types of lattice tower to be installed for this Project: 1. Heavy Suspension Towers (5HS) 2. Dead End-Tension Tower (5DE) / 5RA (Right Angle) 3. Light Angle-Tension Tower (5LA) 4. Medium Angle-Tension Tower (5MA) 5. 5T (Transposition Tower) Towers will be between 62 to 70 m high, depending on terrain and location. The tower platform footprint is approximated at 40m × 40m. 413 towers in total (35 AT and 378 intermediate)
Route length - overhead	177km
Transfer capacity	2200 MVA
Project Costs:	
Total Cost—Overhead Lines and substations	Not available
Estimated cost—Overhead line	Not available
Project Construction Duration:	2021 to 2025
Project status:	In progress, expected commissioning in 2025

Packages	Line Length	Commencement Date	Completion Date	Contract Duration
A	81 km	1 Nov 2021	30 Sept 2024	35 months
B	96 km	1 Nov 2021	30 Sept 2024	34 months

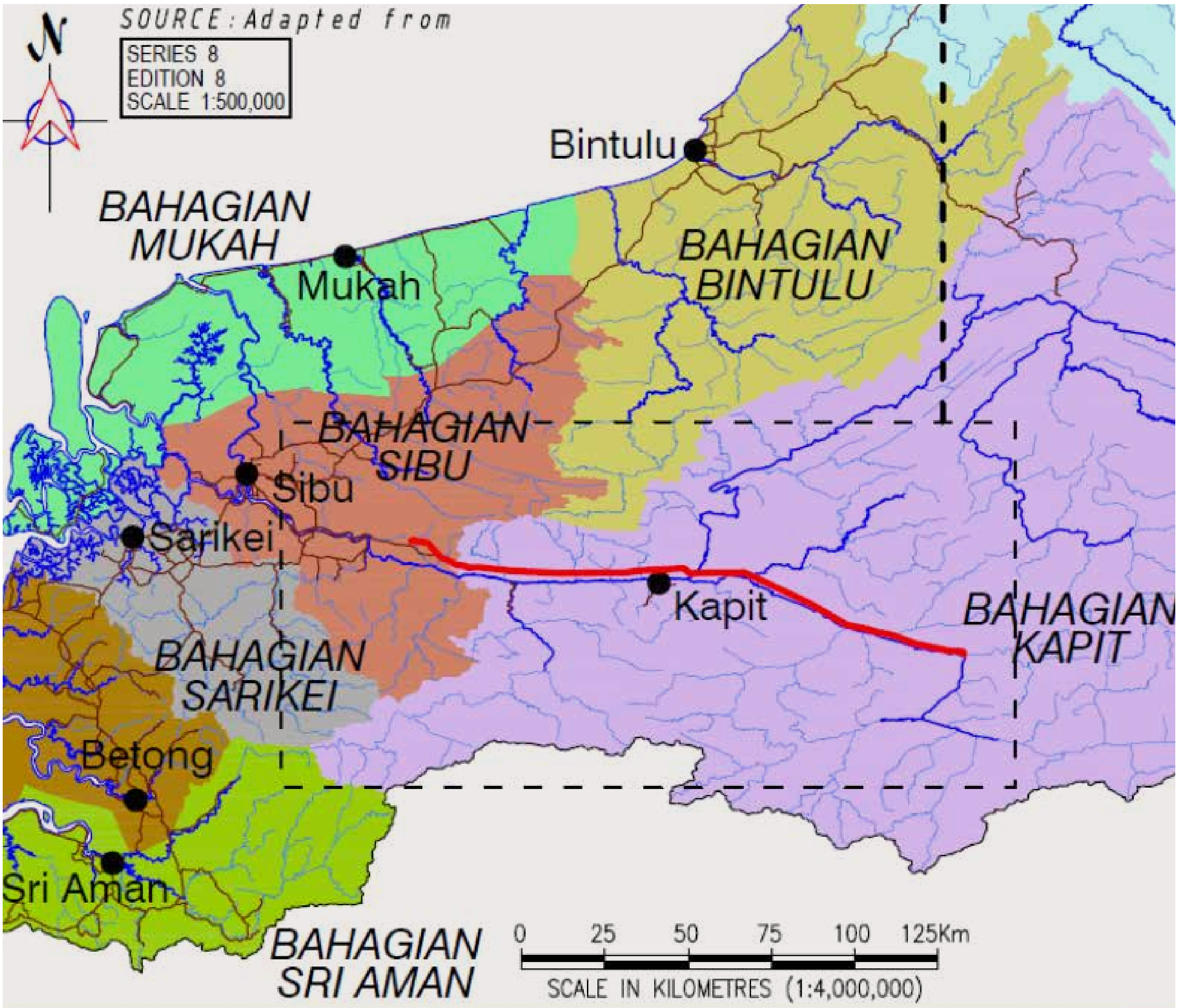

Figure 18. Baleh–Mapai 500KV Transmission Line Overview Map (Sarawak Energy)

Typical overhead line structures for the project are shown in Figure 19. The steel lattice towers shown are 70m and 93m high respectively.

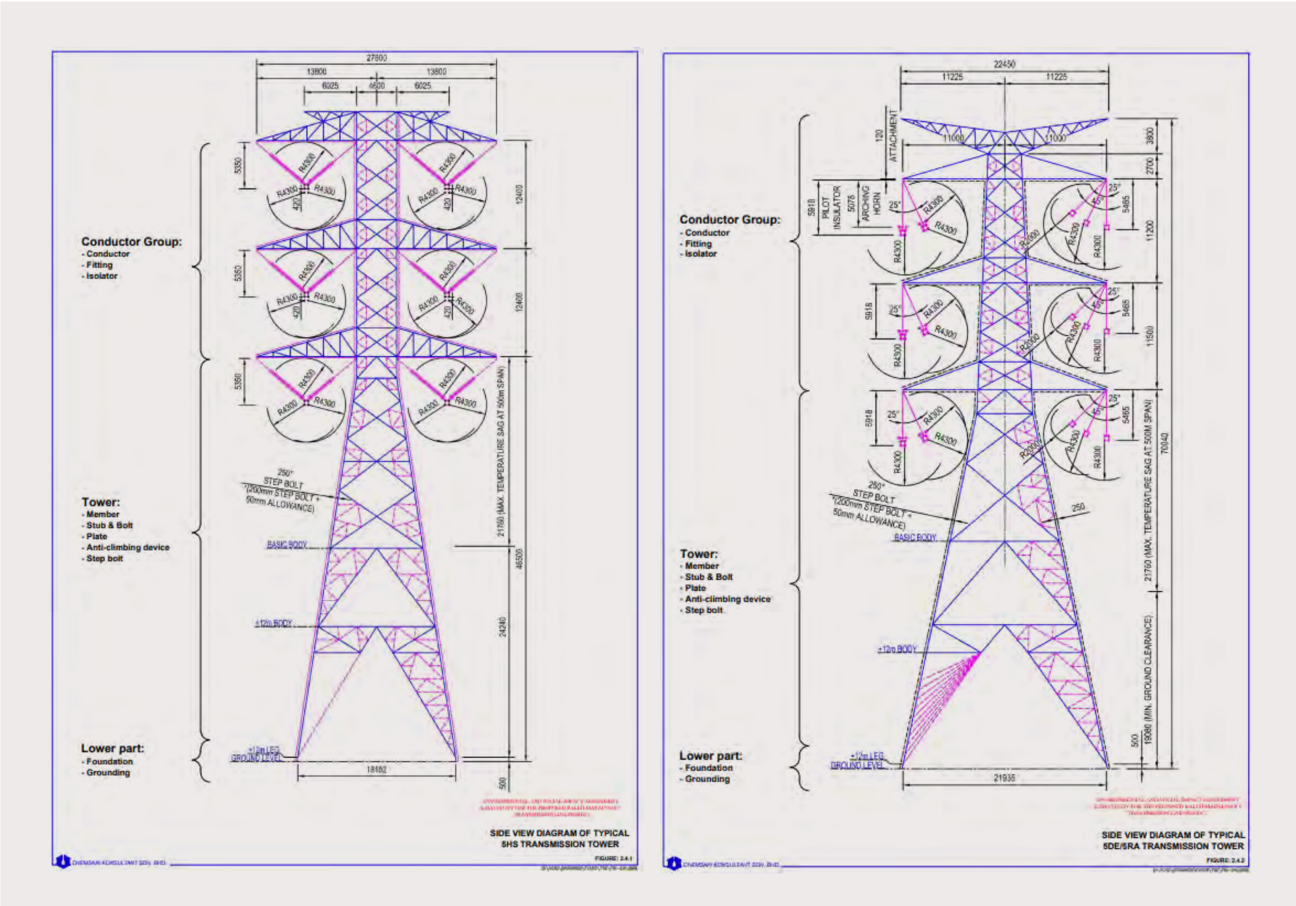

Figure 19. OHTL Structure for Baleh-Mapai 500kv Project (Sarawak Energy)

Table 8. Baleh-Mapai 500kV OHTL Project–Design Clearances (Sarawak Energy)

Table 2.4.4: Electrical Clearance for Lattice Tower 500 kV Transmission Line

Minimum Vertical Clearance to be Ensured from the Line Conductors at Maximum Sag to Ground or by Various Crossings	
To ground	12.0 m
To main road crossing (highway)	18.0 m
To roads, streets, alleys, parking lots, non-residential driveways and other areas subject to truck traffic, tracks and railroads	15.0 m
To water at maximum flood level except navigable rivers, to buildings or structure upon which people may regularly stand	12.0 m
Over major navigable river crossing to water at maximum high-water level including 5 m electrical clearance	50.0 m
Over non-navigable river crossing to water at maximum high-water level	29.0 m
To metal clad or roofed buildings or other structures upon which people may occasionally stand.	6.0 m
To overhead power or telecommunication lines (to cradle)	5.0 – 8.0 m
Minimum Horizontal Clearance to be Ensured between the Line Conductors at Maximum Sag and 45 degrees Swing Angle and Object Near to the Line	
Buildings	6.0 m
Danger trees zone	4.3 m
Minimum Clearance to be Ensured between the Line Conductors at Maximum Sag and 45 degrees Swing Angle and Object Near to the Line	
Side ground clearance	12.0 m

Source: Sarawak Energy Berhad, 2020

A right of way (ROW) with a width of 50m will be established for the Project. The design vertical and horizontal clearances to structures are documented in the ESIA study in Table 8.

Environmental and Social Aspects

The Environmental and Social Impact Analysis (ESIA) Study for the project is found on Sarawak Energy's website [14]. The report considered impacts on several aspects:

- Land use
- Soil erosion
- Water quality
- Air quality
- Noise
- Wastes
- Greenhouse gases
- Traffic and transportation
- Biological resources
- Social resources
- Cultural Heritage
- Public health and Safety,
- Occupational health and safety

Major and moderate impacts identified in Construction Operation and Maintenance were:

- Loss of customary land, crops and livelihood
- Communicable disease (Covid 19)
- Influx and interaction with construction workforce (non local)
- Occupational safety and health

Employment opportunities and capacity building was identified as a positive impact.

Community and Stakeholder Engagement

Engagement and consultations on environmental issues with community members, institutional stakeholders, and potentially affected communities in the form of stakeholder meetings, focus group discussions, social and health surveys, public display of the Environmental and Social Impact Assessment terms of reference (online and physical), etc. were carried out since October 2020. The engagements process involved both formal and informal discussions. The feedback generated through these meetings has been incorporated as much as possible into the design of the project.

The government is compensating landowners impacted by this project and other nearby related projects [15] [16].

3.5 Case Study 4—Powering Sydney's Future—A 330kV Underground Transmission Line

Overview

TransGrid's Powering Sydney's Future project delivered a new 330kV AC underground electricity cable between Potts Hill and Alexandria, along with upgrades to three substations, to help meet the city's future energy needs. [17] The cable route length is approximately 20km. The 330kV cable also replaced 50-year-old cables, which were reaching the end of their serviceable life.

The cable was installed mostly along roads, with some work in parks. Construction involved cable bridges and under-bores (underground crossings) to cross rail corridors, rivers, main roads and underground services.

The project was completed in 2023.

Project Details

A summary of the project technical details is provided in Table 9.

The project was subject to the Australian Energy Regulators (AER) RIT-T approval. The Project Assessment Conclusions Report [19] submitted in November 2017.

Construction Aspects

A map showing the route of the underground cable transmission line is provided in Figure 20. The cable route traversed a very densely populated area of Sydney between Potts Hill and Alexandria. The 330kV underground cable has been installed in PVC duct-banks, mostly along roads, with some work in parks.

Cable bridges were constructed in places and horizontal direction drilling under the ground at some locations to cross rail corridors, rivers, main roads and major underground utility services.

The typical trench dimensions were 2m to 3m wide and 1.2m to 2m deep.

There are a total of 16 cable joint bays (see Figure 21) along the route. The joint bays are formed using pre-fabricated concrete sections with completed dimensions approximately 10m long, 3m wide and 2m deep.

Cable sections up to around 900m in length were installed between joint bays (see Figure 22 and Figure 23).

Table 9. Project Details—Powering Sydney's Future 330kV Underground Transmission Line

Project owner:	**Transgrid**
Underground Cable:	
Voltage	330kV AC
Circuit configuration	330kV XLPE cable system consisting of one cable per phase of 2500mm^2 copper conductor, smooth aluminium sheath.
Construction type	Standard configuration is trefoil, in a duct bank. Ducts were laid for two circuits but only circuit installed initially. The other set is for future use. One of the sets of trefoils is inverted. There are some locations such as bridges with flat formation, and some HDD locations both in flat and trefoil formation.
Route length - underground	20km
Transfer capacity	750MVA (1312A)
Cable manufacturer	Taihan Electric Wires (South Korea)
Project Costs:	
Total Cost	$235M AUD (2017) [18] i.e. $11.75M per km
Estimated cost—Overhead line	Not available
Project Construction Duration:	2021 to 2025
	Dec 2019 Contract award Jan 2020 Start of detailed design Feb 2020 Published EIS Submissions Reports May 2020 Project determination Jul 2020 Completion of detailed design Nov 2021 Main construction Mid 2023 Permanent Road restoration
Project status:	Completed 2023

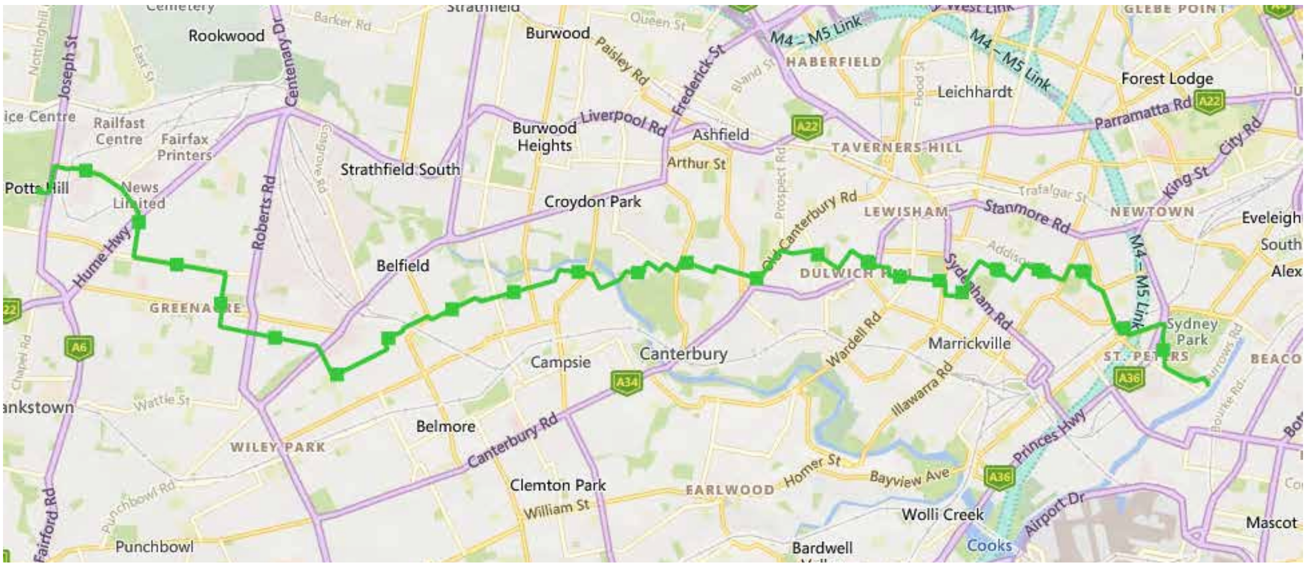

Figure 20 Powering Sydney Future 330kV Cable Route Showing Joint Locations (Transgrid)

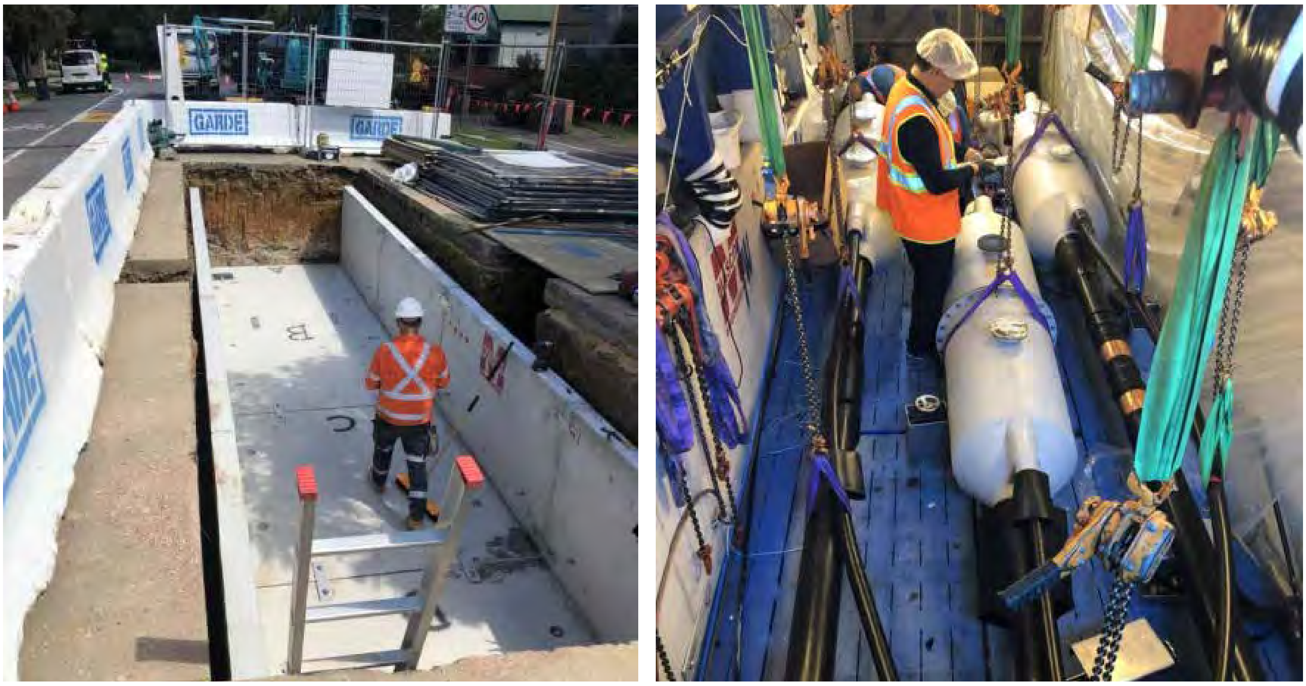

Figure 21. Powering Sydney's Future—330kV Cable Joint Bay (Transgrid)

Figure 22. Powering Sydney's Future 330kV Cable Trench and Conduit Installation (Transgrid)

Figure 23. Powering Sydney's Future—330kV Cable Drum (Transgrid)

No new reactive compensation plant was required for the project. Existing plant at substations was considered adequate.

The project construction occurred over a period of approximately 18 months.

Environmental and Social Aspects

The Environmental Impact Statement [20] identified the key impacts as:

- traffic and transport;
- noise and vibration;
- air quality;
- electric and magnetic fields;
- landscape character and visual amenity;
- soils and contamination.

There were other relevant environmental aspects considered for the project including:

- surface water and flooding;
- groundwater;
- biodiversity;
- land use and property;
- Aboriginal heritage;
- non-Aboriginal heritage;
- social and economic;
- hazards and risks;
- waste management;
- cumulative impacts

Regulatory approvals following the EIS were completed in February 2020.

Community and Stakeholder Engagement

The following community and stakeholder groups were consulted during the planning and approval phases of the project.

- impacted stakeholders including schools, childcare centres, businesses, property/landowners, residents, healthcare providers, consumer groups, emergency services and religious institutions;
- Aboriginal stakeholders, including Local Aboriginal Land Councils;
- elected government officials and local government, including councils in the local government areas of Sydney, Canterbury-Bankstown, Inner West, and Strathfield;
- government authorities including Roads and Maritime Services, NSW Environment Protection Authority, NSW Office of Environment and Heritage, Department of Industry—Water, Water NSW, Transport for NSW, Greater Sydney Commission, NSW CBD Coordination Office, Department of Education NSW;
- major development proponents/transport operators including Sydney Motorway Corporation, Sydney Metro, Sydney Light Rail, Sydney Trains, Australian Rail Track Corporation;
- utility providers including Ausgrid, Sydney Water, Telstra, Optus, Jemena, Viva Energy, Sydney Metropolitan Pipeline;
- special interest groups, including community, environmental, pedestrian and bicycle user groups;
- directly impacted communities (within 100 metres of the project area); and the broader community.

During the construction phase special consideration was made in relation to the engagement and communication with the culturally diverse communities along the route. Tailored communications to suit the specific needs of such multi-cultural groups were employed.

An overview of the community and stakeholder engagement is provided in Figure 24.

Transgrid also worked to provide meaningful support to local businesses directly impacted by construction on PSF by engaging Realise Business to implement a strategy to help businesses ride out building work with minimal disruption. During construction Transgrid also provided $190,000 in community grants to support the work of local not-for-profit groups along the project route. The project is due for completion in mid-2023 with final road restoration works being the last activity.

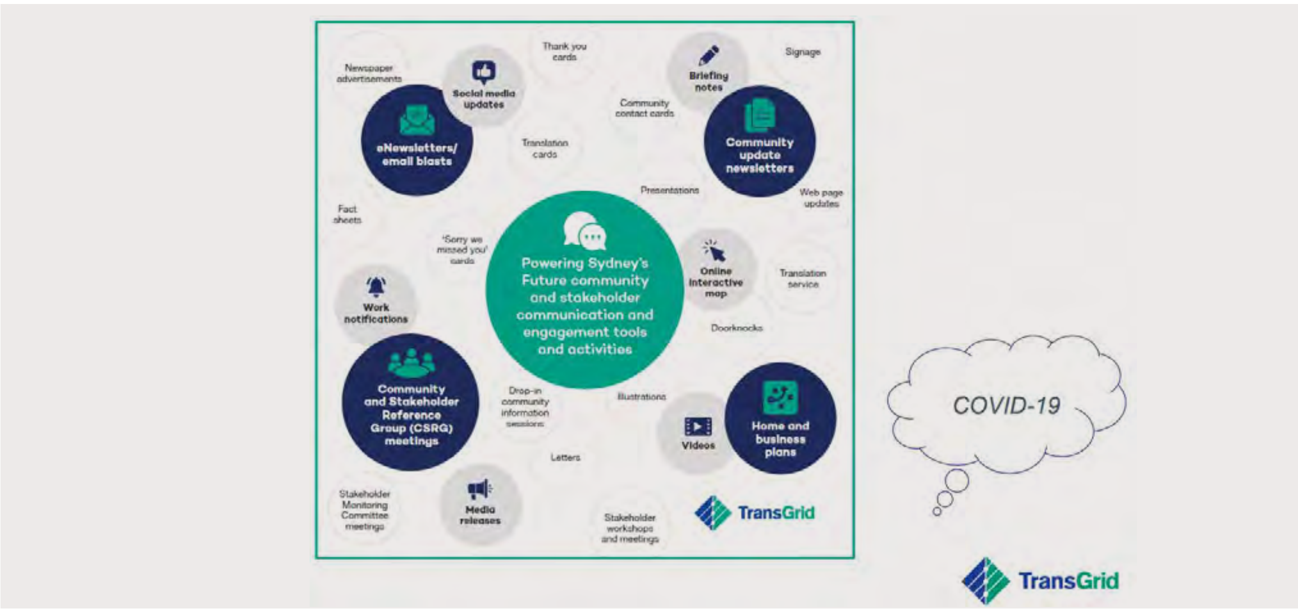

Figure 24. Powering Sydney's Future—Community and Stakeholder Engagement Strategy (Transgrid)

3.6 Case Study 5—Hinkley Point C Connection Project 400kV Transmission Line, UK

Overview

The Hinkley Connection Project [21] is a new high-voltage electricity connection between Bridgwater and Seabank near Avonmouth. It is a significant investment in the region's electricity network and will enable us to connect new sources of low-carbon energy to homes and businesses, including Hinkley Point C, EDF Energy's new power station in Somerset.

The new connection will be 57km long, consisting of 48.5 km of overhead line and 8.5km of underground cable through the Mendip Hills Area of Outstanding Natural Beauty (AONB).

National Grid (UK) constructing what will be the world's first operational T-pylons, and is also exploring different, more sustainable approaches to construction that potentially reduce traffic and impact on the environment.

The project is currently in progress a series of work packages involving different sections of the route. Overall completion is expected in 2026.

Project Details

A summary of the project technical details is provided in Table 10.

Construction Aspects

A map showing the overall scope of the Transmission Project is provided in Figure 25. The 400kV line comprises 48.5km of overhead line and 8.5km of underground cable. There also associated 132kV transmission line works involving some underground sections.

Table 10. Project details—Hinkley Point C Connection Project, 400kV AC

Project owner:	National Grid (UK)
Overhead Lines:	
Voltage	400kV AC
Circuit configuration	Double circuit
Construction type	Lattice tower and T-Pylon (2x850mm^2)
Route length - overhead	48.5km
Transfer capacity	2820 MVA post fault rating at 900
Underground Cable:	
Voltage	400kV AC
Circuit configuration	Double circuit
Construction type	2 x 2500mm^2 XLPE cables per circuit
Route length - underground	8.5km
Transfer Capacity	2404 MVA continuous rating per circuit
Cable manufacturer	
Project Costs:	
Total Cost—Lines and substations	£655.7M UK (2020) [22]
Estimated cost - overhead	Not available
Estimated cost - Underground	Not available
Project Construction Duration:	2022 to 2026
Project status:	In progress, expected commissioning in 2025

Figure 25. Overview Map—400kV AC Hinkley Point C Connection Project (National Grid)

Figure 26. Hinkley Point C Project - 400kV T-Pylon structures (National Grid)

Figure 27. Hinkley Point C Connection Project--400kV Underground Cable Works (National Grid)

The project involves the world's first T-Pylons installed in between Bridgewater and Loxton I Somerset, completed in early 2023 [23]. The T-Pylons at 35m high and are around one third shorter than traditional steel lattice towers, but considerably wider and affects land use more.

The T-pylon design, the first major UK redesign since 1927, has a single pole and cross shaped arms, and is around one third shorter than traditional high-voltage pylon design with a smaller ground footprint. The new design was selected from over 250 designs entered into an international competition run in 2011, organised by the Royal Institute of British Architects and government (the then Department of Energy and Climate Change). With a need for new energy infrastructure to enable progress towards net zero, the competition sought a new design to reduce impact on the local environment and surroundings. A photograph of the structures is provided in Figure 26.

Along with offshore routes, underground cabling and continued use of traditional lattice pylons, the new T-pylon design is a potential technology choice for future projects. Each new transmission network project is assessed on a case-by-case basis, with the technology used by National Grid based on planning policy and regulations set by Ofgem as well as engineering, environmental and cost considerations.

400kV Underground cable installation works have commenced with a section at Mendip Hill completed. Photographs of the works in progress is shown in Figure 27.

Environmental, Community and Stakeholder Engagement

National Grid commenced planning on the Hinkley Connection Project in 2009. After detailed analysis, it was concluded that a new connection between Bridgwater and Seabank substations would be the most appropriate and cost-effective solution. Once connection points were identified, an independent environmental review of the area, otherwise known as the Hinkley Point C Connection Project Route Corridor Study (RCS) was undertaken—attending to consideration of corridor selection and land access.

Over the next five years (2009-2014), several stages of pre-application consultation occurred and in total received more than 11,000 pieces of feedback, which helped shape plans. Planning included attention to biodiversity, rights of way, waste management, construction traffic, and noise and vibration and therefore attended to issues regarding community consultation, social licence, and minimal environmental impact. Key issues were visual impact, ecology and perceived socio-economic effects on tourism.

Changes to the original design occurred because of pre-application public consultation including:

- choosing the route of an existing overhead line owned by Western Power Distribution (WPD) to *minimise the impact on the local landscape*.
- removing more than 67km of existing overhead line to make way for the new connection
- putting 9km of WPD's network underground between Nailsea and Portishead
- putting 8.5km of the new connection underground through the Mendips Hills Area of Outstanding Natural Beauty (AONB)
- using T-pylons for 81% of the overhead connection.

Many of these changes are related to minimising the impact on the local landscape.

The National Grid was required under the Planning Act 2008 to submit a Development Consent Order for nationally significant infrastructure projects, which includes overhead power lines 132,000 volts and above. Applications to the Planning Inspectorate had to accord with National Policy Statements (NPSs), issued by the Government. Six NPSs have been produced for the energy sector, including for electricity networks and nuclear power.

In May 2014 a Development Consent Order application was submitted to the Planning Inspectorate. On 19 October 2015, the planning inspectors made a recommendation to the Secretary of State. Permission was granted on 19 January 2016.

From a regulatory perspective National Grid have consulted on the Preliminary Environmental Impact Assessment (PEIR). This document sets outs National Grid's preferred route and explains their methodology and identifies the likely impact on the proposals on the environment.

National Grid has developed practices around Visual Impact including undergrounding for new transmission line connections and undergrounding of existing overhead lines, as described in their presentation "National Grid Electricity Transmission Environment consultation July-August 2018 [21]. In this presentation they state that their approach to planning transmission line is:

"In principle…

- *The Government does not believe that development of overhead lines is generally incompatible with our statutory duty*

In practice…

- *New above ground electricity lines can create adverse landscape and/or visual impacts*
- *This is dependent upon their scale, location, degree of screening and the nature of the landscape and local environment*
- *These impacts can often, but not always, be mitigated"*

Further information on National's Grid approach is outlined in their public document "National Grid Our Approach to Consenting (April 2022)" (https://www.nationalgrid.com/electricity-transmission/document/142336/download).)

Considerable *engagement with the community* was undertaken which included initiatives such as

a) Working with schools through
    a. Investing £250,000 UK into STEM in local schools- helping schools across the Hinkley Connection Project deliver an improved education experience through its Education Fund by providing activities and equipment that teachers would otherwise not be able to afford. In 2022/2023 this constituted supporting 103,950 children from 382 local schools, including 22,375 children from disadvantaged backgrounds. Since the start of construction in 2018, the NG supported 425,040 children, including 87,182 children from disadvantaged backgrounds. NG have made 1,240 grants with £1.1m used for Science, Technology, Engineering and Maths (STEM) activities and equipment. https://www.nationalgrid.com/electricity-transmission/hinkley-connection-project-helps-

over-400000). In addition, archaeologists working on the Hinkley Connection Project ran an educational session and assembly for primary school students in Winscombe, North Somerset, helping to inspire the next generation of historians.

b) *Working with communities* such as Somerset Councils, the Mendip Hills AONB (area of outstanding natural beauty) and other Statutory Consultees.
   a. Attending to concerns regarding the *visual impact* of the Sealing End Compound, particularly the impact it will have on the view from Crook Peak out over the Somerset levels towards Brent Knoll. The removal of the existing 132KV power lines through the Lox Yeo valley was welcomed by the community.
   b. Attending to details that need to be explained, for example, the locations of monitoring kiosks and details that show how the underground cables will negotiate the river crossings. This *helped ensure social license*
   c. Protecting wintering birds and other wildlife, by scheduling construction activities within Portbury Wharf Nature Reserve to take place between March and September. Portbury Wharf Nature Reserve (https://www.nationalgrid.com/electricity-transmission/portbury-wharf-nature-reserve-upcoming-works) *reducing environmental impact.*

The National Grid worked with Copper, a communications agency, to help with *effective stakeholder engagement*. The collaboration commenced in 2009 and is currently ongoing allowing for engagement through the project from planning through to construction. The collaboration was stimulated by significant local opposition to the proposals throughout the planning and development stages which posed a risk to the project if the opposition was to continue into the construction stage. The National Grid needed to switch the communications approach from 'reactive' to 'proactive' and reposition the narrative to concentrate on the project's benefits. To minimise the risks of project delays, opposition and criticism National Grid with Copper aimed to:

1. Provide clear and timely information to stakeholders about the work in their area too, and quickly respond to any concerns. This was achieved through activities such as maintaining and regularly updating a project website, making it the 'go to' place for stakeholders to learn the latest information. In addition, should there be any concerns amongst the public, a responsive 24-hour contact centre service enables the local community to get a swift response.
2. Devise procedures to inform and update local communities and other stakeholders about construction work and the steps National Grid and its contractors take to reduce local impact. This has established positive relationships with local community groups and parish councils and use these links to help spread information as widely as possible assisting with the gaining of social license. Copper has communication with more than 10,000 householders.
3. Put processes in place to monitor the mood of local communities, to identify and respond rapidly to any emerging issues."

The outcome from this is that[3] *"despite the highly disruptive nature of the work, there is widespread public acceptance of the project." To date, "a minimal number of complaints have been received and no issues have been escalated by local residents or community stakeholders to the media or their elected members. These successes have given National Grid the confidence to reposition the project narrative going forward. In the future, communications and engagement will place an even greater emphasis on the positive impact and benefits National Grid will bring to the area over the next five years and beyond."*

In summary, the planning and consultation, the outcomes for this project were:

1. An overhead route of approximately 48.5km in which a the new 400kV line replaced existing 132kV lattice tower structures with mainly new aesthetic 400kV T-Pylon structures.
2. An 8km underground section was built through the Mendip Hills, which is described as an "Area of Natural Beauty" (AONB).

3.7 Case Study 6—Suedlink DC3 and DC4 HVDC Transmission Link Germany

Overview

With a length of around 700 kilometres and a transmission capacity of 4000MW, SuedLink is the largest infrastructure project in Germany's energy transition. In the future, SuedLink will connect hydroelectric power plants in Scandinavia, wind farms in the north and solar parks in southern Germany. The connection makes it possible to flexibly network fluctuating renewable energy sources, thus ensuring a stable and secure power supply.

[3] https://copperconsultancy.com/our-work/hs2-national-grid-hinkley-point-c-connection-project/

The project is currently reported to be the longest underground transmission project in the world. Project cost is currently estimated at €11B EUR. The project has commenced with completion expected in late 2026.

SuedLink consists of two high-voltage direct current transmission links from Wilster and Brunsbüttel in Schleswig-Holstein to Bergrheinfeld/West in Bavaria and Großgartach/Leingarten in Baden-Württemberg. The two connections each have a transmission capacity of 2000MW and are laid as underground cables. The SuedLink output is equivalent to about four nuclear power plants and can supply around ten million households with electricity. Along with the underground cables, commercial fibre optic cables are laid along the entire route. These offer municipalities in rural areas in particular a great opportunity to benefit from high-speed Internet. Both underground cable connections are listed as independent projects referred to as DC3 and DC4 Both lines run side by side over a long stretch, the so-called main stretch.

Suedlink is a joint project involving Transmission system operators TenneT as the owner of the northern section, and TransnetBW as owner of the southern section. In their project information the benefits of HVDC are described as [24]:

- *Lower transmission losses when transporting electricity over long distances.*
- *In contrast to AC cables (AC = "alternating current", i.e. three-phase current), HVDC underground cables can also be used over long distances (several hundred kilometers). With AC cables, the length of the sections is limited by technical and economic parameters.*
- *High transmission capacity Flexibility and system stability of the power grid are increased.*

The German Federal Government has put the policies in place for expanding the grid more quickly and gaining public acceptance for it[4]. Following the agreement within the governing coalition in July 2015, the cabinet gave the go-ahead in October 2015 for an increased use of underground DC cables. On 3 December 2015, the Bundestag adopted the draft legislation, as amended by the coalition party groups, and the bill passed the Bundesrat on 18 December 2015. The new rules entered into force at the turn of the year 2015/2016. The Suedlink project has therefore been progressed as a HVDC underground project.

Even with the adoption of underground transmission for the project, there were many concerns raised by communities, landowners and farmers which are being considered by the project developers TenneT and Transnet BW in the regulatory approval processes. Location of large AC/DC converter stations is one such concern.

Project Details

A summary of the project technical details is provided in Table 11.

A map showing the overall scope of Suedlink HVDC Transmission Project is provided in Figure 28.

[4] https://www.cleanenergywire.org/news/germany-passes-laws-grid-chp-keep-energiewende-going

Table 11. Project details—Suedlink HVDC Transmission Line, Germany

Project owner:	**TenneT and Transnet BW**
Overhead Lines:	
Voltage	-
Circuit configuration	-
Construction type	-
Route length - overhead	-
Underground Cable:	
Voltage	+ 525 kV DC
Circuit configuration	2 x 2000MW HVDC circuits 4 x VSC converter stations, Rigid Bipole system[5] with metallic return cable
Construction type	525kV DC 3000mm^2 copper conductor XLPE cable. Direct buried cables, ducts, HDD and special installations
Route length - underground	700 km
Transfer Capacity	4000 MW
Cable manufacturer	Prysiam
Project Costs:	
Total Cost—Lines and substations	€11B EUR (2022)
Project Construction Duration:	Construction 2021 to 2026
Project status:	Commenced, expected completion 2026

[5] HVDC Light® Reference list (ABB Group)

Figure 28 Project Overview Map—Suedlink HVDC Project (TenneT, TransnetBW [25])

Cable Installation

The two 2000MW underground circuits of SuedLink will comprise XLPE-insulated 525kV cables as shown in Figure 29. The total cable length of the transmission system over a route length of 700km.

The cables will be laid in four parallel trenches with about 10m from each other in the central trunk of the transmission system. The trenches will be excavated up to 2m-deep beneath the ground. An example of the trench profile for one circuit is shown in Figure 30.

Examples of direct buried HVDC cable installation are provided in Figure 31.

Although most of the cable route is proposed to be direct buried cable installation, alternative methods will be required in some sections e.g.:

- Cables installed in buried ducts.
- Direction Drilling sections under waterways and highways.

Figure 29. Suedlink HVDC XLPE Cable (Prysiam Group [26]).

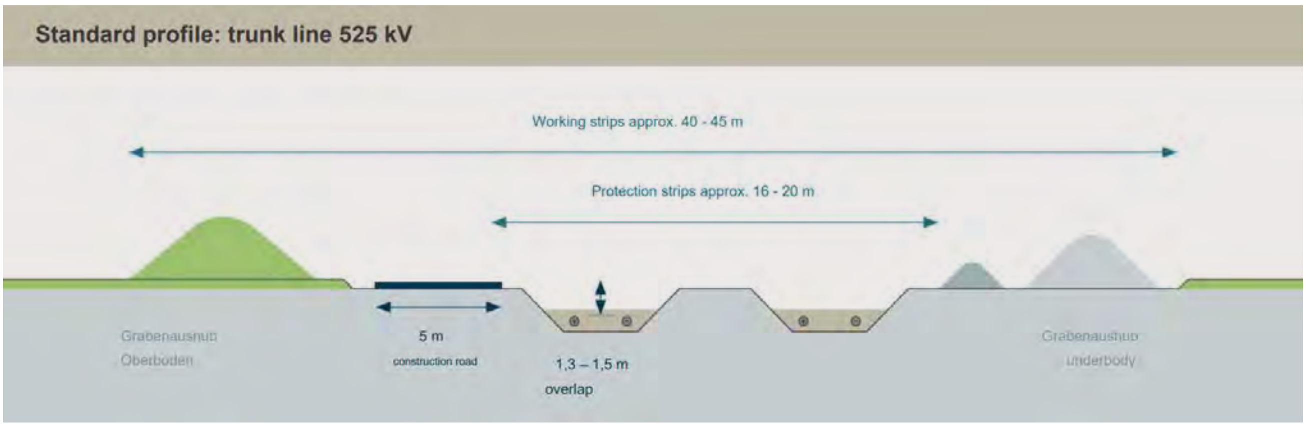

Figure 30. Suedlink—Typical Cable Installation for One HVDC Circuit (Tennet, Transnetbw [24]).

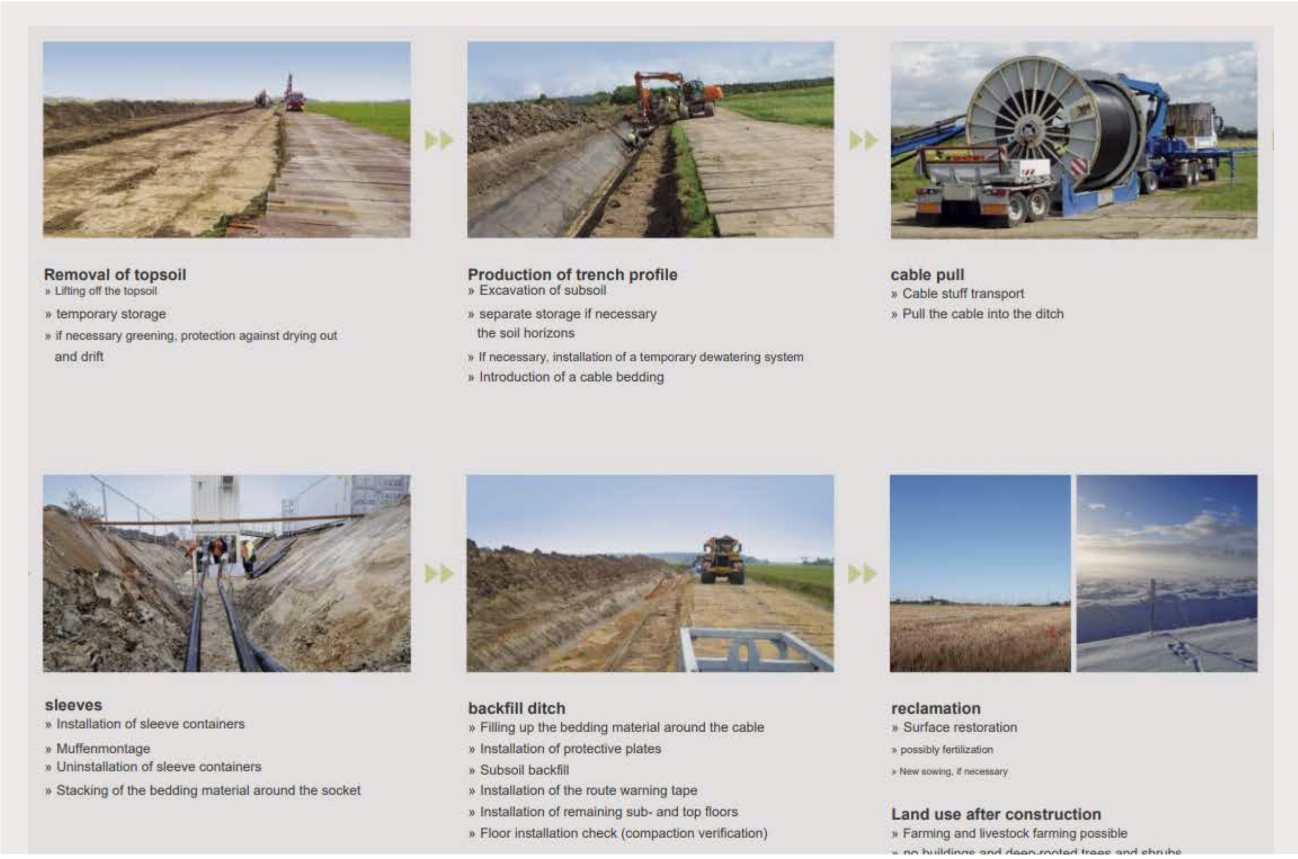

Figure 31. Suedlink—Example of Direct Buried Cable Installation Phases (Tennet, TrasnetBW)

Converter Stations

The converter stations in Schleswig-Holstein, Bavaria, and Baden-Württemberg for the SuedLink transmission system will be designed to operate both as rectifier and inverter depending on the direction of the flow of electricity transmission. Hitachi energy has been awarded a contract for the DC4 project converter stations. An Image of proposed stations is shown in Figure 32.

TenneT is responsible for the operation of the converters in Schleswig-Holstein and Bavaria, while TransnetBW is responsible for the converter in Baden-Württemberg.

Regulatory Approvals

The Federal Government has decided on the need for SuedLink and laid it down in the Federal Requirements Plan Act. . The law also stipulates that direct current connections should primarily be planned as underground cables. SuedLink is identified as projects 3 and 4 in the *Federal Requirements Plan Act*.

SuedLink is approved by the Federal Network Agency (BNetzA) in accordance with the Network Expansion Acceleration Act (NABEG) as part of a public and multi-

Figure 32. HVDC Converter Station (Hitachi Energy [27])

stage process. At the end of this process, a concrete line route is determined. SuedLink is currently in the planning approval process, i.e. in the last stage of the approval process. Individual sections were defined for the planning approval process. A final decision on the route of the cables was made in 2021, with cable production and background infrastructure starting in 2022. Cable laying has commenced as of March 2023.[6]

SuedLink is divided into 15 sections. The manageable size of each section facilitates planning, approval, and later construction. In addition, the “short line” between all stakeholder groups on site enables direct and more personal participation in the project.

Environmental Aspects and Concerns

Key aspects of environmental planning and assessment for the project include [28]:

- Mapping of flora and fauna
- Subsoil investigations
- Archaeological investigations
- Further ground investigations (e.g. explosive ordinance, soil mapping, thermal conductivity measurements)

Preliminary investigations in the approval process included extensive research in order to avoid large spatial obstacles such as settlements, roads. Considerations in corridor selection included:

- Where exactly will the SuedLink cables run?
- Which method and which devices do we use when laying the underground cable?
- How can we best reconcile the needs of people, nature and the environment?

Soil preservation is a particular focus for agricultural impacts. Soil performs numerous services and functions for nature and society. In addition, the soil is the production basis for agriculture and forestry. In addition to other functions, the ground is also a transport medium for power transmission. The common goal of soil protection is therefore the sustainable preservation of soil functions. That is why protecting the soil is also a special concern for us at SuedLink in all project phases.

Communication and engagement

Consultation and engagement on the Suedlink project and proposed corridors commenced around 2014. Many of the original concerns citizens had relating to the

Figure 33. Protestors at a Suedlink rally in central Germany in 2019 (DW [29])

impact of overhead transmission lines were addressed by the 2015 decision of the German Government to place them underground.

Concerns raised by citizens regarding the impacts of underground transmission on the environment have tended to be regarding local issues. At a rally in central Germany in 2019, farmers “suggested the cable would heat and disrupt the soil, making it less fertile for growing crops” [29]. Residents in a village in Northern Bavaria were concerned that the planned substation will soon “encircle them with routes”; and that a popular piece of forest could possibly disappear [30]. Kiel and colleagues [31] noted in interviews with citizens that the “deterioration of the landscape” was an issue of concern. However no specific issues mentioned.

Social Aspects and Concerns

When focusing on social issues surrounding placement of underground transmission lines, it is evident that in areas in Northern Bavaria (Lower Franconia) and nearby parts of Central Germany, the strong local cultural and social identities of these areas have framed their concerns with the Suedlink. Objections have been raised by citizens in these areas to the notion of “outsiders” coming in taking over things in their local area. A particular regional community lower Franconia which was proposed as the site for one of the terminal converter stations, felt that the companies have no interest in the local areas or communities, and that money from the region is being taken out by these entities and nothing reciprocated [32]. A participant in a rally in 2019 commented that they dislike being told what to do by these outsiders [29].

[6] https://www.energyprojectstechnology.com/first-dc-underground-cables-reach-interim-storage-facility/

Economic Aspects and Concerns

Concerns raised by communities also focus on economic issues. Some of these were local relating to the loss of employment and the knock-on effect on the local economy due the fact that local power suppliers (nuclear power plants for example) would be closed down and the energy supplied from elsewhere [32].

Original farmers' concerns about the loss of revenue due to the construction work and ongoing presence of the underground lines on their land [32], have tried to be addressed by the offer and acceptance of compensation by farmer associations across a number of regions in Germany in 2022. [33].

TenneT advises on their website[7] what forms of compensation are available for impacted parties:

- *"For owners: Compensation for the permanent use of the property (protective strips, access routes if necessary) and associated payments*
- *For owners: Compensation for the temporary use of the parcel*
- *For those who cultivate agricultural land: Compensation for growth damage*
- *For those who cultivate agricultural land: Compensation for consequential damage*
- *For those who cultivate agricultural land: Compensation for disadvantages in subsidy programs and bonuses*
- *For those who cultivate agricultural land: flat-rate expenses*
- *For those who cultivate agricultural land: Compensation for economic difficulties"*

There is also a broader economic concern raised by citizens' action groups in recent years about the "multi-billion euro costs of the project" and that "it had not been thought through properly" [29]. They indicated a preference for smaller decentralized power sites using power produced near where it is used and have proposed an alternative plan to divide Germany up into 80 areas which would each produce electricity for the end user" [29] [30]. A protest in 2022 stated "Instead of building a monster line from north to south, Germany should rather focus on decentralized energy supply with photovoltaics, wind energy and hydrogen. In the future, the company will no longer be as dependent on suppliers as it has been in the past. Even the war in Ukraine has not changed the fact that the power line is unnecessary" [34].

In 2023, one media source noted that "activists don't just want to move the route projects to other places, they want to prevent them as a whole. They see the projects as too expensive and unnecessary and that the routes could also transport nuclear power from abroad" and that, "there is no need for dinosaur lines if the energy transition is implemented decentrally and locally", and that they do not trust that the lines will use energy only from renewable sources [30].

Summary

The move by the German Government to make Suedlink an entirely underground project continues to raise environmental objections from areas specifically impacted by the laying of cable or the presence of substations. However, more notable in recent years are the importance of local social issues and economic criticisms raised by citizens groups in the affected areas.

[7] https://www.tennet.eu/de/suedlink-entschaedigung-und-schadensregulierung.

4.

Conclusions

4.1 Current Australian Projects

The related themes necessary for achieving social license and project acceptance uncovered during the systematic literature review were highlighted and reinforced in the current Australian 500kV projects: Humelink (NSW), VNI West (Vic) and Western Renewables Link (Vic). A key finding from all three is the importance of recognising the context, both historical and current, in which the project is occurring. Noting that project proposals and announcements, technology type, levels of communication and engagement, host individual and communities' knowledge and awareness of the technology, will influence the context and how the project is perceived. There were multiple findings from across the three projects. Key findings include:

- The need to have clear justification for route selection, why the decision was made and to provide enough time for community members to understand the implications of the proposal.
- A sentiment by host communities in all three projects was that project coordinators were quite dismissive of the topic of undergrounding, including their sentiment regarding the long-term advantages of underground transmission. Many in host communities argued that the initial cost and time investment of undergrounding would be far outweighed by the significant benefits it offers.
- Community Consultant Groups were established to improve the dialogue between project proponents and local stakeholders.
- A lack of leadership at the local level, in some instances, meant that decisions were delayed and without clear communication, led to misinformation being introduced into the community.
- Indigenous groups raised concerns around construction ground disturbance directly disturbing and destroying archaeological artifacts and structures, along with vegetation clearance removing the protective cover and concealment of archaeological sites that could impede the ability to effectively protect the site during a fire.
- The proponents, sought expressions of interest for cultural heritage surveys which have now been conducted in collaboration with Registered Aboriginal Parties, providing valuable insights for assessing impacts and implementing appropriate mitigation measures.
- Impacts on health and safety included concerns about increased mental health and wellbeing - coupled to this were examples of engagement fatigue where people were being asked to engage in multiple processes, not only for transmission line projects but also renewable energy projects.
- The potential for increased bushfire risks was also raised as both a health and safety and environmental concern, in particular transmission lines hindering effective bushfire responses therefore increasing their risk of exposure in the case of a fire.
- There were significant concerns raised around the impacts on land use and property values including increased traffic on local roads, decreased tourism in some areas, impacts on farming operations and access.
- Alternative transmission technologies such as HVDC or hybrid HVAC and HVDC networks are being promoted by some stakeholder and advocacy organisations
- Following the findings from the NSW Parliamentary Inquiry into the feasibility of undergrounding the transmission infrastructure for renewable energy projects there has been a new Select Committee Inquiry announced that will hand down their findings in March, 2024.

4.2 International Case Studies

The six case studies from Australian and international projects, involve projects which have been completed or are in the design phase and include 400 and 500 kV HVAC overhead and underground, 330kV HVAC underground and one HVDC transmission project.

- Key findings include the importance of extensive community and stakeholder consultation, with on-going engagement undertaken to gain approval and minimise the risk of project delays and opposition. For example, the National Grid UK's document - the Preliminary Environmental Impact Assessment (PEIA) set out the preferred route, explained their methodology and identified the likely impact of the proposals on the environment from the beginning.

This transparent approach was deemed by the proponent to help minimise opposition to the project.

- Other factors that were considered to influence project success included the use of aesthetic overhead transmission line structures combined in some cases with the need for underground sections to be installed. The downside of these structures, however, is the greater width of the structures and larger easement requirements and land-use restrictions.
- The Hinkley Point Connection Project (UK) involved the replacement of an existing 132 kV lattice steel tower line with new aesthetic 400kV T-Pylon structures. The community had become used to the existing transmission line and the new structures were designed to be more aesthetically pleasing. Additionally, the proponents were prepared to underground 8.5 km of the route in an area, because it was recognised as an area of natural beauty.
- In the case of the UK T-Pylons and in the Danish case, Thor-gi tubular steel structures were used; which are more compact with a lower height compared to traditional steel lattice towers for the same system voltage. The downside of these structures, however, is the greater width of the structures and larger easement requirements and land-use restrictions.
- Case studies from Denmark (400kV) and California (500kV) also demonstrated the need for underground sections; ranging from 5.6km to 26km respectively. The rationale for underground sections were in response to community concerns, or political / regulatory interventions.
- Appropriate compensation was also deemed a critical facilitator, particularly to farmers and landholders. For example, in Denmark the company, Energinet, established an agreement with the farmers' organisation on how to compensate farmers and landowners if overhead lines or underground cables are on their property. Landowners adjacent to line were also eligible for compensation based on a proximity distance criteria scale.
- The Powering Sydney project is a 20km long 330kV underground cable transmission line, linking major substations in a heavily populated urban environment. The case study provides perspectives on managing a project that has significant impacts during the construction phase, affecting many diverse communities, major roads and local businesses.
- The case study of the Baleh-Mapai 500kV transmission line in Sarawak involves a double circuit overhead line traversing 177km of mainly rural and remnant forest areas. The case study provides an overview of the project's detailed Environmental and Social Impact Assessment and stakeholder engagements with affected communities.

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Appendix A:
Review of Current NEM Projects: Humelink, VNI West & Western Renewables Link

1. HumeLink

The HumeLink project involves a 500 kV transmission upgrade connecting Project EnergyConnect and the Snowy Mountains Hydroelectric Scheme to the existing Bannaby substation [1].

1.1 Community and Stakeholder Engagement

One landowner and community advocate, presented a review of HumeLink's engagement process with landowners and the community [2]. The findings of the review relate to the experience of the landowners impacted by the consultation process. Accordingly, they suggested that the community engagement was not transparent as there was no clarity on who is responsible in project decision making, how/when decisions will be notified, which decisions are negotiable and how/when community input will be sought. Only landowners within the project corridor were found to be included in the process, and not landowners adjacent to the corridor. Landowners were not always treated with respect, and it was felt that their anxieties about the projects were misunderstood. The review examined the maps, letters, fact sheets, landowner packages and web pages involving the project and found they were not always appropriate, up to date and user friendly. It was also felt that any alternative options or feedback proposed by landowners were not seriously explored. Rod Stowe listed twenty recommendations for Transgrid to improve their community engagement.

Transgrid has committed to reapproach their community and stakeholder engagement by adopting all twenty recommendations from the Landowner Advocate Report. As highlighted in the Implementation of the Landowner Advocate's Recommendations on HumeLink Report [3], the recommendations of Stowe as well as the actions taken by Transgrid are listed as follows:

Table 1 Recommendations by a Landholder and Actions Taken by Transgrid

Recommendation	Actions Taken
1. "Re-set" landowner and community consultation by holding a meeting with all potentially impacted parties to: a. examine all proposed transmission route options (including those proposed by landowners) with detailed advice as to feasibility and reasons for exclusion; b. have experts available to discuss all aspects of the project; c. provide advice on how Transgrid is using international best practice infrastructure technology in transmission line project; and d. provide advice on the remaining steps in the consultation process and how they will be conducted.	Place Managers (individuals responsible for overseeing and managing a specific location, ensuring its efficient operation and maintenance) have reached out to meet with all landowners within the study corridor to: Outline the Engagement Reset and confirm our commitment to improve to the quality of engagement; Discuss the project generally, including the decision making process, the route options, infrastructure and technology that is being considered, the project's timeline and next steps in the process; Seek feedback on the consultation process, particularly understanding the best way to engage with landowners; and Communicated the channels that Transgrid will engage regularly, including through regular check-ins and newsletters. Place Managers schedule and hold face-to-face meetings and regular phone check-ins. Community engagement improvements were also discussed through the CCGs, webinars and meetings with landowner action groups. Key Transgrid subject matter experts and industry experts have provided advice and participated in key meetings, including the Australian Energy Infrastructure Commissioner (AEIC), Andrew Dyer, and the undergrounding expert, Amplitude, as the independent consultant for the community advising on the undergrounding study. All feedback received from landowners, stakeholder groups and the community are registered in our consultation management process and considered as part of the project planning process. Landowners and other stakeholders have been provided with detailed information on how their feedback has been considered. We have considered alternative route options based on feedback provided by landowners, stakeholders and the community and provided detailed information on how these options have been considered and if not progressed, why this is the case. Additional advice and discussions held during meetings and briefings with stakeholder groups have been documented into FAQs [4] and published alongside other materials on the HumeLink website to be available to all parties.
2. Review the mid-year time frame for disclosure of the proposed transmission route and advise landowners.	During the start of the Engagement Reset, the mid-2021 time frame was updated to the end of 2021 to allow time to genuinely engage with landowners and the community. This was communicated to landowners by Place Managers through direct engagement and mentioned in the August newsletter. The timeframe to provide formal notification of the narrowing of the corridor to 200m was subsequently extended until early 2022. This was to balance providing certainty for some landowners, providing time for landowners that were newly included in the study corridor and to assess community provided corridor alternatives.

Recommendation	Actions Taken
3. Conduct a general information session with each regional group along the corridor prior to the commencement of each new stage of the consultation process, such as the commencement of on-site visits. This should explain the process, what it aims to achieve, how it will be conducted and what will be required of them. This should be supported by a fact sheet on the website at the same time.	Key information on the stages of the consultation process, the upcoming proposed field activities, their timing and what to expect have been discussed in webinars, the Landowner Brochure, newsletters, and periodic meetings with landowners and CCGs. Each stage of the consultation process has information available on the HumeLink website. For example, the Route Selection Fact Sheet provides information on how Transgrid conducts the route selection process, whilst the Ecology Survey Fact Sheet and the Cultural Heritage Fact Sheet provides details on the process and what to expect during the field surveying activities within private property.w
4. Review the number of staff required to conduct the consultation on this major project using a best practice model.	Transgrid has used the advice from industry experts and lessons learned from other Transgrid major projects to gauge the level of full-time staff needed for the engagement program. The Engagement Team has been resourced accordingly and consists of the Community Engagement Lead, a Strategic Lead, a Team Lead, three Place Managers, a Communications Officer, a Systems and Support Officer, and support staff. All of these team members work with other teams within the HumeLink project team to deliver engagement activities.
5. Review the list of landowners it is consulting with to ensure that all appropriate landowners are included	The list of landowners has been updated based on looking through all properties within each route area and discussions with landowners, the community, and stakeholders. Place Managers have reviewed the list to ensure it is comprehensive. The list continues to be updated as the consultation process progresses, including other interested parties who sign up to the newsletter.
6. Review the capacity, skills and suitability of staff and contractors involved in landowner and community engagement activities.	Industry experts have been used to assess the Engagement Team, and the wider project team (particularly those with external facing roles), and resources uplifted as needed. All members of the Engagement Team were assessed on their capabilities based on their skills, previous experience, and qualifications (e.g. all members of the Engagement Team have IAP2 certification or equivalent industry experience). This was done by both the Community Engagement Lead within the Project team and other senior members within Transgrid's operations and human resources teams.
7. Provide appropriate training to all engagement staff focusing on empathy and customer centrality in business operations.	A set of minimum training requirements was developed for each team member who would engage with external stakeholders, including those outside of the Engagement Team such as the Project Director, the Land Access and Acquisition Team and other roles that provide ad-hoc support to engagement activities. The training requirements include the IAP2 certification which provides the fundamentals of community engagement and best practice guidelines, and also training on developing empathy and dealing with challenging situations. All members of the Engagement Team and the Land Access and Acquisition Team were assessed against the training requirements, particularly on empathy and customer centrality. Training was issued where there were gaps in their capability.

Recommendation	Actions Taken
8. All Transgrid staff involved in landowner engagement activities be required to: a. comply with Transgrid guidelines for property visits i.e. provide accurate information about the identity and number of staff/consultants attending the property. Any variation to the originally agreed arrangements should be renegotiated with the property owner; b. generally, ensure the number of Transgrid staff/consultants attending a property does not significantly exceed the number of owners present at the property. (e.g. a ratio of five Transgrid staff to one property owner would normally not be considered desirable.); and c. ensure that all landowner feedback/communication is responded to in a timely manner and comply with commitments to provide advice by a specific timeframe.	The HumeLink guideline on accessing and visiting properties was updated and enforced for all staff to follow. Overseen by the Community Engagement Lead, all property visits are conducted in pairs of one Place Manager with one Land Access Officer. Place Managers and Land Access Officers worked with landowners to receive and update property access agreements in the form of Consent to Enter forms. These forms are in the process of being updated with clearer messaging. The process on receiving, acknowledging, considering and responding to enquiries, complaints and feedback was reviewed and updated. This is documented and tracked within Transgrid's consultation management platform.
9. Re-examine how it represents key features on the maps it provides to landowners so as to explain how data is sourced.	All base maps were reviewed and updated against feedback collected to date. The interactive map was relaunched on HumeLink's website after a comprehensive review and update with the ability to highlight comments and the sources of information for particular features, and for users to provide comments and feedback. The maps are checked on a regular basis and linked to the interactive map.
10. Review its consultation documents to remove excessive irrelevant images and marketing material and to provide a less clinical and impersonal tone	A comprehensive review of all collateral and consultation documents was conducted to ensure they are appropriate and provide a less clinical and impersonal tone. The Landowner Advocate was included in the document review process prior to distributing and/or publishing online on the HumeLink website. The AEIC Andrew Dyer has and will continue to provide feedback on materials. Training on tone of voice and writing in plain English is included in the minimum requirements for the team members involved in engagement activities
11. Utilise its website more to provide a 'source of truth' for responses to questions that arise and to share presentations that are given to one group of landowners with all the affected landowners so that all are aware of the same information.	The HumeLink website was relaunched in a format where it is easy to access key documents, as well as a section dedicated to landowner resources. The following items are published on the website to ensure all landowners, the community and stakeholders have access to the same information: • CCG presentations and associated meeting minutes (with details on the Q&A section) and list of participants; • Webinars/information sessions summaries; • Newsletters that have been distributed; • Relevant fact sheets; and • Regulatory documents, such as the Project Scoping Conclusions Report, Project Assessment Draft Report and Project Assessment Conclusions Report.

Recommendation	Actions Taken
12. Consider the use of a newsletter to provide progress reports on the consultation process.	Regular newsletter issues have been planned in alignment with project phases and milestones to provide timely information to landowners. For example: • The August issue introduced the Engagement Reset, reaffirmed Transgrid's commitment to improving the quality of engagement, introduced the CCGs and provided other information on the project; • The September issue introduced the Place Managers, provided information on the updated study corridors (where some of the previously scoped corridors are no longer required for HumeLink, other corridors were narrowed and new study corridors emerged), introduced the field investigations and surveys (including the Ecological Survey and the Cultural Heritage Survey), and promoted the Landowner Assistance Program and the Community Partnerships Program; and o The upcoming February issue will focus primarily on introducing the narrowed corridor. These are all published on the HumeLink website. The team continues to actively seek suggestions from landowners on what they want to see in the next newsletters.
13. Revised project maps, reflecting appropriate information provided by landowners, be uploaded at relevant intervals.	All maps were assessed against previous feedback gained from landowners, stakeholders and the community prior to relaunching the interactive map on the HumeLink website The team updated and implemented a new process to review feedback and comments on the online interactive map (i.e. review and post all comments unless they are specified to be private). Land Access Officers and Place Managers have met and will continue to meet with each landowner on the narrowed corridor with up-to-date maps with all information from previous interactions with the landowner and relevant info from the online interactive map.
14. Q and A be prepared on the question "Why doesn't the information I provided about my property and/or surrounds not appear on the map?"	FAQs are published on the HumeLink website, which provide a response to the question. The team have discussed map features specific to landowners at CCGs and Action Group meetings.
15. In individual discussions with potentially impacted landowners, Transgrid staff have regard to feedback received about the specific property and explain why landowner requests can/cannot be acceded to.	The process for receiving, addressing, considering and responding to feedback from landowners has been updated and is embedded in the team as a business as usual process. For example, we have considered alternative route options based on feedback provided by landowners, stakeholders and the community and provided detailed information on how these options have been considered and if not progressed, why this is the case. Land Access Officers and Place Managers have met and will continue to meet with each landowner to discuss concerns regarding their property, including the use of maps that accurately reflect their property, how their property will be impacted and the next steps in the process. A list of negotiables and non-negotiables has been developed for the Engagement Team to use when corresponding with landowners, stakeholders and the community.
16. Formally respond to the matters raised by Kyeamba landowners at the meeting of 31 March 2021	The team formally responded to Kyeamba queries in July 2021, and we continue to engage with Kyeamba landowners as part of the consultation.

Recommendation	Actions Taken
17. Advise affected landowners of its intended response to the Advocate's recommendations.	Our commitment to achieve the Advocate's recommendations was discussed and outlined with all landowners and stakeholder groups through check-ins, meetings and letters at the beginning and continuously throughout the six-month period. It is also publicly stated on HumeLink website and through various media releases
18. Consider making a limited EAPS like service available to potentially impacted landowners who might be experiencing anxiety during the route selection process.	The Landowner Assistance Program (through Assure) was introduced and continues to be offered to all landowners through property visits and phone calls. Information on the Program is available via the HumeLink and Transgrid website and printed in newsletters (which are also available on the website). Affected landowners and community members have free access to the program.
19. Consider the use of a landowner from a previous project to speak with the landowners who are potentially affected by HumeLink.	The team has discussed and explored internally within Transgrid the appropriate platform and medium to potentially use landowners from other projects. We have found that there is a lack of willingness for this to occur. We are actively looking at other options to achieve similar outcomes.
20. Consider the establishment of one or more reference groups to provide input into the consultation process for the HumeLink project.	CCGs were established where members can engage in the project planning process and on issues of key community concern. Bespoke reference groups will be established where possible. The steering committee for the independent undergrounding study provides the model for this.

1.2 Community Consultative Groups

Recommendation 20 emphasised the requirement for establishing reference groups for the HumeLink project. As a direct response to this recommendation, the project successfully established Community Consultative Groups (CCGs) to involve a diverse range of stakeholders at every stage of the proposal to provide valuable input and feedback. The initiative seeks to foster effective communication and collaboration among various stakeholders involved in the HumeLink project, including Transgrid, local community groups, landowners, and councils. Its primary objective is to create a platform for two-way communication, allowing Transgrid to provide updates on the project and address any concerns or queries raised by the community [5]. Similarly, it offers an opportunity for community members, stakeholders, and local councils to seek information from Transgrid and provide valuable input to refine the project corridor and contribute to the subsequent Environmental Assessment process.

As highlighted in the CCG Code of Conduct [6] (Attachment A), to facilitate a comprehensive representation of stakeholders, each group within the initiative consists of a maximum of 15 members. This includes three representatives from Transgrid, one member from each council and one from each land council, and one representative from each established landowner group within the CCG area. The remaining members are drawn from recognised community groups, with preference given to groups, and individuals who have expressed their interest in participating. As of writing, the CCGs have had meetings in the following months:

- 2021: October, November,
- 2022: February, April, July, September, October, November, December,
- 2023: February, March, May

The Code of Conduct also highlights how the CCGs should strive for equitable gender representation and include diverse age groups. Coverage along the project corridor is crucial for comprehensive representation. Invitations were extended to Chambers of Commerce, Progress or Resident Associations, Indigenous groups, Local Environmental Groups, Landcare/Bushcare organisations, Tourism Associations, and industry associations such as Forestry Groups and NSW

Farmers. The CCGs selection process considered specific expertise, skills, and a broad range of local organisations to foster inclusive dialogue and effective decision-making. As of April 2022, the three groups across five Local Government Areas (LGAs) of CCGs were formed [7].

1.3 Summary of Stakeholder Engagement and Interest

The following table is sourced from the HumeLink Scoping Report [8] and highlights how Transgrid has engaged with stakeholders as well as their key interests:

Table 2 Summary of Stakeholder Engagement and Interest

Stakeholder	Engagement	Topics of Interest
Community	HumeLink newsletter and fact sheets Website and Interactive Map 1800 number and HumeLink email CCGs Webinars, information sessions and public displays Support services, such as independent counselling	Local employment opportunities Environmental and social concerns Cumulative impacts Community sponsorship opportunities Community benefits Opportunities for improved communication and consultation Opportunities to collaborate for better regional outcomes Impact to local businesses
Landowners	One on one meetings and site visits HumeLink newsletter and fact sheets Targeted notifications Website and Interactive Map 1800 number and HumeLink email CCGs Webinars, information sessions and public displays Support services, such as independent counselling	Impact to local farm businesses and landowners Easement guidelines Compensation Opportunities for improved communication and consultation Environmental and social concerns
Government (political representatives) **Local State Members**	Briefings / presentations Briefing Notes HumeLink newsletter and fact sheets	Community sentiment/issues arising Constituent concerns Media interest Regulatory considerations
Local Government (elected officials and Executive staff)/Councils	Councillor briefings Council presentations Emails / phone calls HumeLink newsletter and fact sheets	Community sentiment / issues arising Constituent concerns Local impacts Media interest Local opportunities and constraints, such as considerations around Tumut airport Use of public vs private land

Stakeholder	Engagement	Topics of Interest
Government (Departmental and Agency) **Heritage NSW** **DPE (NSW) (including Biodiversity Conservation Division)** **DAWE (Fed)** **Department of Primary Industries (NSW)** **Forestry Corporation of NSW** **Centre for Property Acquisition (NSW)** **Transport for NSW** **Rural Fire Service**	Briefings / presentations Technical meetings Interface meetings Emails / phone calls HumeLink newsletter and fact sheets	Field survey requirements Hunting restrictions Impact of proposed routes on firefighting and fuel reduction burns Impact on operations Compensation Opportunities to share lessons and to collaborate for better regional outcomes
Traditional Owners and other Aboriginal representative groups/Land Councils	Briefings / presentations Emails / phone calls HumeLink newsletter and fact sheets CCGs Website and Interactive Map Community sponsorship program	Culturally significant sites Cultural heritage survey requirements and findings Opportunities for improved communication and consultation Community sponsorship opportunities Opportunities to collaborate for better regional outcomes
Community groups **Community organisations** **Service groups (Rotary etc)** **Issue-specific interest groups (e.g. environment, health)** **Local business** **PIAC, EUAA, ECA, St Vincent de Paul, Tesla, AiGroup**	Briefings / presentations HumeLink newsletter and fact sheets Website and Interactive Map CCGs Community sponsorship program Support services, such as independent counselling	Local employment opportunities Community sponsorship opportunities Opportunities for improved communication and consultation Opportunities to collaborate for better regional outcomes
Industry representative groups **NSW Farmers Association**	Briefings / presentations HumeLink newsletter and fact sheets Website and Interactive Map Community Consultative Groups Support services, such as independent counselling	Impact to local farm businesses and landowners Easement guidelines Local employment opportunities Community sponsorship opportunities Opportunities to collaborate for better regional outcomes Opportunities for improved communication and consultation Compensation
Major development proponents and renewable generators (e.g. Snowy Hydro, CWP Renewables, Tilt Renewables, Spark Renewables)	Briefings / presentations HumeLink newsletter and fact sheets Website and Interactive Map Technical meetings Interface meetings Emails / phone calls	Workforce capacity Cumulative impacts Interface management Constraints and opportunities Opportunities to share lessons and to collaborate for better regional outcomes

Transgrid's engagement with landowners and stakeholders within the corridor resulted in feedback across a range of themes. The following table from the HumeLink Scoping Report [8] highlights these themes received up to November 2021:

Table 3 Feedback Themes

Theme	Number of times topic was raised	Focus of feedback
Proposed alignment	364	Location of route Preferences for alignment Concerns about the alignment Proposed alternative alignments Timeframes for route refinement Level of influence on alignment Consultation timings and process What it means to live with a powerline Easement guidelines Route selection process Compensation process Known and unknown constraints Use of public versus private land
Impacts on land use and property	220	Protection of productive agricultural land Current and future land-use plans Existing farming infrastructure Impact to farming operations Property access Gates and livestock Biosecurity Easement guidelines Construction impacts Consent to enter protocols
Impacts of tower	97	Tower locations Size and shape of the towers Impact to visual amenity Impact to property value Impact to farming operations Level of influence on tower placement Easement guidelines and exclusion zones Design safety features
Impact on the environment	48	Protecting Landcare plantings Clearing requirements Construction impacts Easement guidelines Identification and protection of heritage items Undergrounding the line Use of public vs private land
Impacts on health	37	Concerns about effects of electric and magnetic fields (EMF) on people and animals

1.4 Biosecurity

The proposal's preliminary impacts include changes in land tenure, potential disturbance to dwellings and infrastructure, land parcel fragmentation, and disruptions to existing land uses [9]. Agricultural activities, horticulture operations, forestry operations, and other land uses within the project corridor are susceptible to these impacts. As a result, there may be interruptions to seasonal cropping and harvesting, biosecurity risks due to construction movements, and temporary restrictions on accessing and using nearby properties during the construction phase [8].

Themes involving biosecurity have been received by Transgrid 220 times as seen in Table 3. Potential impacts on terrestrial ecology highlighted by Transgrid [8] include the direct loss of vegetation and habitats, which can disrupt the delicate balance of ecosystems. Additionally, the damage to habitats, vegetation, and foraging areas poses a threat to the survival of various species. The injury or mortality of fauna can also further exacerbate the negative ecological impact. The disturbance caused by noise, vibration, movement, and human presence can disrupt natural behaviours and stress wildlife. Lastly, there is a risk of unintentional introduction or spread of weeds and pathogens, which can harm native plant species and potentially impact the entire ecosystem.

Following a meeting with the CCGs in March 2023 [10], it was apparent that some members expressed concerns regarding the effectiveness of the protocols implemented by contractors in addressing biosecurity issues during the construction phase. These individuals raised concerns about the possibility of the protocols not being strictly adhered to, resulting in the persistence of biosecurity problems. It was emphasised that the existing measures might only serve to reduce the risk rather than eliminate the potential threats. Furthermore, there were concerns that the current Property Management Plan (PMP) might not sufficiently address or account for potential future risks that could arise from the construction activities. These latent impacts could emerge over time, potentially affecting the terrestrial ecology beyond the project's completion.

A representative for Resist HumeLink has raised concerns surrounding overhead transmission infrastructure conflicts with agriculture [11]. They referenced the Managing Farm-Related Land Use Conflicts in NSW research report by the Australian Farm Institute [12] which highlights how all levels of government need to protect agricultural assets to secure the future of the industry. They claimed the project does not consider modern farming practices such as drones and GPS which cannot be utilised in proximity to overhead transmission lines.

1.5 Cultural and Heritage Sites

The HumeLink project extends across the lands of the Wiradjuri, Ngunnawal, Ngarigo and Gundungurra people [8]. Construction ground disturbance, which includes activities such as excavation and grading, can directly disturb and destroy archaeological artifacts and structures as highlighted in the Scoping Report [8]. Vegetation clearance can remove the protective cover and concealment of archaeological sites, exposing them to further risk of damage or destruction. The removal of vegetation can also result in the loss of important contextual information that helps archaeologists interpret and understand the significance of the site. Within the designated heritage study area, which encompasses a one-kilometre-wide corridor on either side of the proposal corridor, a total of 291 Aboriginal heritage items/recordings have been documented and included in the Department of Premier and Cabinet Aboriginal Heritage Information Management System (AHIMS).

One of the thirteen FAQs present of Transgrid's website discussing HumeLink questions what engagement practices has been considered and performed to Indigenous groups and people [13]. In April 2021, the HumeLink project team actively engaged with Aboriginal stakeholders and invited expressions of interest from the community to determine the cultural significance of Aboriginal objects and places within the project area. Registered Aboriginal Parties (RAPs) were involved in cultural heritage surveys and provided valuable insights for assessing impacts and implementing mitigation measures.

During a meeting with the CCGs in March 2023 [10], a member expressed concern regarding the placement of powerlines over culturally significant sites. The member commented that if a fire were to occur in the vicinity of the site, the presence of the powerline infrastructure could impede the ability to effectively protect the site. According to Transgrid, the risk of unintended accidents would be reduced by following established Transgrid procedures (like designating restricted areas around recognised Aboriginal cultural sites) [8].

A discussion with Snowy Valley CCG members in February 2023 [14] highlighted an important perspective regarding the concept of heritage and its significance to local communities. It was emphasised that while Transgrid may not consider trees planted by farmers as heritage, for the farmers themselves, these trees hold great value as they represent a legacy and contribute to the creation of heritage. The term "heritage" was deemed to be disconnected from its intrinsic value. Members expressed concern about Transgrid's plan to remove hundreds of trees that hold significance for future generations. They stressed the importance of city personnel involved in this project understanding the perspectives of country people and recognising how they perceive and value different aspects of their land and heritage. Transgrid representatives suggested raising these concerns with the Land Access Officers, highlighting the need for open dialogue and the inclusion of local community voices in decision-making processes.

1.6 Economy

Residences which are within the corridor of the project will receive compensation payments. This includes Strategic Benefits Payments of $200,000 per kilometre of transmission, paid in instalments over 20 years once the project is energised [15]. Easement Payments are assessed by the Land Acquisition (Just Terms Compensation) Act 1991 [16] and are paid to landowners in addition to compensation payments. Additionally, Transgrid offer a Community Partnership Program which offers up to $5000 grants for non-profit organisations local to the Transgrid assets or construction [17].

From the minutes of a CCG meeting held in March 2023, a CCG member commented they will not accept a $5000 grant from Transgrid as they 'do not endorse what Transgrid is doing' [10].

In the same meeting, it is clear CCG members are unhappy with Transgrid and the AEMO. They requested a copy of the 2022 Integrated System Plan (ISP) [1], but it was received months after the request. CCG members also requested to meet with the AEMO in the CCG meeting a month prior, however no meeting was scheduled. The CCG members want to be 'involved in conversations with key decision-makers' and are concerned Transgrid are 'not representing concerns of the community'. They submitted an additional requested to meet with a representative from AEMO or the government, which has been taken on notice by Transgrid project member attendees.

The ISP suggests that net market benefits would be $3 million more if HumeLink were scheduled to be delivered in 2028-29 in Step Change (sudden transformation that occurs in a relatively short period) and 2033-34 in Progressive Change (gradual and continuous development). A CCG member questioned the timeframe for completing the project and requested the project to be slowed down in order to deliver a better outcome for impacted communities.

A representative for Resist HumeLink sent a letter to the AEMO, highlighting the omission of costs to communities in transmission infrastructure evaluation [11]. They raised concerns regarding property devaluing of homes in proximity to overhead transmission lines. The Land Acquisition Act 1991 only covers residences which have transmission line infrastructure on the property. The representative highlighted how neighbouring properties suffer from the decrease in valuation, but do not receive this compensation.

They also highlighted how the Regulatory Investment Test for Transmission (RIT-T) aims to select the transmission investment option which maximises net economic benefits. However, RIT-T does not consider the cost of the environment and is insensitive to environmental impacts.

The representative, is deeply concerned about the negative impact of overhead transmission on the lifestyle of farmers, as how it significantly affects the desirability of the landscape for farming. Consequently, this detrimental effect on agriculture poses a threat to local businesses, leading to a substantial "loss of economic stimulus for rural areas".

They also claimed tourism of NSW is also impacted due to the obstruction of natural landscapes due to transmission towers. She highlighted how NSW visitation increased 41% from 2014 to 2019 and expenditure of $14.3 billion in 2019, as well as how regional Australia is a visitor attraction due to its natural landscape.

1.7 Undergrounding

In late 2021, Transgrid received requests from the community and landowners to investigate the possibility of constructing the HumeLink project using underground cables instead of overhead transmission lines. However, an underground feasibility study scope of works presented in April 2022 by Transgrid [18] presented four concept design as well as design variants for consideration which can be summarised:

Table 4 Undergrounding Design Concepts Summary

Options	CAPEX	Schedule
Overhead line	$3.3 Billion	4-5 years
Design 1A	$17.1 Billion	≈ 11 Years
Design 2A-1	$11.5 Billion	≈ 7 Years
Design 2B-1	$9.0 Billion	≈ 7 Years
Design 3A-3	$9.6 Billion	≈ 6 Years
Design 3B-3	$7.5 Billion	≈ 6 Years
Design 4A-5	$11.5 Billion	≈ 6 Years
Design 4B-5	$9.1 Billion	≈ 6 Years
Design 4C-2	$10.4 Billion	≈ 6 Years

The cost of burying the HumeLink transmission lines amounts to at least an estimated $17.1 billion, which is five times greater than the current cost of the overhead line project, standing at $3.3 billion. This excessive cost was deemed not sustainable since it would ultimately be borne by commercial, industrial, and private electricity consumers. Opting for underground transmission lines would also result in a significant project completion delay of up to six years which compromises later works for renewable energy and interstate connections to the grid.

1.7.1 CCG Response to Undergrounding Study

CCG representatives from Snowy Valleys CCG, Wagga Wagga, Cootamundra, Gundagai CCG, and Upper Lachlan, Yass Valley CCG submitted the CCG Representatives' Position on HumeLink Undergrounding Study Report [19] in response to Transgrid, expressing their concerns. They found the Undergrounding Study report to be heavily focused on the negative impacts of undergrounding while neglecting to represent any of the potential positive benefits. Additionally, the CCG representatives suggested that the cost estimates for the underground cable components were significantly higher than other estimates available in the AEMO Transmission Cost Database and from reputable Australian-based high voltage cable experts. The representatives claimed that there were technical inaccuracies regarding AC and HVDC underground cable installation and operation in the report, which seemed biased towards highlighting the negative aspects of undergrounding. To illustrate their point, they provided an example wherein the consultant based their assumptions on the Transgrid EHV Cable Design and Installation Manual, which primarily addresses the installation of long-distance AC and HVDC cables in rural and non-built-up areas. However, the consultant applied techniques for the installation of relatively shorter distances of AC underground cables in built-up areas, leading to inconsistencies and potential inaccuracies in their findings.

The CCG representatives have expressed dissatisfaction with the methodology used for the cost estimates related to undergrounding and have specifically requested clarification on how scaling factors have influenced these estimates. They have voiced their concerns regarding responses that rely solely on "engineering judgement based on experience and understanding of the HVDC market" as the basis for the cost estimates. According to the representatives, they find the consultants' inability to justify how they have adjusted historical values to account for market changes to be problematic. This lack of transparency raises concerns about the accuracy and reliability of the estimates provided.

Additionally, the CCG representatives highlighted the consultants' failure to provide MW/MWh values used in determining the operational expenditure (OPEX) costs associated with undergrounding. The representatives argued that a fair comparison between the underground and overhead options cannot be made until the calculations and assessments of losses and costs have been presented and thoroughly reviewed. The representatives asserted that it is crucial to consider the total electrical losses in the comparison. They believed that the underground option should demonstrate lower losses than those incurred by AC overhead lines.

The CCG representatives expressed dissatisfaction with the proposed alternative route assessments for undergrounding and raised concerns regarding the constraints highlighted in the report. They argued that the inconvenience caused during a short construction period should not be the sole determining factor for the project's location, as they found it unconvincing. Furthermore, the representatives disagreed with the inclusion of unlicensed airstrips and bushfire-prone land within the designated kilometre corridor as constraints for undergrounding. They believed that these factors should not be considered limitations for the underground option. They also asserted that the constraints presented in the report were derived from land studies conducted for overhead routes, making them unreliable for assessing the feasibility of undergrounding. The representatives highlighted inconsistencies in the definitions of bushfire-prone areas between the NSW Rural Fire Service and Transgrid. They suggested that certain properties in the area, marked as bushfire-prone on the Rural Fire Service maps, had not been officially designated as such by Transgrid. This discrepancy raised concerns about the accuracy and consistency of the constraints used in the report's assessment.

Lastly, according to the CCG's consultant, the commissioning schedule mentioned in the report is deemed excessive and should not exceed a maximum of two to three months. By implementing this adjustment, the schedule for certain options would be reduced to less than 6 years, making it more comparable to the AC overhead line's timeline.

1.7.2 Response from Transgrid

This letter prompted a response from the Major Project Delivery Director of Transgrid [20] to the Community Consultative Groups' representatives, who found the original report to be consistent with other national and international experiences and benchmark studies. The Director highlighted how Transgrid operates under the National Electricity Law (NEL) and therefore must present the most efficient route for transmission that adheres to the long-term interests of consumers of electricity with respect to price, quality, safety, reliability and security of supply of electricity.

Transgrid claimed their assessment of options involved a detailed examination of the relevant costs and benefits associated with the electricity supply to consumers. They stated their evaluation considered various factors, including the capital cost of the proposed solution, ongoing operational costs, market benefits, expected reliability, and the impacts on landowners, the community, and the environment. Based their analysis of the report's findings, it became evident that undergrounding HumeLink did not align with these criteria.

The letter acknowledged that the original report thoroughly evaluates the visual impact advantages of undergrounding, along with its implications for wildlife, bushfires, and reliability. However, it was found the cost of undergrounding HumeLink will surpass that of an overhead line. Furthermore, the additional time required to implement an undergrounding solution further enhances the project's costs. Considering these factors, it became apparent that undergrounding HumeLink was not a viable option.

1.7.3 CCG Meeting

During a meeting between CCG members and Transgrid representatives [10], the topic of undergrounding was further discussed. In this meeting, a CCG member raised a question regarding the potential reconsideration of undergrounding if Transgrid encountered significant cost increases for the towers due to unfavourable ground conditions. In response to this query, Transgrid stated that the cost comparisons already considered the risk of increased costs resulting from changes in ground conditions.

During the discussion, the issue of safety in relation to bushfires was extensively debated, with a focus on how the implementation of undergrounding could enhance protection and eliminate risks for communities. Concerns were raised regarding the potential danger posed by keeping overhead lines energised during fires, as it could jeopardise the health and well-being of residents. CCG members emphasised the need for equitable treatment of people in communities, urging that their safety should be prioritised as much as those in cities. Transgrid responded by highlighting their collaboration with the Rural Fire Service to develop appropriate protocols addressing these concerns. However, these assurances were met with continued apprehension from CCG members. One member expressed their belief that if Transgrid genuinely cared about the impacts of bushfires, they would prioritise undergrounding the line as a proactive measure.

During the discussion, a member cited the Australian Energy Infrastructure Commissioner's criticism of the suitability of the RIT-T in restricting undergrounding considerations. Another member emphasised the need to account for ongoing social and environmental costs alongside financial considerations. Another member requested Transgrid to estimate the cost of building a small underground portion, to which Transgrid responded by highlighting collaboration with international companies to inform their cost estimates.

Members raised concerns about the cost comparisons of undergrounding and whether maintenance costs were adequately considered. One member specifically mentioned their awareness of an underground gas pipeline that was efficiently laid 32km over 8 weeks. In response, Transgrid highlighted that the challenging terrain along the HumeLink route was a crucial factor contributing to the difficulties and complexities associated with undergrounding.

During the discussion, there was a question raised about the potential reduction in road traffic with the implementation of undergrounding. However, it became apparent that such a comparison had only been conducted for overhead lines, with no assessment made specifically for the underground option. A CCG member pointed out this discrepancy, highlighting that Transgrid's lack of planning and consideration regarding traffic for the undergrounding option suggested a lack of seriousness in considering undergrounding as a viable alternative. This comment expresses the concern that Transgrid may not be giving sufficient attention to exploring the potential benefits and implications of undergrounding.

A CCG member inquired whether there would be a comparison between the visual impacts of undergrounding and those of overhead transmission lines. Another CCG member expressed the view that Transgrid should approach the HumeLink project through a co-design process involving the community, farmers, Rural Fire Service, security experts, environmentalists, and council members. They highlighted the importance of engaging with these stakeholders and working collaboratively to ensure that decisions are not imposed upon the community.

1.7.4 HumeLink Alliance Inc.

HumeLink Alliance Inc. started an independent ecological campaign against the HumeLink project, advocating to put the project underground to prevent disfigurement of the landscape and community damage [21]. They claim the proposed towers have the potential to cause bushfires, hinder firefighting efforts, create electromagnetic fields with health impacts, render farmland unusable, industrialise the landscape, decrease land and property values, destroy native habitats, disrupt aerial and drone activity, interfere with GPS signals, threaten animal habitats, create constant noise, and be prone to collapse in storms and high winds.

They claim underground options instead offer advantages as the lowest impact solution. The risk of underground cables causing bushfires is minimal as power transmission is unlikely to be interrupted during bushfires or severe weather events, eliminating the need to shut off power and facilitating firefighting efforts. Access for emergency services and aviation operations remains largely unaffected. Once construction is completed, there is minimal impact on private land or existing land use, as the easement can be designed to fit within road reserves. The possible location of the cables along roadways significantly reduces the impact on flora and fauna. Furthermore, the underground cables result in no visual impact, and the converter station occupies a comparable area to a typical AC terminal station with much of the equipment housed indoors, minimising visual and land-use impact. Along the transmission line, there is no audible noise, and the option presents little to no electromagnetic field impacts.

However, they state communities have been advised Transgrid's towers are the only solution and are pleading with State and Federal Government to consider these alternatives.

1.7.5 Resist HumeLink

An article for Resist HumeLink [11] discusses the detrimental effects of visual pollution caused by transmission towers and raises a valid question regarding the lack of undergrounding initiatives in New South Wales, as opposed to other countries that have recognised the visual amenity and environmental benefits associated with underground transmission systems. The author also highlights the ongoing projects of companies such as Star of the South and Marinus, which are advocating for the undergrounding of transmission lines in the National Electricity Market. They claim undergrounding not only improves the aesthetic appeal of the surrounding landscape but also minimises potential negative impacts on the environment.

1.8 Traffic and Transport

Transgrid released a Traffic and Transport Impact Statement [22], highlighting temporary increases in traffic on local roads, adversely affecting the performance of the road network. Furthermore, both the construction and operation of the project will lead to temporary road closures and the deterioration of road conditions. Specifically, the construction interacts with 14 roads in Wagga Wagga, 18 roads in Snowy Valleys, 5 roads in Cootamundra-Gundagai Regional, 13 roads in Yass Valley, and 26 roads in Upper Lachlan Shire.

During a CCG meeting conducted on May 2023 [23], a CCG chair raised concerns regarding road safety and dust. A Transgrid project member highlighted mitigation for dust from trucks does not include wetting down of council roads but only access tracks. They suggested there will be other mitigation measures such as ensuring loads are covered when transporting dust generating materials. CCG members were concerned that when a truck moves along the road it throws up dust and this will not be mitigated by covering the load. High volumes of truck and vehicle traffic will further damage already poor roads. The CCG members felt that Transgrid should be required to bring the roads back to better condition.

1.9 Noise and Vibration

As a method to engage with community and stakeholders, Transgrid hosted Community Information Webinars. A webinar in May 2023 [24] highlighted possible sources of noise and vibration. This included site establishment work, vegetation clearing, civil works for access tracks or compounds, and laydown areas. They also noted that noise issues can arise from the construction of transmission lines, involving the use of plant and equipment, concrete batching, and the erection of steel components. Similarly, noise is generated during the construction of new substations and modifications to existing substations, including civil works and the erection of new buildings and steel structures. There are also vibration impacts from construction equipment and noise from construction traffic.

During a CCG meeting conducted in May 2023 [23], a member emphasised the importance of conducting a Property Condition Survey before construction begins due to the specific requirements for tower concrete footings. However, in response, a Transgrid project representative explained that the vibration assessment would examine vibration levels near structures to determine if a dilapidation report was necessary. They mentioned that the EIS assessment did not identify any buildings affected by vibration, but once the final tower locations were determined, Transgrid would assess whether further evaluations were required before construction.

Another CCG member inquired about the number of sites designated for noise monitoring. The project representative confirmed that there were only nine sites for monitoring noise in the EIS. However, they mentioned that contractors would be responsible for monitoring noise during construction. A CCG member raised another question concerning noise monitoring for houses adjacent to power lines. Transgrid clarified that noise levels would be monitored during construction, and if noise levels were expected to exceed the acceptable limits for a certain period, Transgrid would engage in discussions with landowners to minimise impacts.

The topic of noise generated by the transmission lines after construction was discussed. The project representative responded that the humming effect (corona noise) from the lines occurred only under specific weather conditions, such as in light rain or when mist is present. The assessment determined that during these conditions, the noise could be heard up to 300 meters away and up to 400 meters away when two lines ran parallel. However, A CCG member mentioned that they could hear constant humming from the existing 330kV transmission lines, not just during specific weather conditions.

Another CCG member inquired about the assessment of agricultural impacts, particularly on livestock and animal well-being, regarding noise and vibration. The Transgrid project representative explained that noise and vibration requirements for the EIS did not cover livestock impacts. The representative added that Transgrid had conducted a literature review on the topic but found limited research on the impacts of transmission lines on livestock.

1.10 Bushfire Management

During the discussions, community CCG members raised concerns related to the impact of transmission lines on bushfire incidents [25]. One member shared their personal experience, stating that their farm was severely affected by fires in 2020, highlighting how the presence of transmission lines hindered their ability to combat the fire effectively. Another member expressed the widespread risk of bushfires and noted that several CCG members and observers had previously experienced fire damage. They questioned procedures in the event of a bushfire and how landowners are expected to manage such situations. Furthermore, a member criticised the fact sheets provided, stating that they focused primarily on minimising the risk of bushfires, which they felt was insufficient information for local landowners. These concerns highlight the need for comprehensive guidance and support in managing bushfire risks in relation to transmission lines for affected landowners. During a separate meeting, a CCG member highlighted that in the previous major bushfire incident, there were 60 outages, emphasising that undergrounding the route would eliminate this risk [26]. They expressed concern about property owners facing significant risks when transmission infrastructure is located on their land during a fire event.

Transgrid claim they are having ongoing meetings with NSW Rural Fire Service, working to identify how HumeLink can further support firefighting efforts as well as targeted learning sessions with local RFS crews and bushfire workshops with the community [8]. They claim their practices meet Electricity Network Safety Management System standards for bushfire management. They state they perform regular vegetation management, regular reviews and inspections of assets to ensure they are fit for purpose, and inspection and management of the easement that supports the infrastructure. Transgrid will implement the Bushfire Risk Assessment (BFRA) which involves identifying and assessing specific bushfire survey areas within the project footprint. Field investigations and desktop mapping are conducted to analyse vegetation, slope, and access, as well as to model bushfire indicators. Mitigation measures are recommended based on the findings, considering local feedback from landowners and the community.

1.11 Route Refinement Decisions

Transgrid conducted community consultation, environmental field studies, and site assessments to evaluate regional constraints and local considerations. This process enabled the refinement of route options to minimise the potential impacts on the community.

As highlighted in the Tumut Area Route Refinement Decision [27], although the route would traverse a longer distance on private land compared to other options, it was deemed to have significantly lower environmental and social impacts. This route affects seven residences within a 500-meter radius and passes through a shorter distance through areas with a high to very high risk of bushfires. This route provides diversification in supply, improved network resilience, and reduced adverse effects on the community.

As discussed in the Bannaby Route Refinement Decision [28], Transgrid prioritised lower environmental impact. They opted for a route that resulted in a smaller area of impacted Plant Community Types and materially lower biodiversity offset costs. This route traverses a shorter distance through areas with a high bushfire risk, having better network resilience than other considered options.

In the Green Hills Route Refinement Decision [29], Transgrid considered an alternative route through the Green Hills State Forest. This option, despite being associated with higher costs and poorer network resilience, reduced the impact on private landowners. Transgrid weighed the benefits to landowners and the removal of five residences within 500 meters of the line against the negative aspects and determined that the alternative route was the preferred option.

As highlighted in the Pejar Dam Route Refinement Decision [30], Transgrid took into account the amenity impact on Pejar Dam for recreational users. While the alternative route has higher impacts on Plant Community Types, including threatened ecological communities, and incurred higher biodiversity offset costs, it avoided crossing over the middle of the recreational dam. This allows for the route to parallel an existing line at the northern end of the dam, providing greater opportunities for paralleling.

2. Victoria to New South Wales Interconnector West (VNI West)

This project consists of a new high capacity 500 kV double-circuit transmission line to connect Western Renewables Link (north of Ballarat) with Project EnergyConnect (at Dinawan) via Kerang [1].

2.1 Project Assessment Draft Report (PADR)

As a response to the PADR [31], twenty-two non-confidential stakeholder submissions were received [32] and the themes of their responses are detailed below.

2.1.1 Support for Increased Interconnection Between Victoria and NSW

Several stakeholders supported the swift advancement of the VNI West project. CVGA highlighted the urgent need for transmission network upgrades to enhance renewable energy generation opportunities in the region for cheaper and cleaner renewable energy and to provide opportunities for regional development [34]. This is further supported by Pacific Hydro who stressed the requirements of reinforcing the power system to enable larger interstate flow [35], and ENGIE highlighted the regions good quality solar and wind resources and potential for wider renewable generation deployment [36].

On the 20th of February 2023, the Victorian Minister for Energy and Resources issued an Order under NEVA, allowing early works for VNI West and the evaluation of alternative connections to WRL [37]. This NEVA Order aims to facilitate earlier project delivery by enabling AEMO to commence early works while completing the RIT-T. The Order also grants AVP functions, including the assessment of alternative project options to accelerate development and delivery of both projects. By considering alternative options for VNI West, this Order reduces delays and ensures reasonable costs for consumers. This enhances the consideration of social, cultural, and environmental factors, expediting project delivery. It aligns with community feedback on the importance of earlier and broader community engagement.

QUEN and PIAC expressed concerns regarding the project's unrealistic timeframe, citing challenges in securing land, easements, environmental approvals, and potential supply chain constraints [38] [39]. However, AVP and Transgrid defend their time estimates based on previous projects and are taking proactive measures to address these concerns [32]. They are engaging with suppliers at an earlier stage and utilising suppliers with multiple supply and production options to mitigate any potential delivery constraints.

2.1.2 Social Licence Issues

Multiple stakeholders emphasised the importance of considering social license issues, which encompass various factors such as the impact on visual amenity, biodiversity, land use, culture, heritage, tourism, and bushfire risk. QUEN states "the stakeholder engagement strategy currently employed by AEMO on the VNI West Project is certainly not the template for landowner and community engagement" [39]. In response, AVP and Transgrid assured the community they commit to the Energy Charter Better Practice Guide to Landholder and Community Engagement Guidelines [40] to mitigate conflicts developed by the co-existence between transmission infrastructure and communities [32].

The Hepburn Shire Council emphasised the impact of the project on the landscape, highlighting the need to address the "specialness" of the landscape and its impact on the future aspirations of the community [41]. The VFF discussed the impacts of the project on regional agriculture, highlighting transmission lines will impact the use of large tractors and irrigation while also rendering digital agriculture incompatible, such as GPS enabled tractors, auto steer and drones [42]. This impact on agriculture production is said to threaten regional jobs in manufacturing and there were concerns that it would also lead to the introduction of biosecurity risks due to the spread of invasive species between properties from construction vehicles.

The VFF and Hepburn Shire Council also discussed the area's vulnerability to bushfires. Hepburn Shire Council discussed the grass and canopy fire risk already present in the region, which is increasing due to climate change. They state the "community simply will not tolerate increased fire risk" and how aerial firefighting is limited near transmission lines, further increasing the dangers [43]. Their submission referenced the collapse of six transmission towers during the Cressy 500 kV Tower Incident in January 2020 due to a convective downburst caused by a severe weather event of high winds [44]. They also mentioned the Kincade Californian fires, which were found to have been caused by failed Pacific Gas & Electric (PG&E) transmission infrastructure which destroyed 374 residential and commercial structures [45]. In response, PG&E implemented undergrounding plans to high fire threat areas for fire risk mitigation [46], prompting Hepburn Shire Council to question the need for overhead lines highlighting their desire to keep communities safe. VFF highlighted the potential delays of fire response due to the prohibition of access of fire trucks under transmission lines according to the Country Fire Authority's Standard Operating Procedures [42]. They state permission is also required from the transmission line owners for aerial helitankers to fly above transmission lines, which can also significantly delay responses which will further endanger communities.

Swan Hill Rural City Council highlighted the importance of benefit sharing with local communities, ensuring that investment in new transmission infrastructure will improve the reliability of local power supplies, particularly in communities that will be hosting infrastructure [47]. The City of Greater Bendigo further emphasised the requirement for community benefit sharing models that extend beyond directly affected landholders and can contribute to the local economy. This includes utilising local suppliers, creating opportunities for community investment structures, establishing opportunities for local training and employment and maximising opportunities for development of complementary industries in the region [48]. CVGA proposed training for future employment in the renewable energy sector, grant programs, and local energy projects investments to reduce power bills, enhance reliability, address local energy needs, and strengthen community resilience [32].

City of Greater Bendigo [48], another individual [49], VFF [42], and Hepburn Shire Council [41] also suggested that the potential negative impacts of transmission infrastructure could be mitigated by co-locating it with existing infrastructure or constructing it underground. Hepburn Shire Council insists undergrounding is more reliable, efficient and has a reduced impact to social and environmental factors. They state there is:

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

It was also suggested the cost of undergrounding is overestimated. For example, questioning the claim that underground cables are 17 times more expensive than overhead [49]. Hepburn Shire Council suggest AusNet's estimation that undergrounding the HVAC transmission line along their proposed routes would cost approximately 16 times more is based on inaccurate information and has been challenged by Amplitude on behalf of Moorabool Shire [41]. Amplitude Consultants estimate the cost of underground HVDC to range between 3.15 and 5.7 times the cost of an overhead HVAC solution [50]. Snowy Hydro commented on the estimated costs and duration of the HumeLink project (see Section 1.8) and highlighted how this excessive cost is not sustainable [51]. AVP and Transgrid maintain that the cost of undergrounding VNI West would be higher compared to using overhead lines and that undergrounding would introduce significant delays to the construction timetable [32]. AVP and Transgrid do not consider undergrounding VNI West a realistic option.

2.1.3 Transparency and Meaningful Consultation with Stakeholders

Mount Alexander Shire Council noted extensive engagement with both the Council and the community is crucial in order to thoroughly comprehend the proposed measures aimed at mitigating any potential adverse effects on local amenities, cultural values, and the environment [52]. Swan Hill Rural City Council also encouraged the AEMO to collaborate with local government authorities in placing new transmission infrastructure away from farmland and built-up areas to support renewable energy generation [47]. Hepburn Shire Council commented on the need for Traditional Owner engagement throughout all stages of the process [41]. These submissions had important themes involving being transparent on what are negotiable and non-negotiable aspects of the project which can be influenced by the community.

Concerns were also raised regarding the transparency of the RIT-T. AiGroup highlighted the need for the transparency of the RIT-T cost benefit analysis process to gain consumer support [32]. AusNet recommends adopting VTIF's approach to enhance "early and meaningful" engagement via thorough consideration of social, cultural, and environmental factors through a multicriteria analysis and strategic land use assessment, as well as outline how local communities are likely to benefit from the development [53]. As a response, AVP and Transgrid provided more information regarding how benefits are estimated, market modelling constraints, cost estimates, the projects interaction with the WRL, and the consistency with government policies relating to emissions and renewable generation. AVP and Transgrid assure they will receive confirmation from the AEMO that the project remains on the ISP optimal development path and delivers positive market benefits to provide confidence to stakeholders that the project will still provide a net positive benefit to consumers [32].

2.1.4 Support Alternative Interconnection Corridors, Further West in Victoria

This includes consultation of the route alignment options, as proposed by AusNet, Moorabool and Central Highlands Power Alliance and Hepburn Shire Council, which originally traversed the area between Bendigo and Ballarat. RWE and Hepburn Shire Council suggested the corridor should be moved further west along a Bulgana to Kerang corridor. As highlighted by RWE [54] this route offers lower density dwellings, increased wind resources, larger agriculture properties, less native vegetation and ecological constraints, fewer regions of cultural heritage sensitivity, and reduced flood risk. GNET note that a route situated further west will not impact constructability and will 'open up increased renewables generation, with greater social acceptance' [55]. This is further supported by the Hepburn Shire Council, who suggests this route is likely to impact fewer properties, communities and valuable natural resources than the proposed link via Bendigo [43]. As a response to the stakeholder feedback, AVP and Transgrid considered five new options that connect VNI West to WRL further west than originally proposed, which account for more factors which impair social licence. These include [32]:

Table 5 VNI West Route Options

Option	Description
Option 1 (to north of Ballarat)	Connects from Dinawan, via the new terminal station near Kerang, to WRL at the proposed terminal station north of Ballarat, and routes via Bendigo.
Option 1A (to north of Ballarat with spur uprate to 500 kV)	Additional spur involving uprate of WRL from the proposed terminal station north of Ballarat to Bulgana from 220 kV to 500 kV following the same WRL route for much of the length except for a slight variation around Waubra
Option 2 (to north of Ballarat plus non-network)	Same as Option 1 but with a virtual transmission line involving batteries at South Morang and Sydney West commissioned in 2026-27.
Option 3 (to Waubra/Lexton)	Connects from Dinawan, via the new terminal station near Kerang, to WRL at a new terminal station in the Waubra /Lexton area (Djaara Country), and routes via Bendigo. This option requires relocation of the WRL proposed terminal station north of Ballarat to near Waubra/Lexton and uprate of the proposed WRL transmission line from north of Ballarat to Waubra/Lexton from 220 kV to 500 kV
Option 3A (to Waubra/Lexton with spur uprate to 500kV)	Additional spur involving uprate of WRL from the proposed terminal station in Waubra/Lexton (Djaara Country) to Bulgana (Wotjobaluk Country) from 220 kV to 500 kV following the same WRL route for much of the length except for a slight variation around Waubra
Option 4 (to Bulgana via Bendigo)	Connects from Dinawan, via the new terminal station near Kerang, to WRL at a new terminal station near Bulgana (Wotjobaluk Country), and routes via Bendigo. This option requires relocation of the WRL proposed terminal station from north of Ballarat to Bulgana (Wotjobaluk Country) and the uprate of the proposed WRL transmission line from north of Ballarat to Bulgana from 220 kV to 500 kV.
Option 5 (to Bulgana)	Connects from Dinawan, via the new terminal station near Kerang, directly to WRL at a new terminal station near Bulgana (Wotjobaluk Country). This option requires relocation of the WRL proposed terminal station from north of Ballarat to Bulgana and the uprate of the proposed WRL transmission line from north of Ballarat to Bulgana from 220 kV to 500 kV following the same WRL route for much of the length except for a slight variation around Waubra

2.1.5 Interaction with the Western Renewables Link

Several submissions queried whether the modelling underlying the PADR treated the interaction between VNI West and the WRL appropriately when determining both the costs and benefits of VNI West. The EGA highlighted how the WRL is treated as an anticipated project as the proponent has not obtained all required consents, approvals, and licenses [56]. Should the WRL not proceed, they claimed this will significantly impact the benefits claimed in the PADR. EGA suggests the RIT-T should consider a counterfactual where the WRL does not exist.

Moorabool and Central Highlands Power Alliance highlighted the inadequacy of the VNI West project's component costs as the components of the WRL are only being built to facilitate VNI West and is claimed as difference in timing of transmission benefits from VNI West [57].

VEPC raised concerns, stating that a significant portion of its costs has been excluded and not evaluated elsewhere [58]. They argued that the expenses related to the North Ballarat Terminal Station and the North Ballarat to Sydenham 500 kV uprate should be considered in the assessment of VNI West for the RIT-T.

In response, AVP and Transgrid constructed an alternative base case that excludes not only the VNI West investment but also the WRL project [32].

2.1.6 Interaction with other major NEM projects

The EUAA raised several points regarding the assessment of VNI West in the PADR [59]. They sought clarification on the assumed timing of EnergyConnect and HumeLink, as well as requested sensitivity testing to evaluate the impact of any delays in these projects. They also highlighted the benefits derived from connecting HumeLink to EnergyConnect and questioned the impact of the EnergyConnect and VNI West connection at Dinawan on the claimed benefits for VNI West. Additionally, they expressed concern about the assumed commissioning date of Snowy 2.0, and the timing of other major transmission augmentations mentioned in the PADR, such as EnergyConnect and HumeLink.

AVP and Transgrid assure the delays in EnergyConnect and HumeLink projects, which are commissioned between three to twelve years before VNI West, will still result in their commission prior to the VNI West project and any impacts arisen from the delay is assumed to be minimal [32]. They state deferred capital investment will not affect investment decisions as this is a major source of market benefits which investors have already considered. They claim delays are expected to not impact benefits such as fuel cost savings from the VNI West commission, and therefore AVP and Transgrid have not included a sensitivity test in relation to any such delay. Similarly, they claim delays in Snowy 2.0 is not anticipated to significantly impact the modelled benefits of VNI West. They suggest there is no double-counting of the expected benefits between VNI West and other major projects in the NEM. RIT-T modelling includes other major network projects in both the counterfactual base and the option cases and no other project benefits have been captured as part of this RIT-T

2.1.7 Consistency of the Assessment with Government Policies Relating to Emissions and Renewable Generation.

There have been raised concerns about how the RIT-T modelling incorporates government policies concerning renewable energy generation and carbon emissions levels. AusNet has expressed the need for clarification regarding the inclusion of the Victorian Government's offshore wind targets, REZ Development Plan, and the VTIF as inputs in the RIT-T analysis [53]. They are seeking information on how these factors are considered to affect the costs and benefits of VNI West. In addition, EPGA has raised inquiries about the inclusion and the potential impact of future Gippsland offshore wind generation within the modelling process [56].

AVP and Transgrid acknowledge that the modelling for the PADR initially did not incorporate the Victorian Government's offshore wind target, as it had not been officially legislated at that time [32]. In response to stakeholder feedback, it has now been included as an explicit sensitivity in the Consultation Report. The Victorian Government's REZ Development Plan and VTIF are not explicitly taken into consideration in the RIT-T analysis, and it is claimed that including them as scenario input assumptions would not significantly impact the forecast outcomes.

2.1.8 The Accuracy of the Cost Estimates Used

EUAA expressed concerns about the comprehensiveness and accuracy of the costs incorporated in the cost-benefit analysis [60]. They also requested additional information about the methodologies that were utilised in conducting the analysis such as the meaning of Class 4 estimates, whether cost estimates utilised cost data from EnergyConnect and HumeLink and whether the potential to achieve efficiencies across ISP projects is captured in Transgrid's cost estimates. AVP and Transgrid note that the cost estimates used are considered to have an accuracy of +/-30% and that the estimate class is determined by the level of maturity of the project definition deliverables [32].

The VFF expressed concerns regarding the precision of the costs incorporated in the PADR analysis and indicated that the final cost of the approved project is anticipated to surpass the projected costs envisioned during this planning phase of the project. [42]. Similarly, it was highlighted the PADR indicates that benefits from VNI West are expected to start accruing in 2023-24, even before formal project approval [61]. During the three years preceding approval, it was claimed the projected benefits amount to a substantial $726 million, accounting for approximately 25% of the total forecast benefits over the 25-year modelling period. It was questioned how the potential approval of VNI West contributes significantly to these early benefits. Considering that the project is set to commence in four years and will take another nine years to complete, there were concerns in anticipation of additional cost escalations. AVP and Transgrid have confirmed that the assessment is conducted in 'real terms', meaning that only real cost increases would be applicable, and they have conducted tests using alternate assumed network capital costs, suggesting that the main findings remain reliable despite realistic future cost increases [32].

VEPC claim AVP and Transgrid has defined VNI West in a way that excludes a large amount of its costs and these costs are not assessed elsewhere [58]. For example, they suggest the analysis conducted does not factor in the time value of emissions. Benefits projected to occur after 2049, when the power system is assumed to be fully decarbonised, have been included despite the likelihood of such benefits not materialising. Additionally, the costs associated with the North Ballarat substation and the North Ballarat to Sydenham 500 kV upgrade have been excluded from the analysis starting from the commissioning of VNI West. Likewise, the VFF expressed concerns about the unaccounted costs of the project, which encompass the loss of amenity, adverse social and environmental impacts, as well as the potential cost to agriculture and tourism [42]. AVP and Transgrid acknowledged that although the RIT-T assessment cannot directly capture these costs, the current assessment reveals that two alternative options, designed to minimise such impacts, are more advantageous for consumers when compared to the proposed preferred option in the PADR [32]. They emphasised that these factors will be further considered, and efforts will be made to mitigate them through the environmental and stakeholder consultation process that follows the RIT-T assessment.

2.1.9 Comments on the Wholesale Market Modelling

EUAA emphasised the advantages of delaying or avoiding generation and storage costs that would occur before the commissioning phase in 2031-32. They suggested that these benefits would start to materialise as early as 2023-24 under the step change scenario. AVP and Transgrid state the wholesale market modelling in the PADR assumes perfect foresight, allowing parties to adjust their investment and operational decisions in anticipation of VNI West's commissioning [32]. The change in modelling the carbon budget to discrete windows better reflects real-world observations in the NEM, where renewable development and operation of storage plants have been observed in anticipation of interconnector projects and policy changes. AVP and Transgrid note that there was an apparent misinterpretation of these PADR results and have revised the presentation of these charts to present these benefits on an annualised basis.

EGA raised concerns about potential omissions in the existing regulatory cost-benefit analysis and its application [56]. They suggested that the net benefit of the investment should be determined by considering not only the transmission investment cost but also all future costs associated with generation, storage, and transmission resulting from that investment. This should be compared against the cost of alternative investments that would be necessary if the transmission project were not constructed.

2.1.10 Queries Regarding the Methodologies Applied for the NPV Modelling and Terminal Value

According to the Summary of PADR Consultation [32], PIAC suggested the Hydrogen Superpower scenario should be excluded from the PADR as the 18% weighting in the estimated market benefits has no credibility. AVP and Transgrid note that RIT-T assessment is required to implement the weightings which are applied as part of this occurs as part of the development of the Inputs Assumptions and Scenarios Consultation (IASR) [62] under the ISP framework and the weighting is 18% [32].

EUAA questioned the assumptions of fuel cost savings beyond 2047-48 and queried on how cost of gas is going to be avoided [59]. Woodley claims avoided fuel costs are incorrectly assumed after the 25 year modelling period as there are no fuel costs to avoid by 2050 due to the absence of fossil fuel generation [61]. AVP and Transgrid state the relevance of any benefits beyond the end of the assessment period is reduced since the investment has already recovered more benefits than it has costs by the end of the assessment period [32]. EUAA question the assumptions regarding 'stranded asset risks' defining the value of capital costs at after 16 years of operation. AVP and Transgrid claim this risk is not considered to be significant as costs are expected to be paid back before the end of the assessment period.

EUAA also question the appropriateness of the 5.5% commercial discount rate and its credibility [59]. AVP and Transgrid specify the percentage is taken from the most recent ISP parameters in undertaking its cost benefit assessment [32].

Another questioned the sixteen year length of the assessment period, highlighting the absence of explanation as to why this period ends three years earlier than the ISP and before the 2050 zero emissions target [61]. He claims this length is too short considering the predicted economic life of fifty years and an even longer technical life. This inquiry was also highlighted by EUAA [59]. In response, AVP and Transgrid extended the market modelling period by two years to 2049-50 [32].

2.1.11 AVP and Transgrid Response to Stakeholder Feeback

As stated in the VNI West Consultation Report: Options Assessment [33], AVP and Transgrid updated the assessment in response to recommendations in consultation to the Project Assessment Draft Report (PADR). These include:

- Considering five new options that connect VNI West to WRL further west than originally proposed, and taking account of a wider range of factors that may impair social licence.
- Extending the modelling horizon until 2049-50 in response to stakeholder feedback.
- Updating the option costs for the New South Wales portion of investment to reflect the New South Wales Government Strategic Benefits Payment Scheme for landowners announced in October 2022
- Improving alignment to the RIT-T instrument and the Australian Energy Regulator's (AER's) cost benefit analysis (CBA) guidelines through better alignment with the 2022 Integrated System Plan (ISP) parameters in a number of ways including:
    - Applying coal retirement outcomes in the same manner across the base case and all VNI West options updated with the most recent retirement announcements including Loy Yang A retirement in 2035 and Torrens Island B Power Station retirement in 2026.
    - Representing carbon budgets better matched to the 2022 ISP, progressively tightening the carbon budgets over time to avoid trading emissions between the early years and later years of study period.
- Modelling the Dinawan to Wagga Wagga portion of EnergyConnect as being built and operated at 330 kV under the base case (as opposed to being built to 500 kV but initially operated at 330 kV, as in the PADR).
- Expanding the scope of the sensitivity analysis and boundary testing conducted, including assessing the impact of changes in transmission costs, and the Victorian Government's announced (but not yet legislated) offshore wind policy
- Increasing the transparency regarding cost estimates and approach to calculating terminal value.

2.2 Additional Consultation Report Submissions

Over 500 submissions were received from landholders and organisations providing their views on the outcome of the assessment presented in the Additional Consultation Report [33]. Approximately 96% of the submission originated from Victoria or are related to Victorian components of the project [63].

The primary concerns raised by individual submissions opposed to the proposed route option include:

Table 6 Response Themes

Theme	Number of Responses
Socio-Economic	416
Land uses	411
Alignment	401
Consultation – Planning/EIS	327
Cumulative impacts	273
Bushfire	266
Easement – Rights	257
Impact to property value	255
Undergrounding	223
Biosecurity	201
Gates/Livestock	200

The main themes present in the stakeholder feedback as highlighted in the Additional Consultation Report Submissions report [63] include:

2.2.1 Stakeholder engagement

'Many' submissions expressed significant concerns regarding stakeholder consultation. This includes the lack of awareness among potentially affected communities about project changes with an insufficient six-week consultation period for potentially impacted stakeholders to make informed submissions. Additionally, the inadequate level of information provided which hindered stakeholder's ability to offer well-founded feedback. There were also concerns regarding the complexity of the information presented which made it challenging for communities to comprehend. Engagement prior to the NEVA order also fell short of best practices, particularly in terms of engagement timeframes. In response, Transmission Company Victoria (TCV) and Transgrid state they will commit to:

- Regionally focused engagement with communities, Traditional Owners, and stakeholders, to understand inherent values, opportunities, and constraints as inputs to a corridor definition process.
- Establishing Community Reference Group/s, to collaborate with the project teams, providing local information and insights to further develop and refine the study corridor.
- Undertaking direct engagement with potentially affected landholders, with dedicated landholder liaisons, to identify the best route alignment and optimise the route based on localised property constraints.
- Engaging with landholders to agree on access arrangements that minimise disruption prior to commencing field studies to inform the environmental assessment.

2.2.2 Agricultural Impacts

Of the 534 submissions, numerous raised concerns regarding limitations on farming operations. This included inability to use machinery, drones, autonomous vehicles or irrigate under transmission lines, decreased land value, insurance considerations, division of paddocks and financial implications of securing work permits. These submissions included the Loddon Shire Council [64] as well as The Victorian Farming Federation who highlight it is the agricultural industry that is forced to bear costs of transmission infrastructure [65]. There were also complaints of property land access such as failure to provide notice of entry or use of chemicals, the spread of weeds, damage to crops and soil due to heavy machinery, failure to close gates and materials left on site causing damage to machinery. AVP and Transgrid assure all they will comply with the consent to enter under conditions such as appropriate access processes for their property, including biosecurity management, gate management, timing, livestock or crop awareness and repairing any damage that might unintentionally be caused.

2.2.3 Bushfire and Weather Risks

Numerous submissions also highlighted risks such as towers falling from severe weather conditions and causing fires, and the inability of firefighters to operate equipment under the transmission lines or use helicopters above. A community member from Blampied Victoria highlighted the Cressy collapse which passed $25.04 million onto energy consumers [66, p. 3]. Another member from Bacchus Marsh highlighted the Bushfire Royal Commission recommendation to have powerlines undergrounded to avoid risks associated with bushfires [67, p. 59]. A submission from the Northern Grampian Shire Council questioned which safety controls are in place and highlighted instances of dust and moisture creating a conductive layer, allowing for electrical tracking or leakage currents [68]. Snowy Hydro commented on the importance of bushfire management to enhance social licence [69]. Mountain and Bartlett discussed the increased likelihood of severe weather from climate change such as lightning, severe winds and bushfires while also commenting on terrorism and military attacks [70]. AVP and Transgrid maintain these risks are considered in infrastructure design to ensure vegetation clearance is maintained, can withstand weather conditions and implement Safety in Design processes. They state they will be constructed with relevant safety management plans, hot work procedures, appropriate staff training and coordination with local Metropolitan Fire Service and Country Fire Service. They claim they will conduct routine maintenance to identify faults, as well as ground, aerial, weather and vegetation inspections and monitoring.

2.2.4 Health and Safety

Approximately 20% of submissions raised concerns about mental health effects such as anxiety during all stages of the VNI West project. A community member from Kanya Victoria referenced the National Farmers Wellbeing Report [71] and commented on how close to half of Australian farmers have had thoughts of self-harm or suicide, while close to a third have attempted self-harm or suicide [72, p. 68]. There were also multiple submissions questioning the risks associated with cancer and electromagnetic fields, referencing the World Health Organisation classification of EMFs as 'possibly carcinogenic to humans', and how transmission lines have links to childhood leukemia [72, p. 90] [66] [73, p. 99]. AVP and Transgrid referenced the Australian

Radiological Protection and Nuclear Safety Advisory (ARPANSA) statement [74] that there is no scientific evidence to establish that exposure to electromagnetic causes health effects. Precautionary action such as monitoring electric field intensity and constructing transmission lines at least 300 meters away from residences was said to be implemented by AVP and Transgrid.

2.2.5 Regional Benefit Sharing and Social Licence

The Pyreness Shire Council suggests revenue from the VNI West project is owed back to affected communities, not just the landowners which host transmission infrastructure [75]. The Moorabool Shire Council highlighted that their region's social licence will improve if renewable energy potential is harnessed to benefit local specialisations, agricultural industries, environmental assets and residential amenity [76]. The EGA however question AVP and Transgrid assumption that wind and solar generation will boost social licence for communities, and suggest this assumption is "prudent" [77]. AVP and Transgrid claim identifying existing and new opportunities for benefit sharing for landholders and communities and is an important part of the ongoing consultation and engagement. The assumption that social licence will increase due to the ability for new generation is claimed to be based on received proposals such as the Victorian Annual Planning Review which shows currently approximately 4,400 MW of generation applications or enquiries in the Western Victoria REZ, and approximately 2,550 MW in the Murray River REZ.

2.2.6 Undergrounding

A large volume of submissions highlighted the mitigation of impacts on flora, fauna, the landscape/visual amenity, reduce bushfire risk through the implementation of undergrounding. While this option will cost more, it is believed by the Pyrenees Shire Council it will provide community benefits and enhance social licence [75]. The Hepburn Shire Council suggested at least implementing undergrounding in areas with high landscape value or home to endangered species should be considered [78]. The Northern Grampians Shire Council claim there is insufficient explanation as to why undergrounding is not technically feasible by AEMO and Transgrid [68]. AVP and Transgrid are considering partial undergrounding in areas where severe impacts cannot be avoided, but state that full undergrounding is not feasible. However, cost effective alternatives such as route diversion, screening, and line tower design will be prioritised.

2.2.7 Cost Inaccuracies

Simon Bartlett (previously a member of the National Electricity Market's Reliability Panel, a Professor of Electrical Engineering and Chief Operating Officer of Powerlink) and Professor Bruce Mountain (Director of the Victoria Energy Policy Centre at Victoria University) submitted a detailed critique of AEMO's Consultation Report [70]. They conclude that AVP has greatly underestimated the cost of combing VNI-West with the Western Renewables Link (WRL-VNI), supplying the following cost estimates:

- AVP have understated the build cost of its preferred option by $1,220m (38%) and understated the operating cost of its preferred option by $5.1bn over 50 years, or $1,012m stated as a present value (PV) in 2020/21.
- AVP's calculation of gross benefits of its preferred option of $3,921m PV is not plausible, and has been overstated by $5,185m PV, giving a (gross) detriment of $3,921m - $5,185m = - $1,264m PV. For the avoidance of doubt this disbenefit is before deducting the cost of WRL-VNI. The additional detriment (separate to the cost of WRL-VNI) will be expressed in electricity markets in the form of electricity prices that will be higher than they otherwise would be.
- After accounting for the Victorian share of the cost of WRL-VNI, a total net detriment of WRL-VNI of $6,778m stated as a PV in 2020/21.

Additionally, they listed the following impacts:

- Increase the exposure of Victoria's power system to natural disasters and terrorism risk.
- Recovering the capital outlay for the project will increase transmission charges in Victoria by at least 70%. The ongoing operation and maintenance charge will increase transmission charges by a further 25%. In round numbers, will therefore double transmission charges in Victoria.
- Affect the efficiency of the Victorian power system by wasting existing transmission capacity (the extensive 500 kV and 220 9 kV network from the Latrobe Valley to Melbourne) and forcing the development of renewable electricity in locations that are further away from Victoria's main load centre and will have a large part of their renewable energy wasted by spillage due to severe congestion on VNI West. This too will push prices up relative to what they otherwise would be.
- Will delay the transition to renewable electricity in Victoria by forcing new renewable entry to wait on the completion of this massive transmission augmentation (which is likely to take eight years to complete). It also undermines the development of onshore renewable generation in Gippsland and adjacent areas and thus wastes the capacity of Victoria's most valuable electrical transmission

infrastructure connecting the Latrobe Valley to Melbourne.

- WRL-VNI lays the foundations for massive additional 500 kV transmission developments in west, central and northern Victoria. This is likely to involve additional expenditure at least as big as WRL-VNI to follow in the decade after WRL-VNI is completed.
- VNI-W was christened "Snowylink South", and its rationale was claimed to be making the capacity of the promised Snowy 2.0 pumped hydro station available to Victoria. But WRL-VNI, according to AVP, makes no perceptible difference to the dispatch of Snowy 2.0 and in reality, Snowy 2.0 will become choked by the congestion on VNI West and HumeLink. Instead. of any gain from Snowy 2.0, AVP's analysis contends that the bulk (75%) of the benefit of WRL-VNI lies in the substitution of pumped hydro generation in Victoria by batteries in NSW.

2.2.8 AVP and Transgrid Response to Stakeholder Recommendations

AVP and Transgrid updated their preferred route in the Identifying the Preferred Option for VNI West Report [79] in response to recommendations in consultation to the Additional Consultation Report Submission. These include:

- Exploring a variant of Option 5 that is electrically similar, but with a different Murray River crossing point and higher hosting limits for renewable generation in the Murray River Renewable Energy Zone (REZ) (V2) – Option 5A.
- Exploring opportunities for VNI West to harness more renewable generation.
- Updating cost estimates to reflect latest market and labour trends as identified in AEMO's 2023 Transmission Cost Database, and the Victorian Government's recently announced additional landholder payments.

And therefore, the refined route recommended by the AVP has the following features based on stakeholder feedback:

- Option 5A presents fewer environmental constraints and avoids intercepting the Patho Plains, an area of significant grassland habitat known to support the endangered Plains-wanderer.
- Option 5A avoids passing near Ghow Swamp, a place of national cultural significance.
- Option 5A is expected to harness more renewable generation in Victorian renewable energy zones (REZs).

2.3 Compensation

The Labor Government announced additional payments for properties which host electricity transmission infrastructure at a rate of $8,000 per year per kilometre of transmission hosted, for 25 years [80]. The CVGA brings attention to the unfairness of this payment system, which puts smaller landowners at a disadvantage due to the disproportionate effects of transmission towers on their properties [34]. They state "fair payment to landholders is essential but not sufficient to secure social license for transmission projects" and highlight how the mitigation of community impact and seeking mutual value outcomes will gain social licence. The Loddon Shire Council also highlight how the infrastructure will be present for 50-100 years, impacting productive agriculture and land values, and therefore the 25 year payment period is insufficient [64].

3. Western Renewables Link (WRL)

The WRL is a new 190km long transmission line extending from Bulgana near Stawell in Western Victoria to Sydenham in Melbourne's North-West via a new terminal station to the North of Ballarat. As published in the Western Renewables Link Consultation Plan [81], the stakeholders defined in this project include:

Table 7 Key Stakeholder Members

Stakeholder group	Key members	
Host landholders and surrounding landholders	Landholders who have a proposed easement on their property	Residents with line-of-sight of transmission infrastructure (Surrounding Landholders)
Broader community members	Local community within the project Area of Interest	Victoria-wide community
Consumer representatives	Australian Energy Regulator Consumer Challenge Panel Energy Consumers Australia	Major energy users Public Interest Advisory Centre
Industry and market participants	Property developers Renewable energy stakeholders Retailers Transmission Network Service Providers (TNSPs)	Renewable energy generator developers Victorian Network businesses Energy generators
Local councils in Area of Interest	City of Ballarat* Hepburn Shire Council* City of Melton* Moorabool Shire Council*	Northern Grampians Shire Council* Pyrenees Shire Council* *Local government area that the proposed route traverses through
Members of Parliament	State Member for Sydenham State Member for Koroit State Member for Melton State Member for Buninyong State Member for Macedon State Member for Wendouree State Member for Ripon State Members for western Victoria	State Members for Western Metropolitan Federal Member for Gorton Federal Member for Ballarat Federal Member for Wannon Federal Member for Mallee

Stakeholder group	Key members	
State (Department and Ministers)	Premier Minister for Planning Minister for Energy, Environment and Climate Change Attorney General Valuer-General Minister for Jobs, Innovation and Trade Minister for Economic Development Minister for Regional Development Minister for Local Government Minister for Industrial Relations Minister for Aboriginal Affairs Minister for Water Shadow Minister for Planning and Heritage Shadow Minister for Energy and Renewables Shadow Minister for Environment and Climate Change Department of Environment, Land, Water and Planning Department of Health and Human Services Department of Jobs, Precincts and Regions Department of Transport Department of Treasury and Finance Department of Premier and Cabinet Regional Development Victoria Central Highlands Regional Partnership	Wimmera Southern Mallee Regional Partnership Victorian Planning Authority VicTrack Invest Victoria Heritage Victoria First Peoples State Relations Department of Transport and Regional Roads Victoria Agriculture Victoria Parks Victoria Corangamite Catchment Management Authority North Central Catchment Management Authority Port Phillip and Westernport Catchment Management Authority Glenelg Hopkins Catchment Management Authority Wimmera Catchment Management Authority Melbourne Water Western Water City West Water Southern Rural Water Fire Services Victoria Country Fire Authority Emergency Management Victoria Electrical Safety Commission Energy Safety Victoria Forest Fire Management Victoria Environment Protection Authority Victoria Municipal Association of Victoria
Commonwealth	Minister for the Environment Minister for Energy and Emissions Reduction Shadow Minister for the Environment and Water Shadow Minister for Climate Change and Energy Department of Agriculture, Water and the Environment Australian Energy Infrastructure Commissioner	Civil Aviation Safety Authority Grampians Regional Development Australia Melbourne Regional Development Australia The Australian Radiation Protection and Nuclear Safety Agency Melbourne Airport
Regulators and policymakers	Australian Energy Regulator Australian Energy Market Commission	Essential Services Commission
Industry Bodies and Associations	Australian Energy Council Clean Energy Council Energy Networks Australia	Central Victorian Greenhouse Alliance Highlands Potatoes and Ag Inc

Stakeholder group	Key members
Special interest groups	Grampians New Energy Taskforce Grow West Loddon Mallee New Energy Taskforce Murray River Group of Councils Wimmera Development Association Australian Wind Alliance National Trust (Victoria) Victorian Farmers Federation Victorian National Parks Association Goldfields Track Association Great Dividing Trail Association Bushwalking Victoria Eureka Orienteers Yes to Renewables Project Platypus Birdlife Australia Australian Conservation Foundation Friends of the Earth Environmental Justice Australia Federation University Bacchus Marsh, Fiskville and Melton Airfields Melbourne and Ballarat Airports.
Community groups	Key local environmental and interest groups (listed below according to LGA) Environment Victoria Western Victoria Transmission Network Project Rippon Association **Ballarat** Ballarat Environment Network Miners Rest Landcare Group Regional Sustainability Alliance Ballarat Ballarat Renewable Energy and Zero Emissions (BREAZE) Ballarat Climate Action Network Ballarat Bushwalking and Outdoor Club Ballarat Field Naturalists Club Bird Life Ballarat **Hepburn** Hepburn Wind (Hepburn Community Wind Park Co-Operative Ltd) Sustainable Hepburn Association Creswick and District Historical Society Transitions Creswick Mollongghip community energy Wattle Glen Landcare Group **Melton** Melton Environment Group Western Plains North Green Wedge Coalition Group Pinkerton Landcare and Environment group Toolern Landcare Group to Melton **Moorabool** Moorabool Environment and Sustainability Advisory Committee (Council advisory committee) Moorabool Landcare Network Moorabool Environment Group Friends of the Lerderderg Bunanyung Landscape Alliance Bacchus Marsh Community Coalition Lal Lal EPA Moorabool and Central Highlands Power Alliance Friends of Werribee Gorge and Long Forest Mallee Pentland Hills Landcare Group Coimadai Landcare Group Rowsley Landcare Group Moorabool Catchment Landcare Group Northern Grampians Wimmera Mallee Sustainability Alliance Friends of the Grampians **Pyrenees** Waubra Wind Farm Community Fund Inc. Waubra Community Foundation Other local community and action groups
Traditional Owner and Aboriginal Groups	**Registered Aboriginal Parties and Traditional Owner Groups:** Barengi Gadjin Land Council Aboriginal Corporation Dja Dja Wurrung Clans Aboriginal Corporation Eastern Maar Aboriginal Corporation Wadawurrung Traditional Owners Aboriginal Corporation Wurundjeri Woi Wurrung Cultural Heritage Aboriginal Corporation Boon Wurrung Foundation Bunurong Land Council Aboriginal Corporation

The Consultation Plan also highlights key stakeholder interests and engagement techniques highlighted below:

Table 8 Stakeholder Interests and Engagement Methods

Stakeholder group	Likely engagement interests and needs	Stakeholder approach
Landholders with a proposed easement on their land; and/or their land is proposed to be used temporarily for construction e.g. laydown	Impacts to property during construction and operation (land use, business, amenity, and environmental impacts) Access to properties for environmental investigations to inform the EES Health and safety concerns including fire risk. How feedback has been considered and/or influenced project or design decisions	Targeted approach including one-on-one meetings Community engagement sessions Webinars Mail outs Community Consultation Group (CCG) Dedicated project hotline and email Consistent point of contact with the project
Surrounding landholders Landholders who live in the vicinity of the proposed route (no specific distance) but do not have a proposed easement	Impacts to property during construction and operation (land use, business, amenity and environmental impacts) Health and safety concerns including fire risk and management Locally specific information about the project, its progression and impacts Social and economic impacts and benefits Community impacts and benefits How feedback has been considered and/or influenced project or design decisions	Community engagement sessions Webinars Mail outs Community Consultation Group (CCG) Dedicated project hotline and email Consistent point of contact with the project
Other community members	Locally specific information about the project, its progression and impacts Social and economic benefits Community impacts Amenity and environmental impacts Potential impacts to sites and areas with cultural heritage significance Local community benefits (and their equitable distribution) Economic impacts Disruptions from construction Reliability and security of network supply Input into preferred consultation approach How feedback has been considered and/or influenced project or design decisions	Up-to-date and broad project information in an accessible format Online engagement and interactive portals Virtual information and interactive information session Face to face sessions Fact sheets/printed materials Advertising Project updates Community Consultation Group (CCG)
Consumer representatives	Environmental, social and economic impacts including local benefits To be informed of approvals processes and opportunities for input Input into preferred consultation approach	Targeted meetings Project updates Fact sheets/printed communication materials
Industry and market participants	Economic and technical aspects of the project Relevant social, economic and environmental impacts Future connection opportunities Interface activities with other transmission network service providers Input into preferred consultation approach	Targeted meetings Project updates Printed communication materials

Stakeholder group	Likely engagement interests and needs	Stakeholder approach
Local councils across western Victoria	Social and economic impacts to local residents and businesses including agriculture Environmental impacts including impacts on landscape and visual amenity Potential impacts to sites and areas with cultural heritage significance Local community impacts and local jobs creation Relevant permits and approvals processes including program and coordination Opportunities for communities and stakeholders to be involved in planning and approval processes Cumulative impacts of other projects occurring in the area Access to public areas for environmental investigations to inform the EES Input into preferred consultation approach How feedback has been considered and/or influenced project or design decisions	Targeted project updates Council Advisory Group Technical Reference Group meetings Targeted meetings
Members of Parliament	Social and economic impacts and community benefits Environment and amenity impacts Potential impacts to sites and areas with cultural heritage significance Measures to avoid, minimise and manage impacts and enhance community benefit	Targeted project updates Targeted meetings
State (Department and Ministers)	Environmental assessment and planning approvals processes Social, economic and environmental impacts Measures to avoid, minimise and manage impacts and enhance community benefit Access to public/crown land for environmental investigations to inform the EES	Targeted project updates Targeted meetings Technical Reference Group meetings
Commonwealth	Environmental assessment and approval Social, economic and environmental impacts	Targeted project updates Targeted meetings
Regulators and policymakers	Environmental assessment and approval Economic and technical aspects Delivery and compliance with necessary approvals/ standards	Targeted project updates Targeted meetings Technical Reference Group meetings
Industry Bodies/ Associations	Network and economic impacts Social, economic and environmental impacts Input into preferred consultation approach How feedback has been considered and/or influenced project or design decisions	Targeted meetings Project updates Printed communication materials
Special interest groups	Environmental, social and economic impacts Potential impacts to sites and areas with cultural heritage significance Approvals processes and opportunities for input Input into preferred consultation approach How feedback has been considered and/or influenced project or design decisions	Up-to-date and broad project information in an accessible format Online engagement and interactive portals Virtual information and interactive information session Face to face sessions Project updates Factsheets/printed materials

Stakeholder group	Likely engagement interests and needs	Stakeholder approach
Community groups	Environmental, social and economic impacts Potential impacts to sites and areas with tangible and intangible cultural heritage significance Approvals process and opportunities for input Input into preferred consultation approach How feedback has been considered and/or influenced project or design decisions	Up-to-date and broad project information in an accessible format Online engagement hub and interactive portals Virtual information and interactive information session Face to face sessions Project updates Community Consultation Group (CCG) Factsheets/printed materials
Registered Aboriginal Parties / Traditional Owner Groups	Potential impacts to sites and areas with cultural heritage significance Social and environmental impacts Economic and social benefits, particularly in relation to Aboriginal participation and employment opportunities Land management issues for Crown land subject to (or under negotiation for) Land use Activity Agreement Input into preferred consultation approach How feedback has been considered and/or influenced project or design decisions	Targeted project updates Targeted meetings

AusNet Services has established the CCG with the aim of enhancing community understanding and engagement with the project as highlighted in the Community Reference Group's Terms of Reference [82]. These groups comprise of up to 20 community representatives selected from Northern Grampians Shire Council, Pyrenees Shire Council, City of Ballarat, Hepburn Shire Council, Moorabool Shire Council, and Melton City Council. The CCG have set objectives that include creating a transparent and accessible forum for discussing community-related project issues, capturing community feedback to aid decision-making, increasing community awareness about the project, advising on effective responses to concerns, and recommending benefit sharing initiatives. CCG members serve as channels for wider community issues, represent community perspectives on local impacts and benefits, receive project progress briefings, and share project information with other community members.

3.1 Undergrounding

Community concerns were raised about the limited consideration of social and environmental impacts in the RIT-T assessment, focusing primarily on economic factors as highlighted in the Role of RIT-T Report [83]. They found there was insufficient detail provided regarding undergrounding and partial undergrounding options. The community seeks more information on alternative options considered in the RIT-T process, aiming for transparency, and understanding.

Concerns were expressed that the undergrounding option was dismissed without a comprehensive cost-benefit analysis considering social and environmental impacts. The report suggested high-level assessment showed that underground transmission cables would be significantly more expensive, up to ten times the cost per kilometre compared to overhead lines. Given the cost difference without additional economic benefits, undergrounding options were not justified under the RIT-T regulations.

Inquiries were made about the consideration of High Voltage Direct Current (HVDC) in the RIT-T process. HVDC equipment was considered but deemed economically infeasible due to higher overall costs compared to High Voltage Alternate Current (HVAC) solutions. HVDC offers technical advantages but requires additional infrastructure to link with the existing HVAC network.

Concerns were also raised about the possibility of passing on additional costs associated with undergrounding to consumers through increased electricity prices. The community noted that the RIT-T does not account for such options. However, AusNet claims its primary purpose is to identify the most efficient option that minimises consumer costs for electricity.

During an April 2021 CCG meeting, the participants engaged in a discussion regarding the various possibilities related to undergrounding. A representative from AusNet services emphasised that undergrounding is not currently being recommended under the RIT, and its consideration is limited to the EES process, specifically addressing alternative options scoping requirements [84]. Consequently, it was concluded that undergrounding would not be included in the delivery contract.

AusNet's Underground construction summary [85] explores various possibilities for minimising impacts along the route. These options, including different designs, structures, and sections of underground construction, will be further examined as part of the Environment Effects Statement. Partial underground alternatives need to be assessed to determine their feasibility and effectiveness in mitigating identified high-impact areas. However, AusNet claims while overhead transmission lines cause less ground disturbance and offer more cost-effective connections for renewable energy generators, they also meet the requirements for electricity system availability and reliability. Overhead transmission lines are a proven solution for projects of this scale and distance. The report claims preliminary estimates suggest that using HVAC technology for underground construction of the Western Renewables Link would cost at least 16 times more than an equivalent overhead transmission line. Therefore, AusNet states overhead construction is most feasible for the full length of the project.

3.2 Compensation

As outlined in the Option for Easement Process and Compensation Guide [86], a summary of payments and compensation includes:

Table 9 Summary of Payment Options

Payment	Amount	Description
Landholder Participation Fee	$10,000 (excl. GST)	Payable to landholders upon completing the Property Specific Details Form and signing the Land Access Consent
Landholder Professional Fees payment	$10,000 (excl. GST)	Eligible if receive the Option for Easement proposal.
Additional legal and professional fees	As agreed	Upon request, we may agree to reimburse further reasonable out of pocket legal costs and professional service provider fees that exceed the Landholder Professional Fees payment
Option Fee	$20,000 (excl. GST)	Payable after the Option for Easement is signed by both parties, as set out in the Option for Easement.
Option Extension Fee	$15,000 (excl. GST)	Payable to extend the initial option period of the Option for Easement by one year
Compensation for Easement Amount	Property specific	The Compensation for Easement Amount is a market value assessment of the easement
Other Compensable Amount	Property specific	A percentage of the Compensation for Easement Amount (excl. GST) payable to landholders to allow for other compensation requirements.
Option Exercise Disturbance Fee	Property specific	Includes Production Loss Fee, which is an agreed amount for the value of lost crops and/or other disturbance due to construction activities, and Construction Licence Fee, amount equal to one year.
Construction Licence Fee	Property specific	Compensation for any loss, impact or interference with land use as a result of required construction activities payable annually
Land Rehabilitation Offset Payment	Property specific	Compensation for any residual impact on land use in the 12 months following the completion of construction. Covers a period of 12 months after the completion of construction and is equal to the previous year's Construction Licence Fee
Reimbursement of reasonable legal fees and disbursements associated with registration of the easement	Up to $2,500 (excl. GST)	reimbursed for the reasonable legal costs related to the registration of the easement and any reasonable disbursements made for the purposes of registering the easement

Payment	Amount	Description
Reimbursement of mortgagee or other third-party consent fees	Up to $1,000 (excl. GST) per consent required	If any mortgagee or other third-party holds an interest in a landowner's property, they will need to obtain their written consent for the Option for Easement. AusNet will reimburse reasonable costs of, and incidental to, securing these consents.
Additional landholder payments	Payment of $8,000 per year per kilometre of new transmission easement hosted, for 25 years	In addition to the compensation and payments as required under the Land Acquisition and Compensation Act 1986 (Vic)
Community Benefit Fund	Waiting on approval within AusNet to total funding amount	Enabling local not-for-profit groups, organisations, and projects to make a positive long-term contribution to the communities within the project area.

In the renewable energy sector, wind developers offer payments to community members based on the distance between their residences and the turbines, as well as the number of turbines within that distance. A CCG member highlighted that although these payments are not mandated by law, it is important for AusNet to recognise the significance of negotiating compensation based on proximity to the infrastructure for ensuring best planning practices and obtaining social licence for the project [87].

A CCG member highlighted the importance to differentiate the Community Benefit Fund (CBF) from compensation as the CBF is not intended to address visual impacts, and it may be seen as unfair that the community as a whole receives benefits while individuals bear the negative impacts [87]. Another member highlighted how these benefits should be granted to impacted communities, not to energy start-ups or for-profit groups [88]. There were also speculations that AusNet are providing these funds as they are 'wanting to buy influence'.

Another member highlighted the Land Acquisition and Compensation Act does not apply to neighbours of easements and does not allow for compensation [87]. They highlight how these community members bear the consequences of the transmission line implementation but are not compensated for it.

3.3 Bushfires

The community have voiced their worries regarding bushfires, which include concerns regarding [89]:

- Fires starting due to project infrastructure.
- Effects on bushfire management, such as planned burning to decrease fuel, ground-based and aerial fire response, and back-burning.
- Difficulties in escaping forest areas during a bushfire event.
- The worsening of fire weather conditions and fire risk due to climate change.
- The impact on Coimadai Primary School, which is identified as at risk in the Bushfire Register.

During a community webinar [90], it was brought to attention that AusNet faced a class action due to its involvement in the 2009 Black Saturday bushfires. The infrastructure was found to have contributed to the fires, leading to concerns about similar sparking incidents within the WRL easement. The Royal Commission investigating the bushfires recommended exploring the feasibility of underground power lines for future installations to reduce the risk of sparking and subsequent fire incidents caused by infrastructure failure, enhancing safety and resilience [91, p. 29]. AusNet noted that the Royal Commission acknowledged that the AusNet transmission network had not caused any fires. The recommendations for undergrounding transmission lines primarily apply to lower voltage lines in the distribution network, not the higher voltage lines (220 kV and 500 kV) in the current transmission network project.

There were also concerns raised regarding operations of firebombing over transmission lines in another webinar session [92]. An AusNet member confirmed they do operate firebombing on powerlines, highlighting its use in East Gippsland. In the event of water bombing operations on power lines, AusNet claim there are protection systems in place to respond accordingly. While such operations may cause some damage, the primary concern is cleaning the insulators before restoring power. The insulators may accumulate residue or retire due to water exposure, necessitating cleaning before reactivation.

During a community webinar [89], an AusNet member highlighted a review conducted by the Victorian Auditor General, in which the average number of fire ignitions from various sources over a 30-year period was examined using data from the Department of Environment, Land, Water, and Planning (DELWP). The main causes of fires in the landscape were campfires, lightning, deliberate lighting, and unknown sources [93, p. 21]. Notably, there were no records of bushfire ignitions associated with transmission networks. However, an average of seven fires per year were started by distribution powerline networks, which consist of smaller, lower voltage poles and wires, differing significantly from the infrastructure discussed in this project.

In the same webinar, there were concerns regarding increased fire risk due to climate change. The AusNet member highlighted climate change under a high emissions scenario can have significant implications for the project's 50-year lifespan. He stated projections for 2070 show reduced winter and spring rain in Victoria, leading to drier fuel conditions and increased fire risk. Higher temperatures, extreme heat, and slightly reduced humidity contribute to these changes. This results in fewer days in the low to moderate fire danger range, with an increase in severe fire danger. To mitigate the potential for fire ignition and enhance fire management, the AusNet member suggested several measures which can be taken. These include managing human causes of ignition and implementing practices to contain fires more effectively. This may involve cultural burning practices, fuel reduction burning, and allocating resources to agencies for improved fire detection and response capabilities. The focus is on preventing ignition and promptly addressing fires to minimise their impact.

3.4 Landscape and Visual Amenity

During a webinar [94], a participant expressed concerns on behalf of landowners residing in AusNet's area of interest. The participant mentioned that these landowners have deliberately chosen to live in the community due to the picturesque views of rolling green hills, which provide a source of solace and relaxation, instantly alleviating the stress of the day. According to the participant, the proposed project has the potential to strip away this cherished landscape, impacting the well-being and enjoyment of thousands of individuals. In response, AusNet addressed the issue by stating that they are actively assessing old heritage sites, considering tourist routes and significant landscapes throughout the region. They aim to strategically position the infrastructure to mitigate these effects and to minimise these impacts, and they will leverage topography and other natural barriers present in the landscape. Another AusNet member claimed they aim to avoid placing the lines on top of hills and instead explore routes around hills to utilise the natural terrain for concealing the transmission lines to some extent. In certain areas, AusNet may consider using smaller towers or splitting the line to reduce the visual impact, even if it requires expanding the easement width in specific locations. They are also exploring options such as non-reflective coating for the structures to make them less prominent in the landscape.

The community provided feedback on the importance of landscapes such as volcanic cones, tourist spots, and night sky views [95]. Concerns were raised about the accuracy of images and how AusNet addresses the perception gap between photos and reality [96]. AusNet then claimed to focus on important community locations and use a 60-70mm lens for depth and scale. They layer the imagery as a 3D model, test it in the field, and ensure is accuracy. AusNet considers night-time impacts and follows Australian Standards to control obtrusive lighting effects, taking existing lighting into account. A CCG member expressed concerns over a heritage bridge that has well-established vegetation. AusNet assures that the impacts on cultural values, indigenous cultural heritage, flora, and fauna are being studied. The assessment will be conducted by the appropriate technical experts to address these concerns.

In a community webinar [92], there were concerns raised regarding loss of property value due to transmission infrastructure. An AusNet member highlighted that compensation is provided to these landowners to ensure they are not financially worse off. The compensation calculation considers various factors, including the property's existing use, market value, expected depreciation, disturbance to farming activities, and special value. Further concerns were raised questioning compensation for landowners with affected visual amenity but who do not host any infrastructure. Compensation for landowners is directly related to the acquisition of the easement. The AusNet member reiterated that compensation serves as a baseline and aims to mitigate the impacts caused by the project. Efforts are made to minimise the visual impact of the infrastructure by carefully selecting its location. While complete mitigation may not be possible, steps are taken to reduce the overall impacts in affected areas. Another AusNet member highlighted that, in line with AusNet's intention to give back to the community, a multimillion-dollar benefit community fund has been established. This fund will be allocated based on the requirements, inputs, feedback, and contributions from the community. The aim is to ensure that the community benefits from the project and has a say in how the funds are distributed.

3.5 Health and Safety

During a community webinar session [92], viewers raised concerns regarding associations between EMF and leukemia. In another community webinar session

[90], according to a representative from AusNet, transmission lines will not be constructed in close proximity to existing dwellings. The representative suggested that a corridor of approximately 80 to 100 meters would be required for a 500 kV line, guaranteeing that there is no overlap with residential areas. Furthermore, the representative stated that existing peer-reviewed studies have not found any conclusive evidence of health effects from living within a safe distance from transmission lines. However, they emphasised the need to consider factors such as field strength, proximity, and duration of exposure. To address proximity concerns, AusNet adheres to strict design guidelines and maintains clearances defined by the Australian Radiation Protection and Nuclear Safety Agency. Additionally, tower heights are designed to accommodate the lowest point of the conductor, ensuring a minimum clearance of 15 to 20 meters.

There were also concerns regarding lighting strikes and flashovers [97]. AusNet claimed there are protection systems in place which can detect when electricity is trying to flash over between the conductor through to the Earth's structure, and it will operate within milliseconds. Regarding lightning, AusNet stated all of their towers are equipped with grounding systems. They have an aerial earth that attracts lightning before it reaches the conductors. In the event that lightning does hit the conductors, AusNet claim their protection systems will detect the overcurrent caused by the strike and promptly trip off to prevent further risks.

Concerns raised regarding the collapse of six Cressy AusNet towers in February 2020 [44] highlight how the incident does not instil confidence in the community [94]. AusNet acknowledges this incident and are actively investigating the matter. They claim feedback and analysis from this investigation will play a significant role in designing the transmission towers for the current project. They claim the collapse occurred under extreme weather conditions in Western Victoria, which are rare occurrences.

3.6 Cultural and Heritage Sites

The topic of impacts to culturally significant sights in a community webinar was discussed [97]. An AusNet member assured a comprehensive Aboriginal Cultural Heritage Assessment will be conducted to understand the landscape and both tangible and intangible Aboriginal values in the project area. Collaboration with registered Aboriginal parties will be established to ensure proper management and protection of these values. Cultural Heritage Management Plans will be developed in consultation with the representatives to address any potential impact, including the possibility of overhead line infrastructure crossing important sites. The member claims AusNet's goal is to work closely with the Aboriginal community to identify their priorities and implement measures that effectively manage and preserve Aboriginal cultural heritage values.

Several considerations have been identified in the Historic Heritage Information Sheet [98] for further investigation and management in the historic heritage impact assessment by AusNet. These considerations include assessing the potential impact of construction works on historic heritage places, evaluating the visual impacts of the infrastructure on the landscape's heritage values, identifying the presence of unlisted heritage and archaeological sites, and ensuring compliance with necessary heritage approvals and consent applications. Additionally, the assessment will consider the proposed nomination of the Central Victorian Goldfields for inclusion on the UNESCO World Heritage List. Additionally, the Geology And Contaminated Land Impact Assessment [99] will address various considerations, including the potential for land erosion, disturbance of contaminated soils, impacts on geological sites, encounter of historic mining waste, and potential contamination from landfill sites, agriculture, and a water treatment plant. The assessment will also evaluate the long-term impacts of soil chemistry on project infrastructure.

3.7 Land Access

In addressing concerns regarding access to the towers once they are installed on a property, including the installation of gates for road access, availability across the entire farm, and potential changes to fence lines and plantations, AusNet provides an explanation of their regular patrol and inspection protocols [94]. They confirm that their transmission lines are patrolled at least twice a year, which involves visual assessments of vegetation and the transmission line itself using drones and helicopters. Additionally, every six years, a climbing assessment is performed to thoroughly check the condition of the bolts and conduct an overall inspection of each tower.

In a CCG meeting [100], feedback received regarding land access raised several concerns. Firstly, the provision of vouchers to incentivise landowners to sign land access agreements created confusion and led to the perception that accepting the vouchers compromised land rights. Additionally, there were complaints about the lack of clarity in the messages conveyed through land access agreements and notices. Some landowners felt that the agreements imposed significant obligations beyond a one-time visit. Issues were also raised regarding the distribution of letters in February/March 2020 and February 2021, as not all landowners received them. Some landowners later received letters stating they were no longer in the area of interest/corridor, causing confusion about the selection process for sending letters. The letters themselves were criticised for lacking personalisation, resembling flyers rather than official correspondence, and not being placed in envelopes. Concerns were expressed that the use of postcodes for letter distribution may not accurately capture all landowners within a community. CCG members requested prior notification of letters to landowners to enable them to follow up with their communities, and AusNet clarified that this could be done at the time of letter distribution, but not before the official announcement. The credibility of AusNet land agents was questioned, particularly their lack of agricultural expertise and understanding of terminology. Lastly, confusion arose about the availability of maps, as some landowners were shown maps while others were informed that maps could not be provided.

3.8 Stakeholder Engagement

The community drop-in sessions generated several concerns among participants of a CCG Meeting [100]. Firstly, the initial round of sessions in 2020 suffered from inadequate advertisement, resulting in some community members being unaware of their occurrence. However, the second round held in 2021 showed improvement, with more effective promotion and helpful staff. Nevertheless, attendees expressed dissatisfaction with the limited notice of project changes provided and the long waiting times at certain drop-in sessions, which restricted their ability to discuss important issues thoroughly. Suggestions were made to implement a booking system and consider offering sessions at later times or on weekends to accommodate commuters from Melbourne. There were also reports of AusNet representatives being unable to provide satisfactory answers to questions, leading to doubts about the effectiveness of the sessions. Furthermore, community members expressed concern about the short time gap between the March 2021 sessions and the planned announcement of the single corridor, scheduled for mid-year 2021. Lastly, some participants are still awaiting responses to their feedback and questions submitted during the March sessions.

In the same meeting, feedback highlighted concerns about the effectiveness of the project phone service. Community members expressed a preference for immediate assistance rather than receiving a call back after a week. Suggestions were made to use a toll-free 1800/1300 number to eliminate call charges for callers. Additionally, there was a request for a “case management” approach, where one designated person would handle all inquiries and provide comprehensive support.

A suggestion was also made in the CCG meeting to organise a town hall meeting where community members could ask questions to a panel consisting of MPs, local government representatives, and AusNet representatives. However, concerns were raised about the perception that all panel members may be aligned in interests and views, despite potentially differing perspectives at this stage of the project. AusNet expressed a preference for smaller group format sessions that allow for a wider range of participation, discussion, and questions. It was recommended that staff involved in interactions with landowners undergo empathy training, as some interactions were perceived as unsympathetic. The group emphasised that the consultation process thus far lacked empathy and caused distress to the entire community, not just landowners.

3.9 Biodiversity

According to the Biodiversity EES Information Sheet [101], the community has shared concerns regarding the existing conditions in the project area. This includes the presence of habitat offered by hollow-bearing trees, riparian corridors along waterways, observations of diverse fauna such as kangaroos, wombats, bats, brolgas, and raptors, and the existence of rare species like Grevillea Steiglitziana and Braid Moss. They have also highlighted areas prone to landslides and important nesting sites for Yellow-tailed Black Cockatoos, as well as sightings of Little Eagles and other bird species, and the presence of platypus and Rakali around Clunes.

In response, a range of considerations have been identified by AusNet for further investigation and management in the biodiversity impact assessment. These include the potential impacts of construction and easement management on threatened flora and fauna species and communities, loss of native vegetation and habitat fragmentation due to clearing, disturbance of native fauna during construction, interference with waterways and wetlands, collision threats to threatened bird or bat species, potential disturbance caused by operating transmission lines, the transmission lines acting as vantage points for predators, and the risk of spreading weeds, pests, or other biosecurity concerns during construction.

3.10 Electromagnetic Fields

During a webinar addressing safety concerns [102], an AusNet spokesperson highlighted the extensive biological studies conducted over the past 40 to 50 years. He suggested these studies consistently found no adverse human health impacts resulting from extremely low-frequency EMFs. The concerns raised by the community regarding the potential impacts of EMFs on livestock have also been thoroughly studied. For instance, he referenced a comprehensive study in Ohio which examined dairy cattle behaviour and production on 18 farms located directly under a 765 kV high-voltage line, with no reported impacts. Similarly, he cited a study in Canada involving various animals near high-voltage lines, including sheep, pigs, horses, and beef cattle, which found no observed health effects.

He stated ARPANSA, the Australian Radiation Protection and Nuclear Safety Agency, recognises the ICNIRP guidelines as international best practice for safeguarding against the potential effects of EMFs [74]. These guidelines establish reference levels for public exposure to EMFs, with limits of 5 kV per meter for electric fields and 200 micro-tesla for magnetic fields. He emphasises measured EMF levels in common household settings and near power lines are considerably lower than these reference levels.

A viewer questioned the safety of pacemakers around electromagnetic interference. Pacemakers and other active implantable medical devices can be sensitive to electromagnetic interference (EMI) generated by high fields around transmission line conductors. The AusNet spokesperson stated manufacturers design these devices to be immune to magnetic fields within reference levels (around 200 micro-tesla). He indicated pacemakers have fail-safe mechanisms that switch to a fixed pacing mode in case of EMI, which is uncomfortable but not medically significant.

A viewer asked if EMI would impact GPS systems. While heavy rain can have some effect on electromagnetic interference from transmission lines, the AusNet spokesperson stated the emissions in question are generally in a frequency range of about 500 kilohertz to 1.5 megahertz, which primarily impacts AM radio. He stated GPS systems, on the other hand, operate at much higher frequencies that are well above this range. Therefore, the transmission line emissions are unlikely to interfere with GPS devices, and there should be no significant impact on GPS functionality.

3.11 Route Refinement Decisions

As presented in AusNet's Updated Proposed Route Overview [103], community and stakeholder feedback, combined with the findings of technical studies, field surveys and investigations, have informed the selection of AusNet's proposed route.

In Bolwarrah, the new route aims to minimise impacts on heavily vegetated areas and potential Aboriginal cultural heritage, while maximising the use of cleared land. Although some clusters of endangered Brooker's gums may still be impacted, efforts are made to avoid a large cluster. The route also takes into consideration the protection of native vegetation and potential habitat for endangered species such as greater gliders, powerful owls, and other threatened and native species. Additionally, it avoids a wetland adjacent to the Moorabool River West Branch, which serves as potential habitat for growling grass frogs, and maximises the distance to houses in the Tooheys Close area, reducing visual impact through screening.

For the section from Mt Steiglitz to Korjamnunnip Creek, the proposed route increases the distance from houses and minimises land use impacts.

In Myrniong, the transmission line route aims to reduce the visual scale of the towers from the township by increasing the distance between the line and the town. It is located in an area where it can be screened or filtered from views along Mt Blackwood Road. The route also increases the distance to some houses on farming land and is set against the backdrop of forested hills and ridges of the Lerderderg State Park, reducing visual impacts on adjacent houses. Efforts are made to minimise impacts on the area of cultural sensitivity associated with Myrniong Creek and its potential for Aboriginal cultural heritage.

In the Darley military camp area, further refinements are proposed to reduce impacts on the military camp site and Grey Box Grassy Woodlands.

Regarding the Merrimu Reservoir, the route has been planned to avoid impacts on the significant ecological values of Long Forest and Aboriginal cultural heritage sites. It maximises the distance to residential properties south of the Diggers Rest–Coimadai Road, as well as the Symington Road and Moonah Drive areas. To preserve the Coimadai Avenue of Honour and mitigate potential social impacts, the route crosses the Diggers Rest–Coimadai Road east of this community asset. It traverses disturbed areas with little tree cover and avoids potential impacts on any future Merrimu Reservoir dam wall upgrade works. The route also minimises impacts on Southern Rural Water's existing quarry operations.

In the Melton-MacPherson Park section, efforts are made to avoid threatened ecological communities and bulokes on properties east of MacPherson Park. A Seasonal Herbaceous Wetland ecological community, listed as threatened, is also avoided to the north-west of MacPherson Park, along with areas of Aboriginal cultural heritage sensitivity. The route does not directly impact the sporting fields at MacPherson Park and follows the boundaries of properties to minimise impacts on landholders. Furthermore, it minimises the impact on the current operations at Melton Aerodrome.

4. Summary of Stakeholder Concerns

Table 10 Summary of Stakeholder concerns

Key Themes	HumeLink	Victoria to New South Wales Interconnector West	Western Renewables Link
Stakeholder Engagement	**Stakeholder engagement:** Community engagement lacked transparency, with unclear decision-making responsibilities, notification procedures, and opportunities for community input. Only landowners within the project corridor were involved, excluding adjacent landowners. Landowners felt their concerns were misunderstood and were treated disrespectfully. Project materials lacked currency and user-friendliness. Alternative options and landowner feedback were not given sufficient consideration. **Compensation:** Neighbouring properties suffer from the decrease in property evaluation, but do not receive compensation	**Stakeholder engagement:** Late communication to potentially impacted communities, insufficient time for informed submissions, inadequate information provided, and difficulties in understanding the project details for communities and landowners. **Social licence:** Offering opportunities for local renewable energy projects would increase acceptance of hosting transmission lines. It was recommended that the project consider the effects on communities early on, considering land uses, local government perspectives, and landscape considerations. Additionally, questions were raised regarding the assumption of social acceptance for wind and solar energy projects.	**Stakeholder engagement:** Inadequate advertisement of community meetings, dissatisfaction of notice of project changes, long wait times for community drop-in sessions, unsatisfactory answers to questions, doubts of effectiveness of sessions. **Compensation:** Some landowners felt benefits should be granted to impacted communities, not to energy start-ups or for-profit groups. Some compensation does not apply to neighbours of easements. Speculations that funds are serving to buy community influence. the provision of vouchers to incentivise landowners to sign land access agreements created confusion and led to the perception that accepting the vouchers compromised land rights.
Proposed alignment	**RIT-T:** Does not consider the cost of the environment and is insensitive to environmental impacts.	**Multi-Criteria Analysis:** The study lacked comprehensive engagement and failed to consider social constraints accurately. Agricultural impacts, mental health, and community opposition was not adequately considered. The MCA ratings lacked justification, and economic factors were prioritised over social, cultural, and environmental aspects. Regional plans and development directions were not adequately considered. Modelling overlooked land value impacts, carbon footprints, and the effects on agriculture and tourism. Errors in cost: accuracy of line length calculations, missing cost components, understated easements and easement taxes, low-cost estimates for power flow controllers, understated OPEX costs, and the exclusion of future network investment	**RIT-T:** Focused primarily on economic factors with insufficient detail provided regarding undergrounding and partial undergrounding options.
Impacts on land use and property	**Tourism:** Impacted due to the obstruction of natural landscapes due to transmission towers **Traffic and roads:** Temporary increases in traffic on local roads affects performance of the road network, construction may cause deterioration of road conditions, air quality affected due to construction trucks causing dust. **Noise and Vibration:** Lack of noise monitoring for landowners who claim they can hear constant humming, noise and vibration can affect the mental health of livestock	**Impact to farming operations:** Inability to use machinery, irrigation, and GPS technologies under power lines. Paddock division, financial implications, decreased land value, and loss of productivity are further concerns. **Property access:** Lack of notice given to landowners, undisclosed chemical usage affecting vendor declarations, weed spread, failure to close gates, crop damage, machinery damage from materials left on-site, and soil impacts due to heavy machinery use.	**Landscape and visual amenity:** Landowners intentionally reside in the community because of the scenic landscape, which will be affected by the transmission lines, leading to a decline in property value. The significance of landscapes, including volcanic cones, tourist attractions, and unspoiled night sky views, is overlooked.

Key Themes	HumeLink	Victoria to New South Wales Interconnector West	Western Renewables Link
Impact on the environment	**Undergrounding:** Proposed overhead towers have numerous negative impacts, including increased bushfire risk, hindered firefighting efforts, health concerns from electromagnetic fields, unusable farmland, industrialised landscapes, decreased property values, habitat destruction, disruptions to aerial and drone activities, interference with GPS signals, threats to animal habitats, constant noise, and vulnerability to storms. The Undergrounding Study report faced criticism for focusing on negatives and neglecting positive aspects. Concerns were raised about cost discrepancies, technical inaccuracies, extended commissioning schedules, and limitations based on overhead route studies. Undergrounding is seen as a solution to eliminate fire risks and promote protection.	**Undergrounding:** Lower impact on flora, fauna, landscape, and visual aesthetics, reduced bushfire risk, lower impact on agricultural productivity, and increased community support. While acknowledging potential cost implications, undergrounding was seen to minimise impacts on communities. Specific requests were made for underground technology in urbanised areas, important agricultural regions, areas of high landscape value, and habitats of endangered species.	**Undergrounding:** Was not considered appropriately as positive aspects were overlooked. **Biodiversity:** Impacts to presence of habitat offered by hollow-bearing trees, riparian corridors along waterways, observations of diverse fauna such as kangaroos, wombats, bats, brolgas, and raptors, and the existence of rare species like Grevillea Steiglitziana and Braid Moss
Impacts on health and safety	**Bushfire risks:** Transmission lines hinder effective fire response for landowners. The provided factsheets lack comprehensive information, only emphasising risk minimisation. Undergrounding the route would eliminate this risk.	**Bushfire risks:** Firefighters face limitations near power lines and falling lines can cause fires. The Bushfire Royal Commission recommends underground power lines. Incident costs, like the Cressy collapse, are passed on to consumers. Increased bushfire risk and route through flood-prone areas are additional concerns. Mental health: Anxiety caused to landowners and community members. Electromagnetic fields: Concerns regarding cancer and health risks on people and animals	**Bushfire risks:** Concerns including fires originating from project infrastructure, which can affect bushfire management strategies like planned burning, ground-based and aerial fire response, and back-burning. Forest areas pose challenges for evacuation during bushfire events. Climate change exacerbates fire weather conditions and fire risk. Coimadai Primary School, identified as at risk in the Bushfire Register, is also impacted. **Mental health:** The proposed project has the potential to strip away this cherished landscape, impacting the well-being and enjoyment of individuals. **Electromagnetic fields:** Concerns regarding cancer and health risks on people and animals
Cultural and Heritage Sites	**Aboriginal heritage:** Concern construction ground disturbance will directly disturb and destroy archaeological artifacts and structures. Vegetation clearance can remove the protective cover and concealment of archaeological sites. Placement of power lines over culturally significant sites impede the ability to effectively protect the site during a fire. **Heritage sites:** Farmers hold differing perspective of heritage and its significance to the community such as the removal of hundreds of trees that hold significance for future generations.		Aboriginal heritage: Concern regarding how transmission infrastructure will impact culturally significant sites.

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Attachment A:
CCG Code of Conduct

HumeLink Community Consultive Group Code of Conduct [6]:

HumeLink Community Consultative Group

Terms of Reference and Code of Conduct

TERMS OF REFERENCE

Background and purpose

TransGrid has committed to reset our community and stakeholder engagement approach and adopt all twenty recommendations from the Landowner Advocate Report. The establishment of Community Consultative Groups (CCGs) for the HumeLink project is one of these recommendations. The groups will initially run through the planning stages of the project.

Three groups are proposed to cover the following local government areas:

- Upper Lachlan and Yass
- Cootamundra Gundagai, Wagga Wagga
- Snowy Valleys

The CCGs purpose are to:

- Bring together TransGrid, local community groups, landowners and councils, to provide an opportunity for two-way communication about the HumeLink project
- Provide a forum for TransGrid to keep the community informed about the project, seek community views and respond to matters raised by the community
- Provide a forum for community members, stakeholders and local councils to seek information from TransGrid and provide input to inform Corridor refinement and the subsequent Environmental Assessment process
- Suggest ideas for community benefits/ project legacy contributions along the corridor
- To provide feedback and guidance to TransGrid about their community engagement approach.

The CCGs will be one of many means by which TransGrid will engage with communities and stakeholders along the study corridor. The CCGs will be a forum for consultation rather than a decision-making body. Where possible, specific recommendations or actions arising from discussions will be agreed through consensus. Where this is not possible, different views and opinions will be noted.

TransGrid has engaged Brendan Blakeley as the inaugural independent chair of the CCGs with secretariat services to be provided by WSP.

Membership of the CCG

Each group will have a maximum 15 members comprising:

- 3 proponent representatives
- 1 member from each council
- 1 member from each land council
- 1 representative from each of the established landowner groups within the CCG area
- Remainder drawn from recognised community groups (first preference), then individuals who have nominated.

Participants must be:

- A member or representative of the local community
- Willing to commit to attending meetings regularly (alternative attendees are permitted if the CCG Chair/secretariat is advised prior to the meeting). The use of alternative attendees should be kept to a minimum. The Chair may request the replacement of any member who fails to attend three consecutive CCG meetings
- Willing to gather input from the community/stakeholder group represented and bring forward any queries or concerns raised in relation to the project
- Able to disseminate information received during the meetings back to the property owners/neighbours/community/stakeholder group
- Able to demonstrate why they have an interest in this project and their key areas of interest.

Selection criteria

- The CCGs should comprise an equitable mix of gender and preferably age groups
- The group should provide for coverage of locations along the corridor
- Members of recognised groups may be given preference over self-nominated individuals, this includes landowner groups
- While landowners are key stakeholders the CCGs should not solely be a forum for directly impacted landowners
- Other groups to be invited to nominate include:
  - Chambers of Commerce
  - Progress or Resident Associations
  - Indigenous groups
  - Local Environmental Groups
  - Landcare / Bushcare
  - Tourism Associations
  - Industry associations such as Forestry Groups, NSW Farmers
- Particular expertise or skills sets
- Breadth of local organisations represented.

Assessment of applications and selection of members will be undertaken by the independent chair of the CCGs and the independent landowner advocate.

Meeting minutes and presentations will be published on TransGrid's website, along with the list of CCG members.

CCG Chair

The independent chairperson must be:

- A convenor, facilitator, mediator and advisor for the CCGs
- Independent and impartial
- The key contact (with assistance from support secretariat) between the CCGs and TransGrid.

The Chair will oversee the preparation and publication of the minutes of the CCG meetings and the Chair's standard fees (and secretariat support) will be paid by TransGrid.

Meeting frequency

The CCGs will meet once every 3 - 6 weeks for the first 3 months. This timing is to maximise the two-way sharing of information during the initial refinement of the corridor and in advance of more detailed planning commencing. Meeting frequency will be reviewed in early 2023.

CODE OF CONDUCT

Working together

The principles underpinning the CCGs that all members and project team representatives must agree to are to:

- Work collaboratively in an open and honest fashion
- Be respectful of all members and their opinions
- Refrain from any form of conduct that may cause a reasonable person unwarranted offence or embarrassment
- Undertake to fairly present the information provided at the CCGs, to their local communities
- Not misrepresent the views of other members of the group outside meetings.

Code of conduct

All members, including the independent chairperson and alternative members, must agree and sign the following code of conduct at the first meeting. Breaches of this code of conduct can be reported to the independent facilitator, who will raise the issue with the member. This may take the form of:

- A verbal warning before or during the meeting (which will be formally recorded in the meeting)
- A written warning after the meeting.

Following three warnings, the independent chairperson may ask the member to leave the group. This position will then be replaced by the independent chairperson.

Members of the CCGs will be expected to:

- Attend meetings, at dates and times agreed by the group
- Advise the independent chairperson in advance if they are unable to attend and who their alternative member will be
- Respectfully engage with other members of the CCGs
- Contribute to an atmosphere of open and constructive participation
- Openly communicate relevant concerns, interests and ideas and make reasons for any disagreement clear in a constructive and thoughtful manner
- Put forward views but also remain committed to open and shared dialogue
- Actively work with the members of the group to try and resolve any issues that may arise during the CCGs work

- Ensure they do not discuss or share information about matters that are identified as confidential during meetings
- Not interrupt when another member is speaking
- Not speak publicly, for example to the media, on behalf of the CCGs
- Not misrepresent the views of other members of the CCGs
- Immediately advise the independent chairperson during meetings of any potential or actual conflict of interest relating to matters under discussion
- Abide by the reasonable directions of the independent facilitator as to the conduct of the meetings.

Operating protocols

The following operating protocols will govern the CCGs:

- Meetings will be held approximately every 3 - 6 weeks for the first three months and then every 2-3 months thereafter
- Conduct of meetings will be informed by social distancing guidelines and health advice
- The meetings may be held in various convenient locations within a CCG area to ensure any travel load is shared equitably amongst members. In the event of COVID restrictions meetings may be held online.
- Meetings will generally run up to 2 hours
- To ensure safe travel meetings will occur during the day and early evenings, suitable times for meetings will be established with members
- A call for agenda items will be issued by the chair two weeks before a meeting, with the agenda then being determined by the chair and distributed one week prior to the meetings
- Technical advisors or specialists will attend as required
- All information provided should be accurate and timely
- Any pecuniary/conflict of interest should be declared by members
- Notes of the meeting will be provided electronically to CCG members within five working days of the meeting, with any comments to be provided within five working days of that time. In the event of any disagreement about the minutes the independent chair will have final say. A final set of minutes will be uploaded to the HumeLink website within 3 weeks of the meeting date
- Recording of the meetings by an electronic device is not permitted without prior agreement of the independent chair and all CCG members
- TransGrid may choose to reimburse reasonable travel expenses incurred by members.

Members may ask the independent chairperson to invite non-CCG members to attend meetings, either as observers or to provide advice to the committee. This may include:

- Representatives of government agencies
- Technical experts or consultants
- Members of the general public.

The independent chairperson is to consult with the other members of the group before issuing the invitation. If there is any disagreement between the members about the invitation, the independent chairperson will have the final say on the matter. Non-CCG members cannot participate in the business of a meeting unless they are invited to do so by the independent chairperson.

Media/social media protocols

To encourage open discussion at the meetings, we require members of the CCGs to adhere to the following media/social media protocols:

- Members of the CCGs are not authorised to provide written or verbal statements to the media/social media purporting to represent the views of the CCG
- The minutes are the authoritative record of the meeting
- CCG members are entitled to utilise media/social media on project matters in a personal capacity, and in doing so must ensure that their views are understood to be personal views and not the views of other CCG members or the project team.

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SEPTEMBER 2023

8.

Focus Group Findings

Exploring Queenslanders' views of high voltage overhead and underground transmission infrastructure

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Executive Summary

This chapter details the results of ten online focus groups conducted with a cross section of the Queensland general public in August 2023. In total 78 participants from across regional and metropolitan Queensland participated. Participants were an even mix of gender and ages ranging from 18 – 29 years of age (9%) through to 60+ years of age (13%) with the majority aged between 30 – 39 years of age (38%). Ongoing engagement with First Nations People and some farmers is still underway and will be reported separately.

The aim of the focus groups was to have an expert share a summary of the key findings from the systematic literature reviews and case studies, comparing overhead and underground transmission lines (Chapters 1 – 7), and to document the participants' responses to the information. This included responses to three questions which included: i) *Based on the information provided, what would you say are the benefits and concerns of overhead and underground transmission lines?* ii) *Who should be responsible for decisions about these types of large infrastructure upgrades?* iii) *If you, as an individual or a community, were to have a transmission line come near you, how would you like to be involved in the decision-making process?* As part of the data collection process, participants were also asked to participate in an online brainstorming session and complete pre- and post- surveys to track their individual attitudes and responses.

When first asked about what they believed were the issues and opportunities associated with overhead and underground transmission infrastructure initial themes included safety; maintenance; costs; environmental impacts; aesthetics; and weather. During the discussion it became clear that most participants did not distinguish between transmission and distribution infrastructure. This appears to be an area that could easily be rectified through improved communication. Safety concerns tended to focus on installation and maintenance and for overhead lines extended to issues of vehicle accidents and weather impacts including bushfires. Maintenance issues were around repairs and reliability with overhead lines being seen as easier to repair than underground cables. Costs issues included installation, maintenance and the need to extend or upgrade infrastructure as well as concerns about transitioning from overhead to underground. As expected, aesthetics was in relation to overhead lines creating visual pollution, being unsightly and ruining landscape vistas. In particular the height of transmission lines. In this instance, both overhead and underground transmission were considered to impact the environment with impacts on local wildlife, the need to cut down trees and other vegetation, and taking up a great deal of space. However some participants volunteered they did create opportunities for wildlife corridors and offer perches for birds. Weather issues tended to focus on Queensland's likelihood of cyclones, storms, floods and bushfires with participants noting that all were likely to increase given the impacts of climate change.

After the expert presentation, from the thematic analysis of the transcriptions arising from the focus groups, the largest category of coded responses were concerns surrounding the higher costs associated with the installation of underground transmission cables relative to overhead lines as reflected in the quote:

> *"We've got wide spaces and a huge amount of countryside and obviously [for the costs involved] to be putting in underground power lines in, you know, the middle of the outback would be absolutely ridiculous."*

Most participants were pragmatic suggesting that it would be hard to justify the additional costs of completely undergrounding all transmission lines, but where there were high density populations, areas of natural beauty or environmental sensitivity a hybrid approach with some undergrounding would be justified. There was also recognition that those individuals who would be impacted by transmission lines should be adequately compensated including near neighbours if the lines were to visually impact them.

When it came to decision making in relation to transmission infrastructure, most participants felt it was the role of government as reflected in the quote:

> *"I think that's the reason why we elect a government, to make those big decisions about that type of thing. So I'd be happy to leave them to make those decisions."*

However, there was a suggestion that the use of an expert panel that could weigh up the pros and cons of the various options may also be helpful in instilling confidence in the decision making process.

Participants were keen to emphasise the importance of engaging and consulting with the communities as part of the process. They like the format of using an independent expert, which they felt could be run with a much larger group, even a local community if needed.

> *"I think if you're talking about how I'd want to be involved if it was coming to my area, I think what you did tonight [with the] presentation, you could do that at a community event like at a hall and say this is all the information. Because you've provided me with a lot of information that I didn't know, plus the advantages and disadvantages. So then it helps people to be informed, because sometimes we get forced into decisions without actually knowing the, you know, the pros and cons about it."*

They also recognised that those most impacted should be given greater weighting when it comes to providing input into the decision making. This potentially reflects the recommendations arising in Chapter 6 around the need for collaborative constraint mapping that allows both transmission providers and communities to weight the various constraints to help develop the preferred route for transmission infrastructure. However, once again there was recognition that there was a need for leadership from government on this matter and that not everyone will be satisfied. While it was clear that impacted individuals need to be adequately compensated, it was felt they should not be allowed to block final projects moving ahead if the processes of engagement had been fair (procedural justice). Collaborative processes that took into account the rights and needs of various groups was seen as important in ensuring projects were able to be deployed. Particularly, given the urgency around the need for action on climate change.

It is important to consider that participants in the focus groups were not directly impacted by current or proposed transmission line developments. Consideration needs to be given as to how views may change if a project was going on near their homes or if they were residents who have, or were to be, potentially impacted by transmission lines. One key theme that emerged from the surveys is that many participants are looking for outcomes that can strike a balance between the differing interests and priorities of local communities. The majority of participants being predisposed to solutions that provided a balance between economic and environmental priorities.

1.

Introduction

This study aims to investigate the benefits and trade-offs between overhead and underground transmission line infrastructure, specifically focusing on issues associated with undergrounding new transmission infrastructure. It seeks to establish a clear and consistent approach to the evaluation of overhead lines and underground cable transmission, including the consideration of community concerns around the need for new transmission infrastructure to connect large renewable energy generation projects. It does this through systematic reviews of the literature as well as incorporating experiences of Transmission Network Service Providers (TNSPs) in Australia and overseas. The study has a particular focus on 500kV infrastructure which is expected to be the system voltage for high-capacity transmission lines in Australia going forward.

Historically, transmission networks in Australia developed from the need to transfer large amounts of power from large coal fired power stations, typically co-located near coal reserves, over long distances to major cities and industrial load centres. In contrast, the proposed large scale renewable generation facilities, mainly solar and wind farms, require greater land areas and are largely being located in greenfield areas with little or no existing transmission network infrastructure. These new developments are naturally creating community interest and concerns around a range of potential impacts, including but not limited to: visual amenity; environment; Traditional Owner lands; agricultural land use; and social licence to operate concerns. This has led to questions surrounding when it is appropriate to underground transmission infrastructure and the likely implications of doing so.

To test the Queensland public's response to the information gathered from the systematic literature review (Chapter 6), in August 2023 we conducted ten online focus groups with a cross section of the general public. Additional engagement is planned with First Nations People and some farmers from regional areas of Queensland. However, this process is taking a little longer to ensure key representatives from Indigenous Prescribed Body Corporates can attend. This chapter presents the findings of the focus groups and summarises the key take aways from the engagement process.

2.

Methods

The focus group were structured in 5 stages, including a pre- and post- survey, a brainstorming session to elucidate participants' baseline knowledge of transmission infrastructure, presentation from an expert (Appendix A) and then time for a facilitated discussion and reflection.

Pre- and Post- Survey

Pre- and post- online surveys[1] were used to capture individual views, knowledge and understanding of transmission infrastructure as well as monitor any changes as a result of the focus group discussion. The pre-survey comprised 21 questions, which were predominantly established scales, adapted to the topic of transmission infrastructure. The questions included participant demographics, socio-economic status and baseline levels of knowledge and experiences with overhead and underground transmission lines. The post-survey repeated some of the pre-survey questions to track any changes in opinions. Additional questions focused on instrumental and experiential aspects including social licence, trust and procedural fairness in relation to transmission infrastructure roll out.

The survey was formatted and tested in-house by the project team using Qualtrics. Survey participants were asked to develop a unique identifier to enable pre- and post- surveys to be matched. Survey data was analysed in STATA18. A total of 78 participants completed the pre-survey, with 75 of those 78 participants completing the post-survey.

Brainstorming Issues and Opportunities using Strategy Finder

Following introductions, participants were asked to engage with *Strategyfinder* software. *Strategyfinder* is designed for collaboratively working on messy problems over the Internet. It uses a process and set of 'rules' that have been developed over 30 years in face-to-face working with management teams. The focus of the process is to explore causality – means-ends – so that agreed actions are negotiated with a full understanding of expected outcomes and ramifications. Participants were asked to first provide up to 5 statements of issues or opportunities relating to overhead transmission lines by noting an "I" (Issue) or "O" (Opportunity) after their written statement. They did this anonymously and were encouraged to write in short phrases rather than single words which can be more open to misinterpretation. A blind gather brainstorming process was used to avoid participants influencing one another with their initial responses. Once the overhead activity was complete the process was repeated for underground transmission cables.

During the ideas generation phase, the material was clustered by the facilitator and subsequently revealed and reviewed with participants. Participants were then prompted to make any further contributions once they had reviewed their group's material and, in some cases, offered up new considerations. The views were captured in the participants' own language and revealed their current perceptions of transmission lines at the time.

Expert Presentation and Focus Group Questions

Following the brainstorming activity, an expert presentation was provided. The presentation was based on the findings from the systematic review of literature focusing on technical, economic, environmental, social and cultural considerations to highlight the trade-offs between underground and overhead transmission lines. Participants were also invited to ask any questions of clarification at the end of the presentation.

Following the presentation, the participants were then asked to provide their reflections based on the following questions:

1. Based on the information provided, what would you say are the benefits and concerns of overhead and underground transmission lines?
2. Who should be responsible for decisions about these types of large infrastructure upgrades?

[1] A copy of the pre- and post- surveys can be found at http://hdl.handle.net/20.500.11937/93795

3. If you, as an individual or a community, were to have a transmission line come near you, how would you like to be involved in the decision-making process?

All discussions were recorded and transcribed. The qualitative analysis software NVIVO was used to collate and categorise all responses.

Participant Recruitment

A market research company, Q&A, was used to recruit members of the public based on their location (regional or metro), aged between 18-39 or 40+, and an even mix of gender. This resulted in eight groups from the general public and two groups of small to medium enterprise business owners. Although responses between the two categories did not show any differences. The online focus groups took place during August 2023 and were comprised of between 7 to 9 people and lasted for approximately 2.5 hours.

Participant demographic characteristics

The demographic profiles of participants are provided in Table 1. There was a 50:50 split of male to female participants, with the median age being 40 years. By age category, 9% of participants were in the 18-29 years age bracket, and 13% were above 60 years of age. More than one third (38%) of focus group participants were between 30 to 39 years of age. Of the total, 41% lived in Brisbane metropolitan area whilst 59% lived in regional areas of Queensland. The majority of participants (82%) were born in Australia and 4% of participants identified as Aboriginal and Torres Strait Islander.

Table 2 shows that the participants of the focus groups were more educated as compared to the Queensland average population with 41% holding a Bachelor or Honours degree and 14% a postgraduate degree. Eighteen percent (18%) of participants held a certificate III or IV, with 9% reporting an education level of Year 12 or below.

Table 1. Participants' demographic characteristics

Characteristics	Frequency (n)	Percentage (%)	Australian population (%)[(a)]	QLD population 2021[2]
Gender				
Male	39	50.0%	49.3%	49.3%
Female	39	50.0%	50.7%	50.7%
Other	0	n/a	-	-
Prefer not to say	0	n/a	-	-
Total	78	100%	100%	100%
Age (n=77)[3]				
18 - 29 years	7	9%	18.9%	12.4%[4]
30 - 39 years	29	38%	14.5%	13.8%
40 - 49 years	17	22%	12.9%	13%
50 - 59 years	14	18%	12.4%	12.6%
60 years or older	10	13%	23%	22.8%
Region				
Metro	32	41%	-	-
Regional	46	59%	-	-
Country born				
Australia	64	82%	66.7	71.4
Outside Australia	14	18%	-	-
Country born				
No	75	96%	-	-
Yes, Aboriginal and Torres Strait Islander	3	4%	3.2%	4.6%
Prefer not to answer	0	0%	-	-

2 Accessed from https://www.abs.gov.au/census/find-census-data/quickstats/2021/3 on 2023/09/11
3 Missing data = 1
4 Includes age 15 to 29

Table 2. Participants' levels of education

Which of the following best describes your educational status?	Frequency (n)	Percentage (%)	QLD 2021[5]
Year 10 or below	1	1.3	18.6
Year 11 or equivalent	-	0	3.9
Year 12 or equivalent	6	7.6	15.5
Trade certificate or Apprenticeship	2	2.6	-
Certificate I or II	-	0	0.1
Certificate III or IV	14	18.0	18.9
Advanced Diploma / Diploma	11	14.1	9.4
Bachelor or Honours degree	32	41.0	21.9
Postgraduate degree (e.g. Masters, PhD)	11	14.1	-
Other (please specify)	1	1.3	-
Not stated/Inadequately described	0	0	11.6
Total	**78**	**100**	**99.9**

[5] Level of highest educational attainment, People aged 15 years and over, Sourced: https://www.abs.gov.au/census/find-census-data/quickstats/2021/3
[6] Bachelor Degree level and above

3.

Results

Focus Group Discussion

Initial concerns and opportunities

The brainstorming information collected on the issues and opportunities in each focus group prior to the expert information session are captured in Table 3. On average, each capture activity lasted for around 10-15 minutes and generated between 20 and 55 statements. There were approximately equal numbers of views for overhead (349) as there were for underground (359) with the total number of statements generated being 708. Based on a review of the clusters generated and reviewed in the focus groups, of the total 12 themes, there were 6 main themes that emerged. These were safety, maintenance, costs, aesthetics, environment and weather. Close examination of the themes and also observation of the discussion that ensued post each brainstorming activity, demonstrates that many of the participants did not distinguish between transmission infrastructure and distribution infrastructure, but saw them as one and the same.

Safety

Safety emerged as one of the two major themes (1st for overhead, 4th for underground). This addressed aspects including safety concerns around the installation and maintenance of transmission infrastructure, residential safety in terms of storm impacts, and other community and residential considerations. Overhead lines were regularly commented upon as having safety concerns after weather events, being hazardous for drivers, creating risks with machinery and tall vehicle use, as well as being subject to vandalism. Bushfire dangers were also identified.

Table 3. Tabulated themes of issues and opportunities captured using Strategyfinder

Themes	Overhead Issues & Opportunities	Underground Issues & Opportunities
Safety	75	43
Maintenance	68	87
Costs	48	61
Environmental Impacts	47	34
Aesthetics	46	51
Weather	36	34
Other	12	11
Jobs	6	4
Alternative Energy Sources	4	1
Electricity Demand	3	11
Technology	3	4
Excavation	1	18
Total	**349**	**359**

Point of entry (roof) was also raised which reinforces that participants did not distinguish between transmission and distribution lines. Safety also touched on issues relating to light, EMF and noise pollution.

Underground cables were seen as safer both from an installation and maintenance perspective, being less vulnerable to weather conditions and driving accidents. However, there was a recurring concern regarding digging, from the perspective of those maintaining them, as well as some concerns about EMF leakage.

Maintenance

Maintenance touched on issues in relation to repairs and reliability and was the other most commented upon theme (2nd for overhead, 1st for underground). Whilst overhead lines were seen as being easier to repair (easier to locate problems), participants held the view that they were more prone to faults, particularly due to adverse weather, vehicular accidents, and vandals. Age of infrastructure was also a consideration.

Underground cable issues focused on the difficulty of identifying them and any problems along with access and repair. There were also concerns on maintenance schedules and their community impact through things such as roadworks. However, underground cables were seen as more reliable (fewer hazards damaging them) and lasting longer (so less maintenance).

Safety and maintenance, costs and maintenance, and maintenance and weather were all often aligned in participants' thinking.

Costs

Cost issues included the installation, maintenance, and extension of lines, and emerged as another frequently raised theme (3rd for overhead, 2nd for underground). Overhead lines were seen as costly to install and maintain (cost of metal, cost of securing the space). There was also a concern regarding the costs of transitioning from overhead to underground. However, alongside this, participants noted that overhead lines were cheaper and more cost-efficient compared with underground. This included being quicker to install and easier to upgrade.

Underground cables were noted as having prohibitively costly maintenance (due to issues relating to technical complexity and additional labour requirements) and construction because of the time needed to install. However, some participants considered they were cheaper to install and maintain as they felt underground lines would likely have a longer life span and be easy to add new services if combined with other cabling e.g., NBN. Also that it would be easier (and therefore cheaper) in new residential developments – again demonstrating confusion with distribution lines.

Aesthetics

Aesthetics focused on the visual impact of the transmission lines and was in the mid-range in terms of the number of comments made (5th for overhead, 3rd for underground). Overhead lines were typically described as visual pollution, ugly, unsightly, ruining a beautiful landscape, diminishing street appeal and an eyesore. The height of the powerlines was commented upon potentially contributing to the negative image.

This contrasts with the views regarding underground lines where participants noted that there were no ugly lines, that there was a cleaner look, that it was better for real estate as the lines were hidden, and that there was a less cluttered landscape. Overall, there was the view that underground lines were superior to overhead lines from the perspective of aesthetics but that both had issues and opportunities.

Environmental impacts

Environment focused predominantly on the natural environment, although did slightly touch on the human environment. Similar, to aesthetics, it was mid-range in terms of the volume of concepts surfaced (4th for overhead, 5th for underground). Overhead lines were seen as interfering with the natural landscape, affecting local animals (in terms of safety and impacting the natural habitat), taking up a lot of space, damaging trees and other vegetation, and requiring trees to be cut down for poles. At the same time seen as creating wildlife corridors and useful perches.

Underground lines were seen as impacting the environment due to the need to dig up of the land, potentially having an impact on the environment through electromagnetic elements seeping into the soil, affecting farm operations and use. As well, that care would be needed in terms of interfering with tree roots and with heritage land. However, when considering the opportunities, underground lines were thought to save wood, were not viewed as a hazard to wildlife, were less impacted by wildlife, and once constructed, allowed green spaces to be developed.

Weather

Weather issues were raised regularly and were mid-range in terms of frequency (6th overhead, 5th underground). As participants were in Queensland, cyclones and tropical storms are a part of life. Overhead lines were seen as attracting lightning strikes, being damaged in strong winds, susceptible to storms, cyclones, and potentially bushfires. Underground lines were not considered to be as affected by wind or fires (except where they had to be fed by overhead lines), but could be affected by floods. Overall weather was seen as a significant impact on the reliability of service, and as several participants noted, with climate change, this is likely to increase.

Benefits and Concerns Post Information Provision

After the expert presentation participants were asked: *Based on the information provided, what would you say are the benefits and concerns of overhead and underground transmission lines?* From the transcriptions 146 discrete responses were recorded. The majority of responses were either concerns expressed in relation to underground transmission lines (n=70) and those that focused on the benefits of overhead transmission lines (n=27). There were an additional 15 responses in relation to the benefits of underground lines and 16 responses expressing concerns with overhead transmission lines. Those and the other identified comments are presented in Table 4.

The largest single category of coded responses (n=42) were concerns about the higher costs associated with the installation of underground transmission cables relative to overhead lines. A typical response reflecting this view was:

> *"We've got wide spaces and a huge amount of countryside and obviously [for the costs involved] to be putting in underground power lines in, you know, the middle of the outback would be absolutely ridiculous."*

Table 4. List of the key themes in relation to the perceived benefits and concerns

Code Name	Total
Benefits of overhead transmission	**27**
Cost Effective	15
Easier to install	4
Easily replaced	1
Lifespan	1
More effective in rural areas.	4
Safety not a concern	2
Benefits of underground transmission	**15**
Aesthetics	3
Environment	3
Near Urban	3
Safety	2
Security	3
Simpler Maintenance	1
Concerns with overhead transmission	**16**
Aesthetics	6
Cultural	1
Electromagnetic	3
Environmental	4
Impact on land value	1
Safety	1
Concerns with underground transmission	**70**
Difficulty of installation	6
Environmental	3
Installation Cost	42
Land Acquisition	2
Lifespan	4
Maintenance	6
More infrastructure	2
New technology	2
Short Distance	3
Combined benefits overhead/ underground	**17**
Favours HVDC transmission	**1**
Infrastructure planning issues	**3**
Jobs and opportunities	**3**
Pro local power alternatives	**3**
Pro underground in the future	**9**
Unsure of benefits or concerns	**11**

Participants also considered how the cost implications impact other areas of our economy.

> *"I think the problem is that we only have limited of money to spend, whether it's at the state, local or federal level. So if someone said we can either put everything underground or we can have free public healthcare for all, Australia, I'll probably go preferably healthcare. So it's kind of, that's called a problem, because you can say that we got all this money to spend on underground, but we could also just spread it out on overhead and then take the rest of the money [for] something else that we really need."*

There were also 15 responses highlighting the relative cost effectiveness of overhead transmission lines with one respondent saying:

> *"I was pretty much on the fence when this started, and then like a few others I definitely turned more [to] overhead. It's just something to do with it seems cheaper. I know it seems it's cheaper to set up."*

Other participants stated that despite knowing some other issues of concern with overhead transmission lines such as their visual and some environmental impacts, they would choose overhead transmission infrastructure because of their cost effectiveness.

> *"I feel like it is the most cost efficient [way] to go overhead and [finding out] what people's problem are [with] the overhead and trying to solve that problem will be easier and more cost efficient than trying to pursue this underground thing."*

However, proximity and aesthetic issues surrounding overhead transmission lines were still a concern to some participants.

> *"[Let's say] I'm a rural guy [who] all of a sudden [has] got a gas pipeline underneath and overhead transmission lines above. Everybody's going, 'It's cheaper to do it that way and it's fine', but not in my backyard, right?"*

The other high response category were those participants who cited the benefits in combining overhead and underground transmission line technologies based on situation and need (n=17). For example:

> *"I feel that everything needs a nice, even balance. You use overhead where it's going to be more cost effective and you use underground where it's going to be more efficient. And I think that, you know developers, if they're working smart, they will deliver in a way that is environmentally friendly, is cost effective, but also it is going to keep the cost down and keep the power on."*

There was another view that emerged based on the presentation that underground is the preferred option but just not at this stage.

> *"[I] absolutely favour the underground, but I don't think we're ready yet. I think for the moment, we need to [consider] with the practical limitations of underground, to be looking at the overhead."*

Who should be responsible for decision making?

The second question asked participants to consider: Who should be responsible for decisions about these types of large infrastructure upgrades? Eliciting 101 responses from the focus groups (Figure 1), the responses either directly nominated their preferred decision maker or tended to focus on the process itself and what it should entail.

The single highest response in relation to decision makers was the government (n=23). When combined with others citing specific levels of government, (i.e. Federal (n=4), State (n=5) and Local (n=6)) the total was 38 of the 101 responses. There was a feeling amongst those participants that being responsible for these type of projects is what governments are elected to do. For example:

> *"I think that's the reason why we elect a government, to make those big decisions about that type of thing. So I'd be happy to leave them to make those decisions."*

The next highest number of responses (n=14) considered a "cross section of stakeholders", as their preferred option for how decisions are made. These included groups such as technical experts, government, landholders, electrical authorities.

> *"I think it needs to be like a joint consensus of the electricity guys [and] like environmental guys. There's probably loads of other people that should be involved who can help. Yeah, come to some sort of happy medium which ticks kind of every box almost. I know there's never going to be an agreement. If you do overhead, somebody's going to be annoyed. If you do underground somebody's going to be annoyed. I don't know who specifically should be involved, but I think it should be a collaboration."*

In addition, a number of participants commented on the process of decision making rather than specifically who should be making the decision (n=14).

"If they, you know, weigh out the pros and cons. Have a good list and a bad list, and work out that way whether it's going to go underground or above ground, as well as taking in the financial aspect of it."

There were also comments about a lack of trust in the decision makers. With some were sceptical that authority figures would make decisions without the involvement of the community (n=7).

"[Its] normally been decided before you have a say anyway. That's why a lot of people don't have a say because they know that very little makes a change, no matter what is said on how individuals and community should be involved in the decision-making process."

Personal involvement in decision making

The final question asked: If you, as an individual or a community, were to have a transmission line come near you, how would you like to be involved in the decision-making process?

Figure 2 provides the breakdown of the 92 discrete responses from all answers to this question. Three response categories were most prominent and included the need for information (n=32), the need to focus on impacted individuals (n=22) and the use of community groups (n=12).

Regardless of involvement, participants discussed the need for people to be provided with the relevant information to make informed decisions (n=32). For example:

"I think if you're talking about how I'd want to be involved if it was coming to my area, I think what you did tonight [with the] presentation, you could do that at a community event like at a hall and say this is all the information. Because you've provided me with a lot of information that I didn't know, plus the advantages and disadvantages. So then it helps people to be informed, because sometimes we get forced into decisions without actually knowing the, you know, the pros and cons about it."

The second category was that participants felt those people directly impacted by the development should be given a greater weighting when it comes to input into decision making (n=22). This was regardless of how the involvement was carried out.

"It is always interesting weighing up, I guess the needs of the many versus the direct impacts. So that's usually where the consultation lies, is the who is directly impacted and then everyone else can have a say on a consultation process. But usually weight is given to those directly impacted people."

The third main set of responses related to the use of meetings (n=6) and community groups (n=12) as

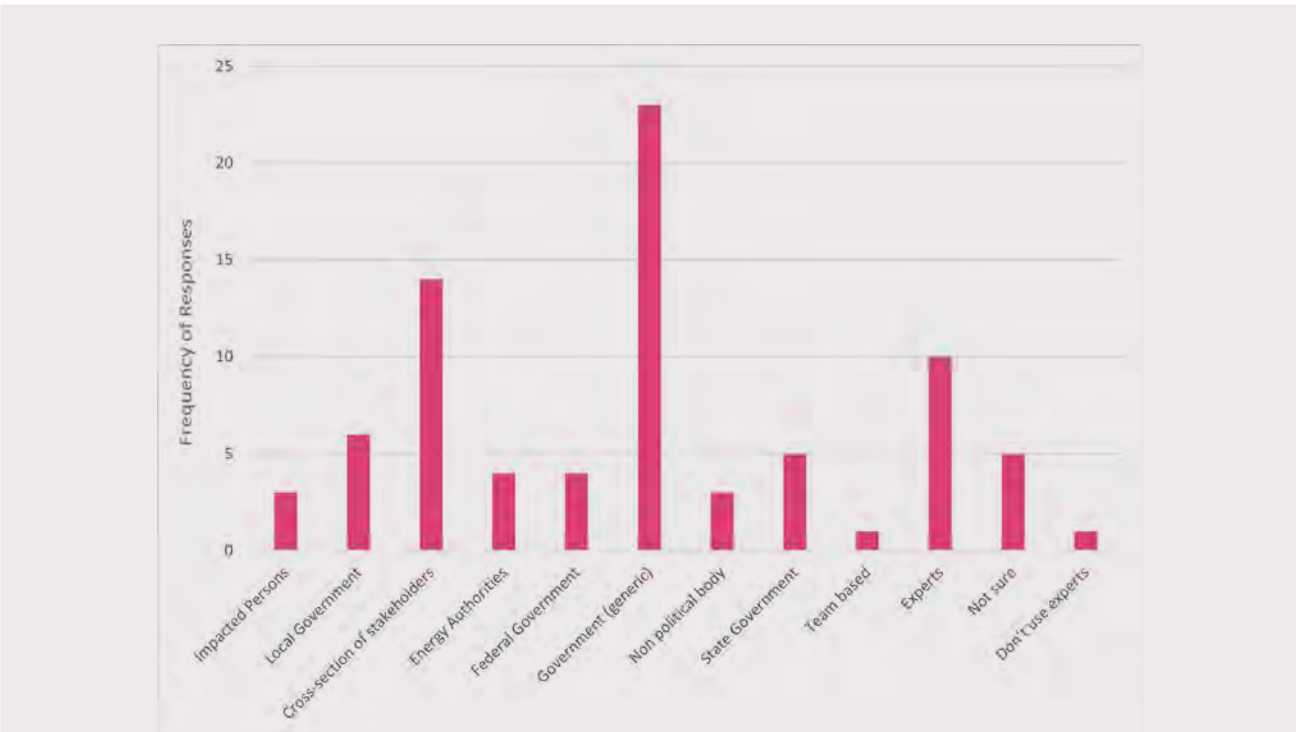


Figure 1. A breakdown of responses to who should be the decision makers

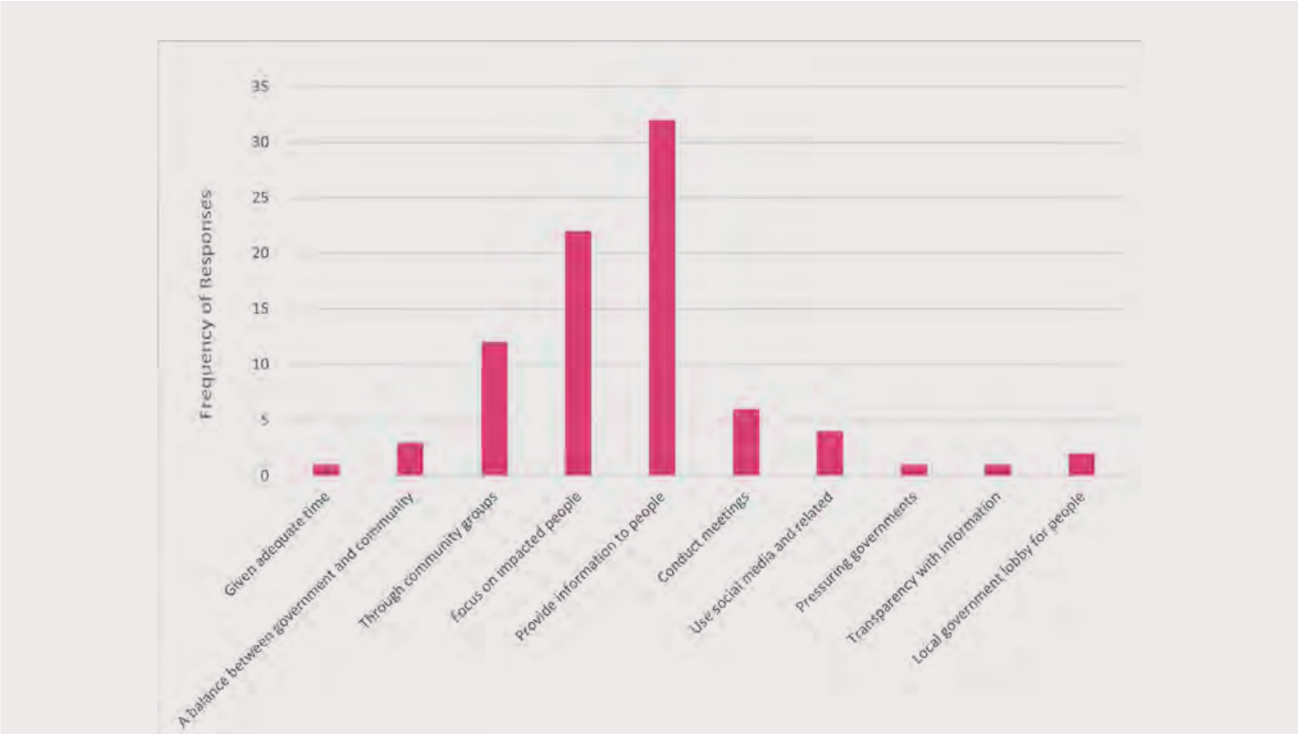


Figure 2. How they would like to be involved in the decision making process

important avenues for contacting people and obtaining feedback on proposed projects.

> *"I would hope that community involvement and information is available. [I hope] that you do information nights not just like this but for the mum and dad consumer. Also do the business evenings where you go: Right! This is what's going to happen, if we are going to underground, it means that these businesses will be impacted in this way [and so on]."*

A final category worth noting were comments that reflected caution in how we involve people in decision making (n=8). Some participants commented on the detrimental impact there can be on the wider community if too much decision making power is given to specific groups.

> *"I've done a bit of work around community consultation as an environmental consultant for a few years. No matter what you propose anywhere, whatever project, you're going to get people who are unhappy. So yes, they need to be consulted, but at the end of the day [we are] a country of 25 million people, predominantly living in cities along the coast [and] I think the benefits overall for overhead power lines outweigh the complaints of a few farmers. If you've been out to rural Queensland, there's a lot of land out there."*

Survey

To capture the individual views of participants more accurately and to complement the qualitative discussion, participants were asked to complete a pre- and post- survey at the beginning and end of the focus groups. A total of 78 participants completed the pre-survey, with 75 of those 78 participants completing the post-survey

Perceptions of climate change and the environment-economy trade-offs

Participants were asked to indicate whether they believed *that climate change is happening now or would happen in the next 30 years* and to indicate how convinced they are that *climate change represents a real problem for Australia* (Likert scale 1=very unconvinced to 7=very convinced). The responses are provided in Figure 3, a and b, respectively. They show that the majority of participants (76%) believe climate change is already happening (Figure 3a) and were convinced (80%) that climate change represents a real problem for Australia, with a mean response of 5.57 (SD=1.62).

Another question asked about the trade-offs between the economy and the environment. *"Energy policy can involve difficult trade-offs between the economy and the environment. Which of the following statements best describes your view?".* There were five possible

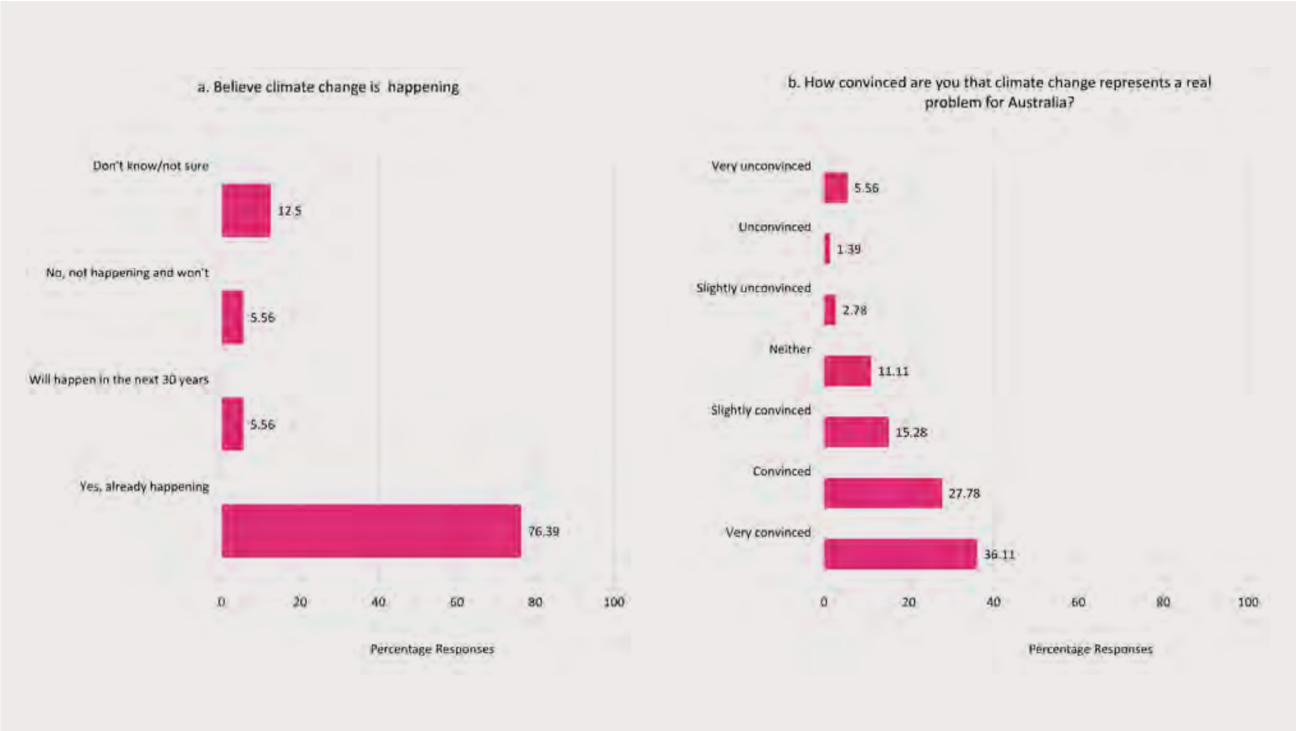


Figure 3. Climate change belief plot

response options, however the majority (64%) of participants indicated *"Both the environment and the economy are important and balancing the two should be the highest priority"*; followed by 26% supporting *"Both the environment and the economy are important, but the environment should come first."*

Awareness of Overhead and Underground Transmission Lines

To ascertain participants' familiarity with transmission infrastructure before being provided with any information, they were asked to indicate their levels of awareness of the two types of transmission infrastructure. Responses included: *i) I have never heard of it; ii) I have heard of it; iii) I have heard of it and could describe it to a friend.* Table 5 provides a summary of their answers. Initially, the majority of participants (64%) indicated they had heard of overhead transmission lines and underground transmission cables (68%). In both instances 24% of participants were confident that they could describe them to a friend. In contrast, at the end of the focus group, the majority of participants felt confident they could describe both underground and overhead transmission infrastructure to friends, indicating a significant shift in the knowledge perception of participants.

Overall support for overhead and underground transmission

Participants were also asked to indicate their level of support for overhead transmission lines and underground cables in both the pre- and post- surveys.

Table 5. Participants' pre- and post- familiarity with transmission infrastructure

	Pre-Survey (%)		Post-Survey (%)	
	Overhead	Underground	Overhead	Underground
Never heard of it	13	8	1	1
Have heard of it	64	68	23	25
Can describe to a friend	24	24	76	73

Responses were measured using a Likert scale (1 = strongly unsupportive to 7 = strongly supportive). Table 6 shows the distribution of responses and illustrates how support changed as a result of participating in the focus groups.

When comparing the difference in mean support between the pre- and post- surveys, there was a statistically significant increase in mean support from 4.2 to 5.7 for overhead transmission lines as a result of the focus groups (Table 7, Figure 4). In contrast, support for underground transmission lines decreased slightly from 5.6 to 5.3. However, this drop in support was not statistically significant. Further analysis by gender and place of birth was not shown to significantly influence support.

Table 8 compares the difference in means across the two types of transmission. Support for underground was significantly higher as compared to overhead during the pre-survey. However, when compared after the focus group, there was no significant difference in support for either.

Table 6. Participant support for overhead transmission lines and underground cables.

	Overhead		Underground	
	Pre- (%)	**Post- (%)**	**Pre- (%)**	**Post- (%)**
Very unsupportive	3	0	0	0
Unsupportive	11	1	0	7
Slightly unsupportive	11	6	0	7
Neither supportive nor unsupportive	39	3	29	7
Slightly supportive	14	17	15	24
Supportive	19	56	29	40
Very supportive	3	17	33	15
TOTAL	**100**	**100**	**100**	**100**

Table 7. Mean T-test assessing respective changes in support for overhead transmission lines and underground transmission cables, pre- and post-

	Pre-		Post-				
	N	**Mean**	**N**	**Mean**	**Difference**	**St Err**	**p value**
Overhead	72	4.2	71	5.7	-1.5	0.2	0
Underground	72	5.6	71	5.3	0.3	0.2	0.15

Table 8. Mean T-test comparing differences in support between overhead lines and underground cables, pre- and post-

	N	Overhead	Under-ground	Difference	St Err	p value
Pre-	72	4.19	5.60	1.437	.23	0.00
Post-	71	5.72	5.28	-.403	.22	.05

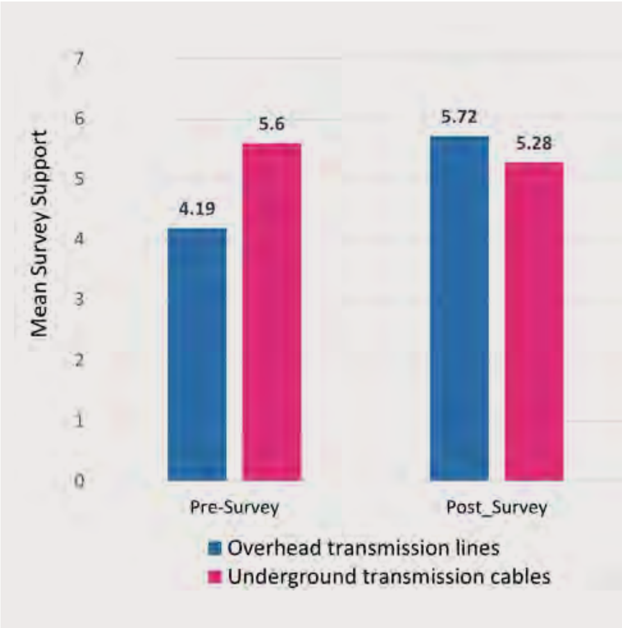


Figure 4. Mean support before and after focus group discussions

Reasons for mid-point selection

Of those who selected the midpoint (4=neither supportive nor unsupportive), a follow up question was asked to better understand their reasons for choosing the midpoint. There were 28 participants who selected the midpoint for overhead lines, indicating that they *do not know enough about overhead transmission line to decide* whilst 39% indicated that the *pros and cons made their support neutral* (Table 9). Of 21 participants who selected the mid-point for underground cables, 71% indicated that they *do not have enough information to make a decision.*

There was a substantial reduction in those choosing the midpoint in the post survey. Only two participants selected midpoint in post survey for overhead lines indicating *the pros and cons made their support neutral.* Whiles amongst the five participants who selected midpoint for underground cables, three indicated *the pros and cons made their support neutral.*

Factors influencing acceptance and a social licence to operate

The literature review showed that technology acceptance and a social licence to operate are influenced by a multitude of factors. These include not only perceptions about the technology itself but more importantly issue relating to procedural and distributive justice, trust, as well as ensuring sufficient regulations are in place to manage safety considerations and to minimise impacts to the environment. The post-survey tested these through a number of questions and responses are detailed below.

Instrumental and experiential factors

The survey questions were adapted from Huijts, Molin and van Wee (2014)[7] to identify how participants evaluated the relative importance people placed on the

Table 9. Reasons for selecting the mid-point

Midpoint selection reasons	Overhead line		Underground cable	
	n	%	n	%
I do not know enough about overhead transmission lines to decide	12	42	15	71
I do not have any feelings either way (positive or negative)	3	11	1	4.8
There are pros and cons, which makes my support neutral	11	39	2	9.2
I did not understand the question	0	0%	0	0%
I have no opinion on this issue	0	0	2	9.2
I don't care	1	3.6	0	0%
Other reason (please specify):	1	3.6	1	4.8
Total (n)	**28**	**100**	**21**	**100**

7 Huijts NMA, Molin EJE, van Wee B. Hydrogen fuel station acceptance: A structural equation model based on the technology acceptance framework. J ENVIRON PSYCHOL 2014;38:153–66. https://doi.org/10.1016/j.jenvp.2014.01.008.

various factors in relation to overhead transmission using best-worst scaling. These included perceptions of costs to build, usefulness to those living in the vicinity, impacts on the environment, safety, economy and health. Table 10 details the number of responses across the range of factors in relation to overhead transmission lines after the focus groups. The spread of responses suggest that individuals felt overhead lines would be more acceptable in terms of their cost to build, would have some benefit to people living nearby and were relatively safe (Figure 5). However, it appears that participants were somewhat concerned with the potential for negative environmental impacts and indifferent to health effects.

Table 10. Factors influencing acceptance of overhead transmission lines

I expect that overhead transmission lines would...						
	-2	-1	0	1	2	
Be built at too high costs	0	2	5	33	31	Be built at acceptable costs
Not provide benefit for people living nearby	5	14	17	16	19	Provide benefit for people living nearby
Have a very negative effect on the environment	1	26	34	8	2	Have a very positive effect on the environment
Be very dangerous	0	14	29	19	9	Be very safe
Be very bad for the local economy	1	3	27	33	7	Be very good for the local economy
Have a very negative effect on the health of people living nearby	2	9	46	10	4	Have a very positive effect on the health of people living nearby

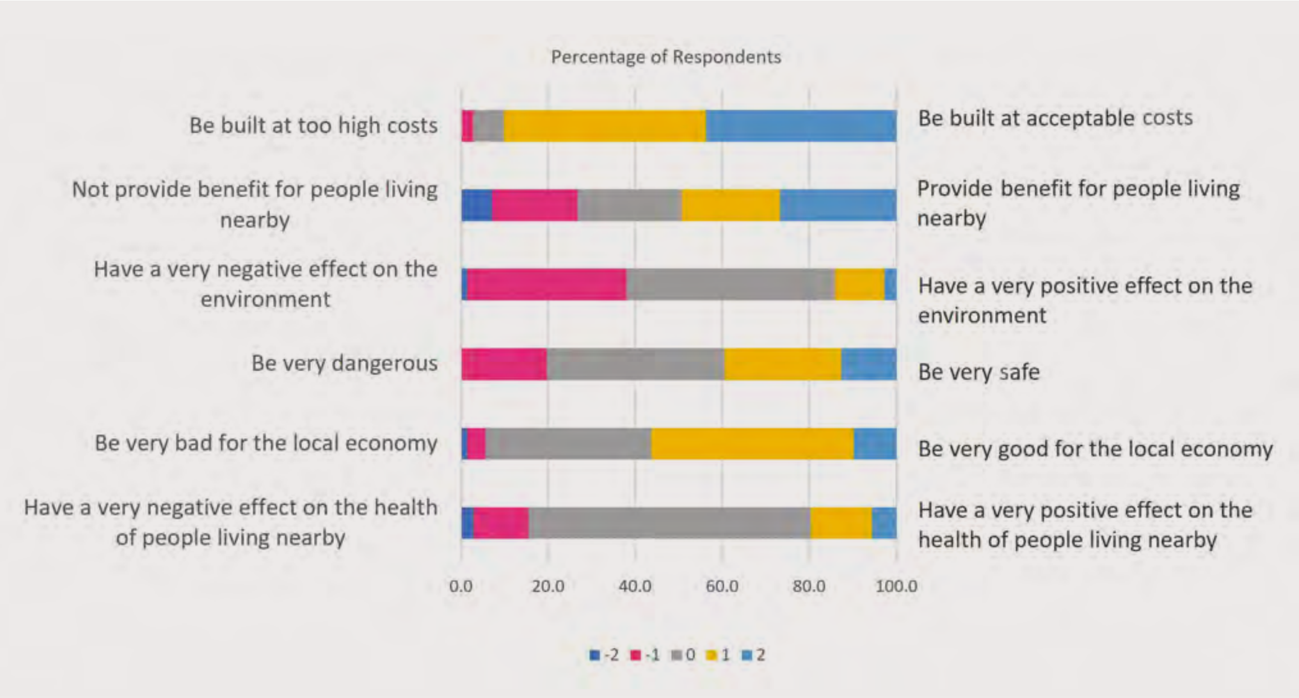


Figure 5. Percentage agreement with factors influencing acceptance of overhead lines

In contrast, Table 11 details the number of responses for underground cables which shows, participants were more positive in relation to all factors with the exception of costs to build when compared to overhead. However, there were still a large group with neutral responses, particularly in relation to effects on the environment, impacts on the local economy and effects on people living nearby (Figure 6). This possibly highlights the complexity of the issue when considering transmission lines, particularly when you are not directly impacted by them.

Table 11. Factors influencing acceptance of underground transmission cables

I expect that underground transmission lines would...						
	-2	-1	0	1	2	
Be built at too high costs	34	22	4	6	5	Be built at acceptable costs
Not provide benefit for people living nearby	0	7	14	25	25	Provide benefit for people living nearby
Have a very negative effect on the environment	0	10	27	23	11	Have a very positive effect on the environment
Be very dangerous	0	2	13	30	26	Be very safe
Be very bad for the local economy	4	11	28	17	11	Be very good for the local economy
Have a very negative effect on the health of people living nearby	1	3	36	20	11	Have a very positive effect on the health of people living nearby

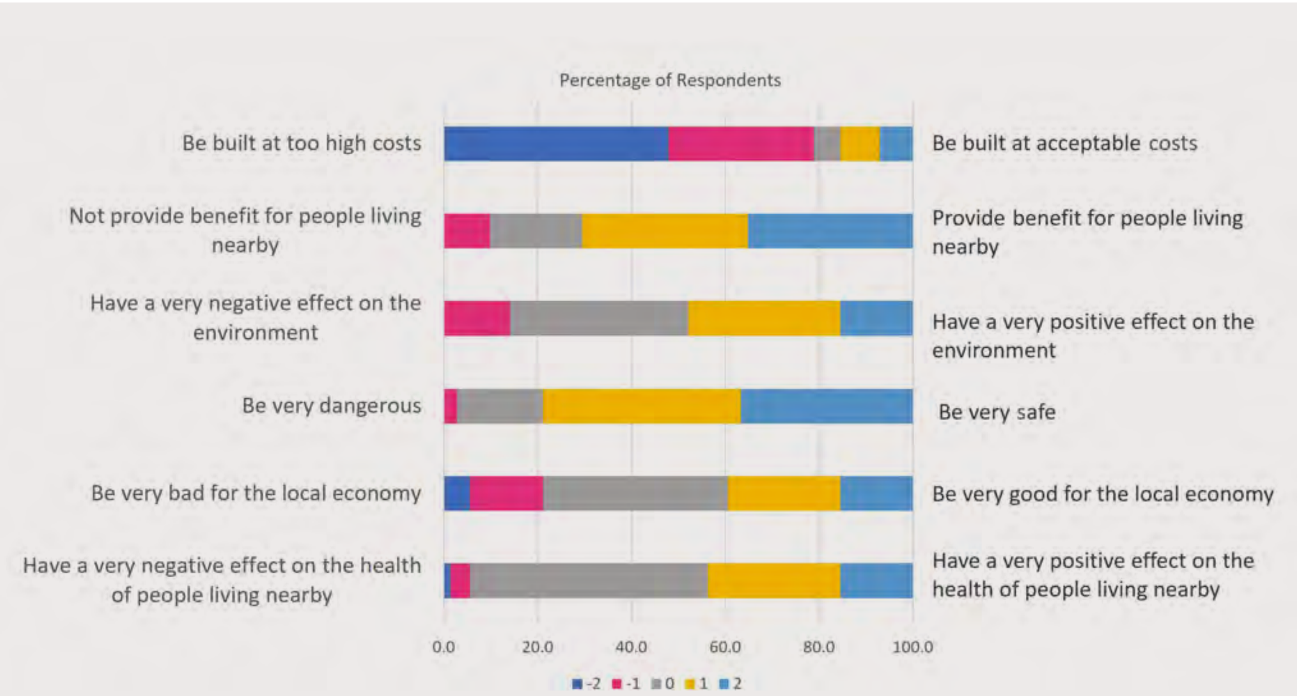


Figure 6. Percentage agreement with factors influencing acceptance of underground cables

Based on the earlier responses of support (Table 6), using the median value of support, participants were split in two categories of either high or low support for overhead and underground transmission infrastructure. For overhead lines, there were 19 participants in the low support cohort and 52 in the high support cohort. While for underground, there were 32 participants in the low support cohort and 39 in the high support cohort. Figures 7 and 8 present the extent to which each cohort's mean response was positive or negative in relation to each of the acceptance factors. The blue colour bar indicates the mean expectation of each factor for the low support cohort and the pink colour bar indicates the mean expectation of each for the high support cohort. It confirms that those who were less supportive of overhead lines were concerned about their uses in local communities and effects on the environment and health. As well, that both cohorts were less comfortable with the costs associated with underground transmission infrastructure.

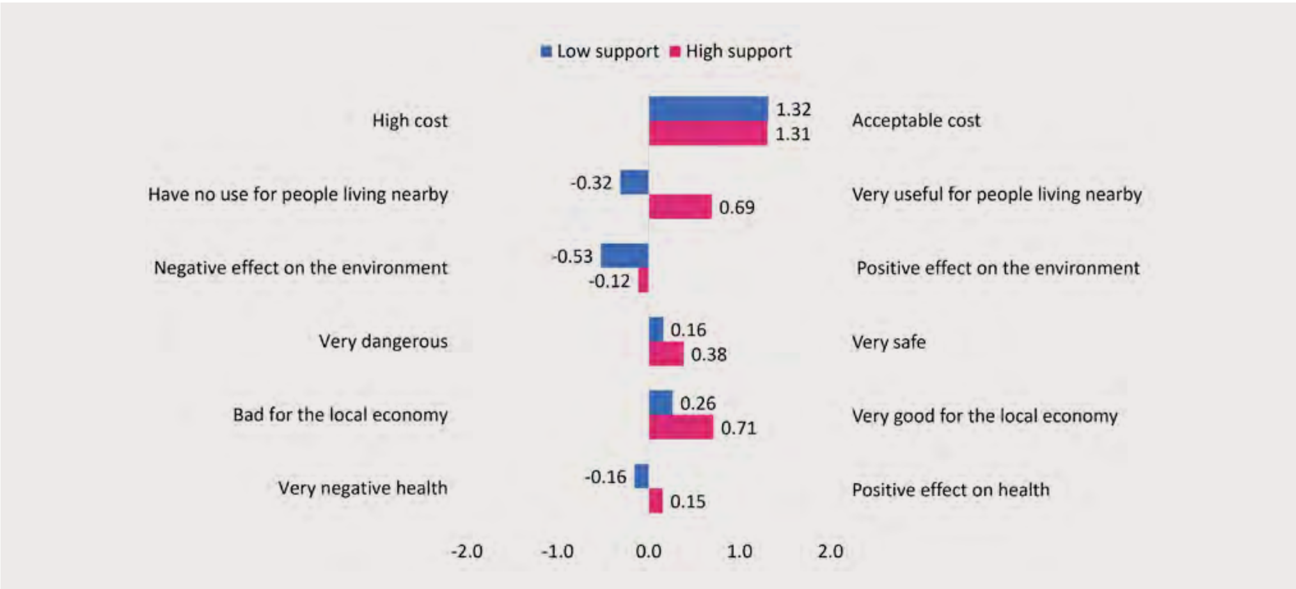


Figure 7. Factors influencing acceptance of overhead transmission lines

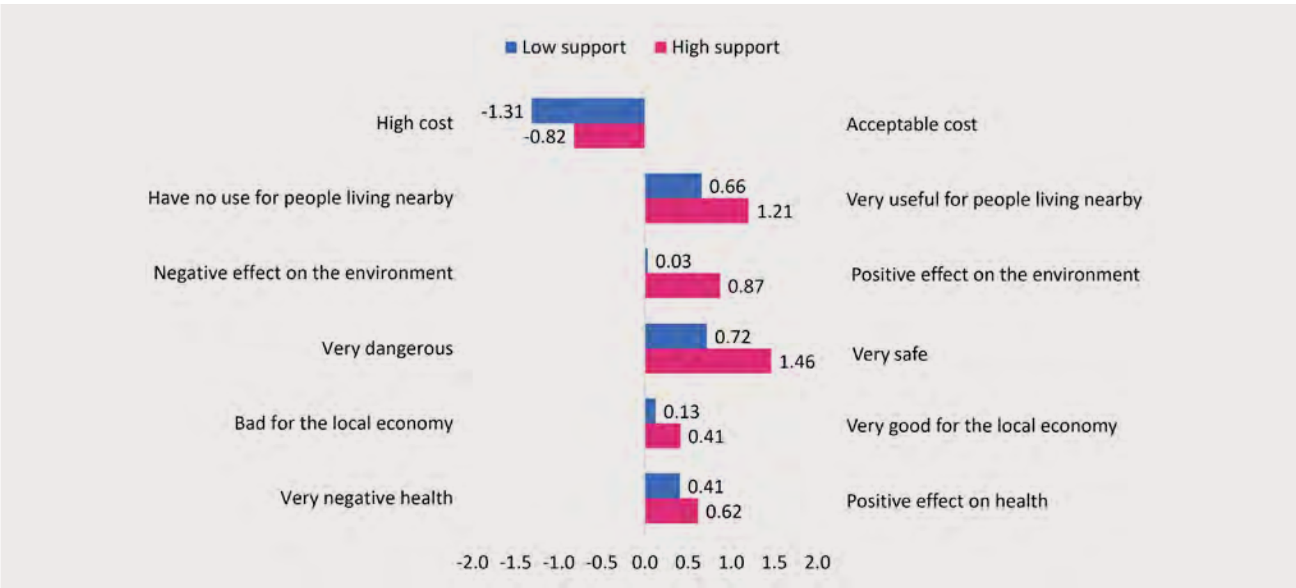


Figure 8. Factors influencing acceptance of underground transmission cables

Distributional Justice

The distributive and procedural justice considerations for transmission projects have been identified as key influencers on their acceptance. Therefore, we investigated participants' perceptions of this through the question, *"When you think about the decisions being made about the placing of an overhead transmission line in your local area, what do you think of the distribution of benefits and drawbacks with respect to yourself and others?"* Responses were in relation to fairness, whether they would be a problem and whether they could be avoided. Using the same method of high and low support cohorts, Figures 9 and 10 illustrate that on the whole perceptions were positive towards both, with some problems foreseen by the use of overhead lines. This potentially relates to the issues that arose in the discussions and were identified in the case studies, such as aesthetics, impacts on the environment and safety.

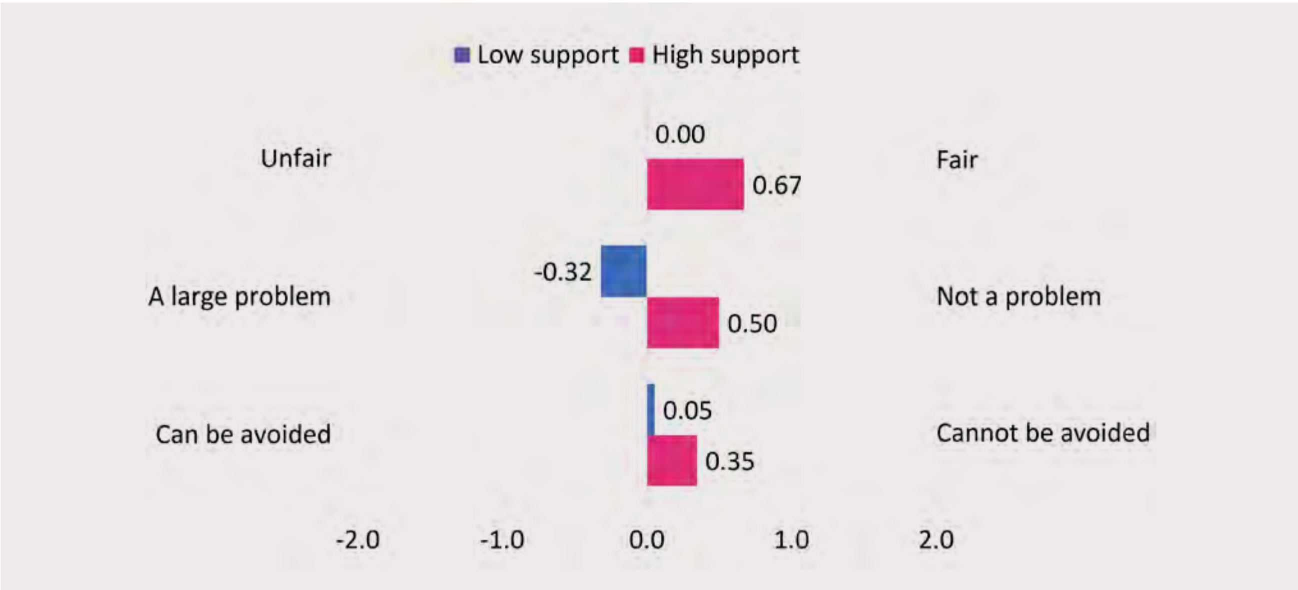


Figure 9. Perceptions of distribution of benefits and drawbacks of overhead lines

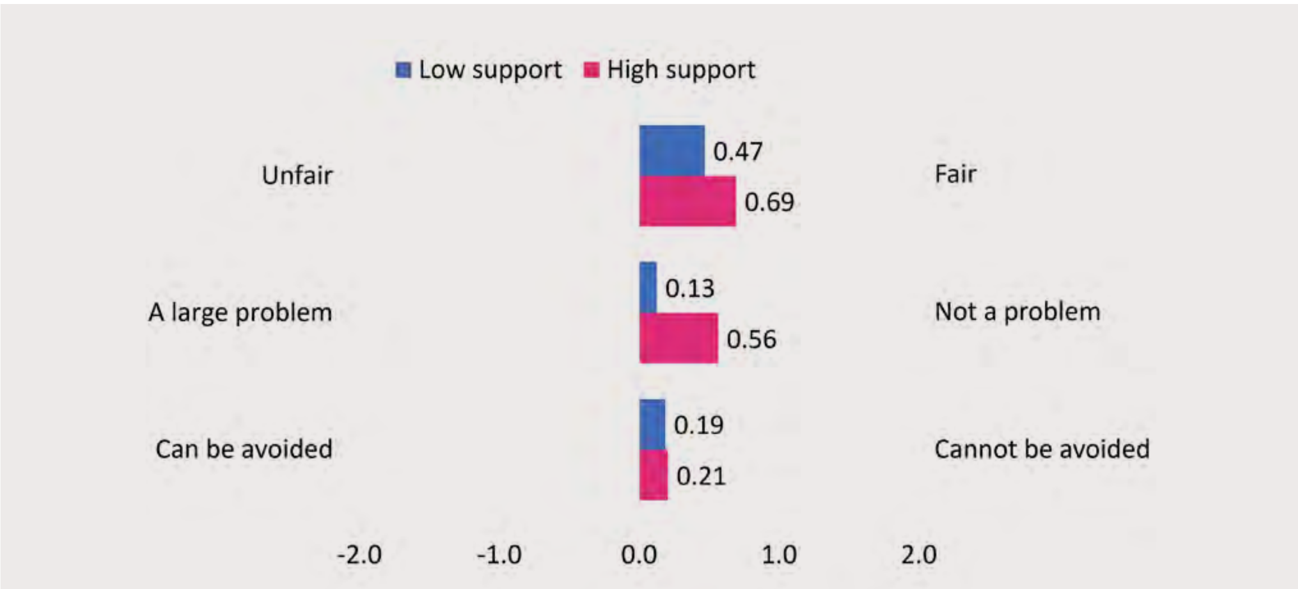


Figure 10. Perceptions of distribution of benefits and drawbacks of underground cables

Trust in Powerlink Queensland

As trust in project developers was identified as crucial for ensuring a social licence to operate and project acceptance, we asked participants to indicate their level of trust in Powerlink Queensland. A series of statements were used that relate to factors linked to a social licence to operate using a Likert scale (1=strongly disagree to 5=strongly agree). The mean responses suggest that most participants had high levels of trust in Powerlink to manage transmission projects appropriately whether they were overhead or underground (Table 12).

Table 12. Trust in Powerlink Queensland in relation to transmission infrastructure

I trust that Powerlink...	Overhead		Underground	
	Mean	SD	Mean	SD
Will make sure that a safe transmission line is put in place	4.2	0.7	4.2	0.6
Have the knowledge and experience to make sure that a safe transmission line is put in place	4.3	0.5	4.1	0.7
Will pay attention and perform safety checks to make sure it stays safe	4.2	0.6	4.2	0.5
Have the knowledge and experience to minimize the impact of the transmission line on the environment	4.0	0.8	4.0	0.8
Have the knowledge and experience to minimize the impact of the transmission line on human health	4.0	0.9	4.0	0.8

Trust in Local, State and Federal Government

When participants were asked to rate their trust in the different levels of government using the same Likert scale (1= very little trust and 5=strongly trust) in relation to engagement and decision making. The mean responses to these statements were much lower than trust in Powerlink. Overall, there was slightly higher trust in local governments compared to state and federal governments (Table 13). The questions may have influenced these responses because they relate to considerations for local residents and engaging meaningfully with communities, which is where local governments would have the most impact.

Table 13. Trust in local, state and federal government

To what extent do you trust that your...	Local Government		State Government		Federal Government	
	Mean	SD	Mean	SD	Mean	SD
Will take the well-being of residents sufficiently into account when planning new transmission projects.	2.9	0.8	2.6	0.8	2.5	0.7
Will make a responsible decision about whether or not to allow a new transmission project to go ahead.	2.8	0.8	2.5	0.9	2.5	0.8
Will meaningfully engage with the community about new transmission projects.	2.8	0.9	2.5	0.9	2.3	0.8

Social norms and consultation expectations

Participants were asked to provide responses to statements relating to their confidence in others (in their local community or wider Australia) to make the right decisions in relation to transmission lines using a Likert scale (1= strongly disagree to 5 =strongly agree). Mean responses showed that overall participants were somewhat confident others would make the right decisions (mean=3.3).

Reflecting issues of proximity and place attachment, individuals were less concerned about being consulted on transmission projects, unless they were in their local area where mean response was much higher. Figure 11 shows that over 70 % of participants either agreed or strongly agreed with the need to be consulted on transmission developments in their local area in contrast to only 22% agreeing or strongly agreeing on the need to be regularly consulted in relation to developments elsewhere in Australia.

Table 14. Average level of participant agreement on decision making and consultation

Statements	Mean	SD
I feel confident others in the Australian community will make the right decisions about transmission line developments elsewhere in Australia.	3.3	0.96
I feel confident others in my community will make the right decisions about transmission line developments in my local area.	3.3	0.98
I should be consulted regularly about transmission line developments elsewhere in Australia.	2.7	0.99
I should be consulted regularly about transmission line developments in my local area.	3.8	0.99

Figure 11. Participants' percentage agreement on decision making and consultation

Discussion

Changing support for transmission lines

Reflecting on the focus groups, the most obvious impact of the expert presentation and ensuing discussion, was the relative shift in sentiment and support from underground to overhead transmission infrastructure. It appears the high cost of underground transmission lines - quoted at 5 to 10 times – seems to have had the greatest impact on the general public's response. Ultimately minimising other concerns that had been raised in the discussions. For example:

> *"I don't like electromagnetic frequency stuff….and don't get me wrong, I really feel for anybody that has overhead powerlines 20 feet from their house. But it seems to me like the underground one, we're all going to have to pay a lot more for, regardless of where we are. And I'm not sure I want to buy into that kind of future."*

> *"Doing the distances we're talking about here, it has to be overhead. There's really no other way, for the cost and for the energy, the maintenance, the inspections. I really think it is really the only option for long distances."*

Conversely the arguments made for the advantages of underground lines such as environmental, aesthetics or reduced maintenance were not sufficient in people's minds to overcome the issues surrounding cost.

> *"The cost is concerning, and I think getting buy in from community over time will be really challenging, particularly if the costs will be passed on. We certainly know from recent examples in terms of a significant costs of power going up, that if people were to be faced with additional costs that would be handed on to them for underground cabling, I think if would be problematic for people."*

Knowledge, Trust, and Decision Making

Another impact of the focus groups was the effect on the participants' perceived knowledge or confidence in the subject matter, which they rated much higher in the post- surveys on the completion of the focus groups. The literature review highlighted the importance of a lack of knowledge in fuelling opposition to projects and the importance of filling knowledge gaps to enhance the acceptance of projects. Whilst this view was not consistent across all the literature, there appears little doubt that the provision of information by a trusted source, the expert, had a significant impact on participants' knowledge and opinions concerning overhead and underground transmission infrastructure. This is reflected in the following quote, highlighting the importance of providing unbiased, accurate information and how it impacts overall perceptions.

> *"I think if you're talking about how I'd want to be involved if it was coming to my area, I think what you did tonight with the presentation, you could do that at a community event like at a hall and say this is all the information. Because you've provided me with a lot of information that I didn't know plus the advantages and disadvantages. So then it helps people to be informed, because sometimes we get forced into decisions without actually knowing the, you know, the pros and cons about it."*

Survey responses also indicated that Queenslanders had a high level of trust in Powerlink, which appears to confirm general confidence in Powerlink's expertise when considering new transmission infrastructure. When it came to trust in the different levels of government, local government received the highest trust. This suggests the importance of proximity, where local councils are closer to where projects are being deployed and potentially seen to have greater interest in local impacts and relatively easy to access.

> *"As far as who makes the decisions, I have got to think maybe (it's hard) it probably should be somewhere around that Council level where the people, you know, if your Council is able to make or at least have certain sway on things. That's the lowest level of government that you can actually front up to and be able to talk to, and deal with. A lot easier than a state member or boardroom member or not."*

Focus group participants demonstrated they had strong connections to their local communities and local issues. This was reflected both in their views on the issues and opportunities initially captured by Strategy Finder where there were many examples identified that were based on personal experience. It was also reflected their feedback and the post-survey responses where the majority of participants felt that consultation should be conducted locally, providing accurate information to impacted communities in some form, whether it is through face to face meetings or via electronic means.

Looking for consensus

Despite the impact that the cost of underground transmission infrastructure had on participant views, a theme that emerged from the survey is that many participants are looking for outcomes that can strike a balance between the differing interests and priorities of local communities. Responses showed that the majority of participants were predisposed to solutions that provided a balance between economic and environmental priorities. The results also showed that the second highest number of responses relating to transmission lines were participants being in favour of combining underground and overhead technologies to achieve the best outcome. When it came to decision making there was also significant feedback supporting the use of a cross-section of stakeholders and weighing up the "pros and cons" as the preferred decision-making process. This was also reflected in the acknowledgement of balancing the needs of those immediately impacted by projects with the needs of the many as shown in the quote:

> *"I'm not against the idea [of consulting impacted people], but I think we have to be careful with letting 200 people potentially make a decision for 2 million people. Very often when there's censorship or there all the stuff, people are crying out about this. You know, ten people said you shouldn't sell this one product, which means that the rest of the country and not allowed to buy this product because then people didn't like it. Letting people [let] their emotions basically make decisions for the whole country is not really the way to go either. So that's obviously balance point then."*

This response demonstrates participants had some understanding of the complexities and trade-offs involved when trying to reach an acceptable solution.

Caution about outcomes

It is important to consider that participants in the focus groups were not directly impacted by current or proposed transmission line developments. Consideration needs to be given as to how views may change if a project was going on near their homes or if they were residents who have, or were to be, potentially impacted by transmission lines. Participants themselves recognised the issue, that despite what their opinions might be, the people impacted need to be considered the most.

> *"I would say these focus groups in the area that's being impacted would be a really good way of doing it. To obtain that sort of feedback and information. I think get doing through a widespread general survey isn't going to get you the information that you want in a particular area."*

Overwhelmingly, the literature is dominated by concerns residents have with the aesthetics, health, and proximity impacts of overhead transmission lines as was reflected in the Strategyfinder initial results. Given the complexity, uniqueness and context of every project situation, careful planning of the forums used and information provided needs to be well considered. As is the case for any responsible innovation and engagement, reflexivity to assess how projects are progressing and any emerging information needs of individuals and communities will help to move the discussion forward. Highlighting the importance of practices that enforce what the public see as procedural and distributive justice elements for engagement and ultimately project acceptance.

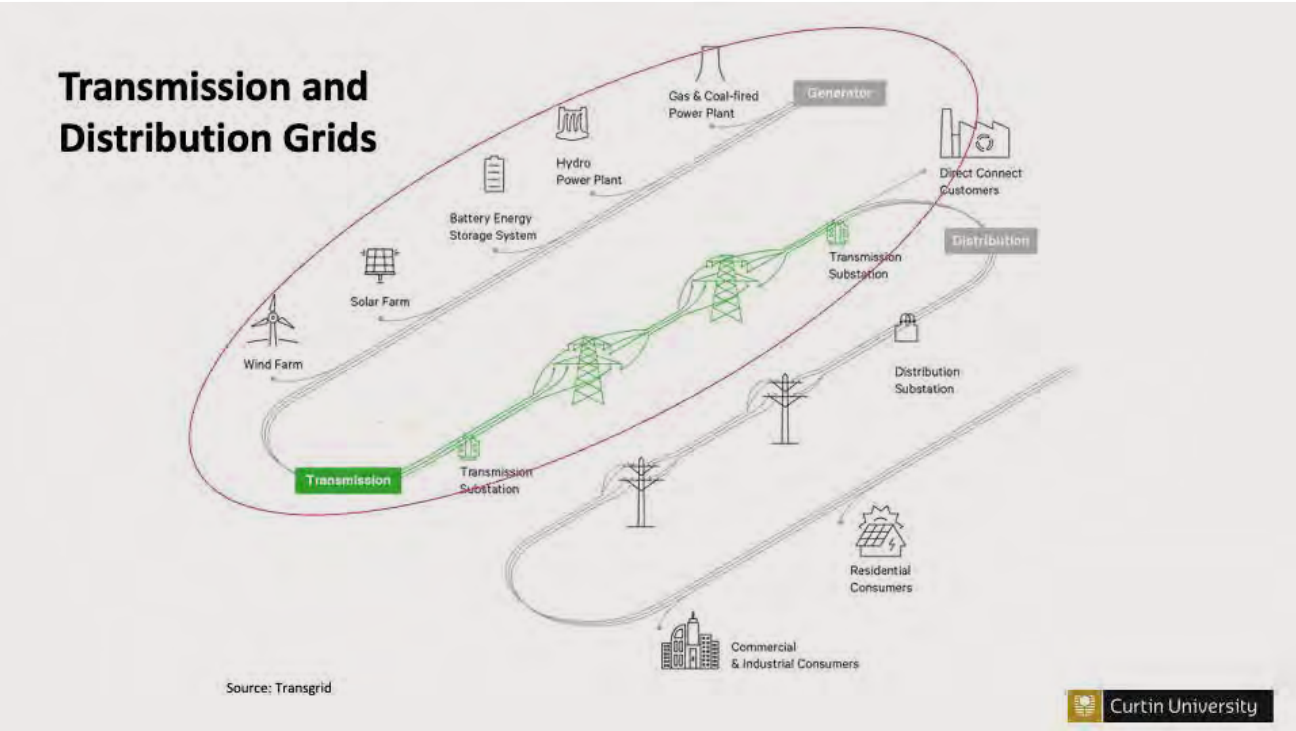
Conclusions

There are a number of conclusions that can be drawn from the focus group discussions.

Key Findings

1. Most importantly that the general public do not distinguish between distribution and transmission lines. Given the significant difference in the two across an electricity network this seems to be an important knowledge deficit that could be overcome.
2. On the whole the participants were very keen to be engaged on the topic and found the focus group format, including a presentation from the expert, as one process that instilled confidence in the participants and how they understood the issue.
3. While it was clear that underground transmission cables were generally more palatable than overhead lines, the majority of participants had a very pragmatic approach to the issue. That is, with the considerable cost differential between overhead lines and underground cables, participants would rather see the additional dollars be invested in other areas such as education and health.
4. There was recognition that it was important that local communities understood the trade-offs between the two choices of overhead and underground, with everyone in favour of impacted individuals being compensated accordingly.
5. Participants also agreed that in some instances, individual land holders will need to be forced to accept projects. In these cases, strong leadership by government was seen as an important and necessary facilitator of projects, particularly in the face of public opposition.
6. Examples provided by participants also reinforced the findings in the literature that the historical context in which projects are occurring will impact positive and negative perceptions of projects. That is, if some communities have not had positive experiences with project developers previously, they are less likely to welcome discussions for new transmission infrastructure projects.
7. The high levels of trust in Powerlink as the organisation responsible for transmission line projects in Queensland suggests participants viewed Powerlink as having the necessary expertise to get the job done, being able to make the 'right' informed decisions in relation to project deployment. Research, cited in the social literature review, emphasised the impact that trust at all levels has on acceptance of projects. Feedback and post-survey data supported this including trust in relation to information supplied, trust in project developers and those responsible for projects, as well as trust in the process of engagement including community involvement in the decision making.
8. The review of the literature (Chapter 6) clearly explains the factors that dominate social acceptance and social licence for transmission projects. Ensuring project developers are aware of these will go some way to help minimise the impacts on communities. Similarly, focusing on the enhanced principles for community engagement where co-design, transparency and collaborative processes are at the heart of the processes will also help.
9. Finally, as mentioned and identified in the discussions with focus group participants. There is a need for all stakeholders within communities to work together to optimise a shared outcome that maximises benefits and minimises impacts. While not always possible, the method outlined for co-design and collaborative constraint mapping between transmission providers and communities can help to go a long way in achieving this by creating community buy in for the final route selection and ultimately minimising opposition.

Appendix A: Copy of Expert Presentation



Moving electrons

High Voltage <u>Alternating Current</u> (HVAC) - most used in Australia and worldwide – stepped up (increased) or stepped down (decreased) when required.

High Voltage <u>Direct Current</u> (HVDC) - good for long distances but needs conversion to connect to the main AC grid.

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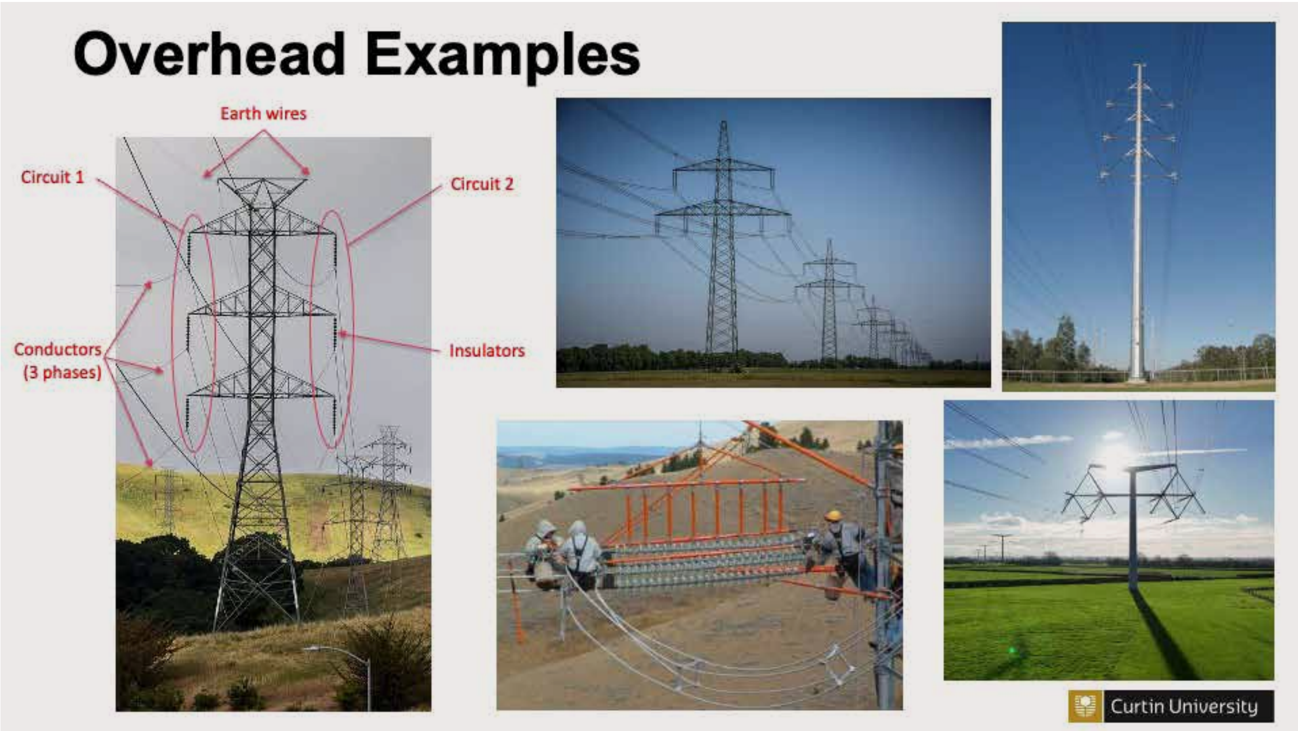
Overhead Examples
Earth wires
Circuit 1
Circuit 2
Conductors
(3 phases)
Insulators
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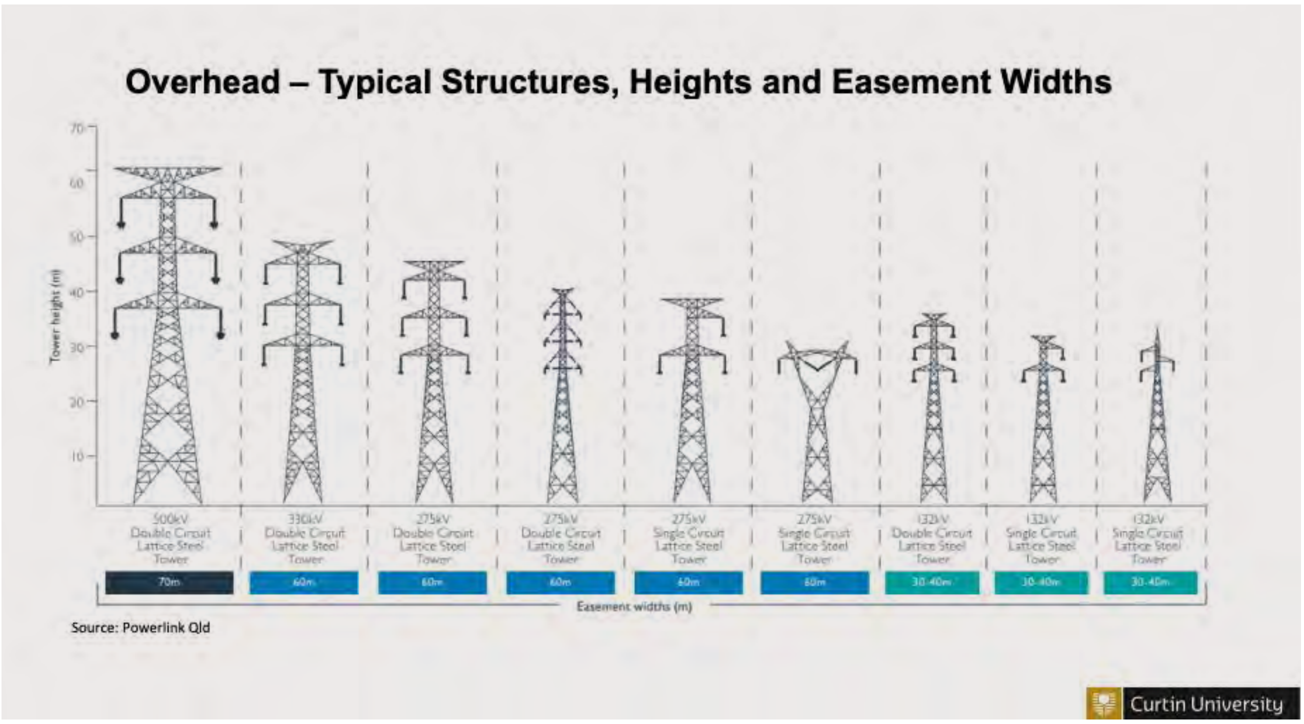
Overhead – Typical Structures, Heights and Easement Widths
Tower heights (m)
70
60
50
40
30
20
10
500kV Double Circuit Lattice Steel Tower
330kV Double Circuit Lattice Steel Tower
275kV Double Circuit Lattice Steel Tower
275kV Double Circuit Lattice Steel Tower
275kV Single Circuit Lattice Steel Tower
275kV Single Circuit Lattice Steel Tower
132kV Double Circuit Lattice Steel Tower
132kV Single Circuit Lattice Steel Tower
132kV Single Circuit Lattice Steel Tower
70m
60m
60m
60m
60m
60m
30-40m
30-40m
30-40m
Easement widths (m)
Source: Powerlink Qld
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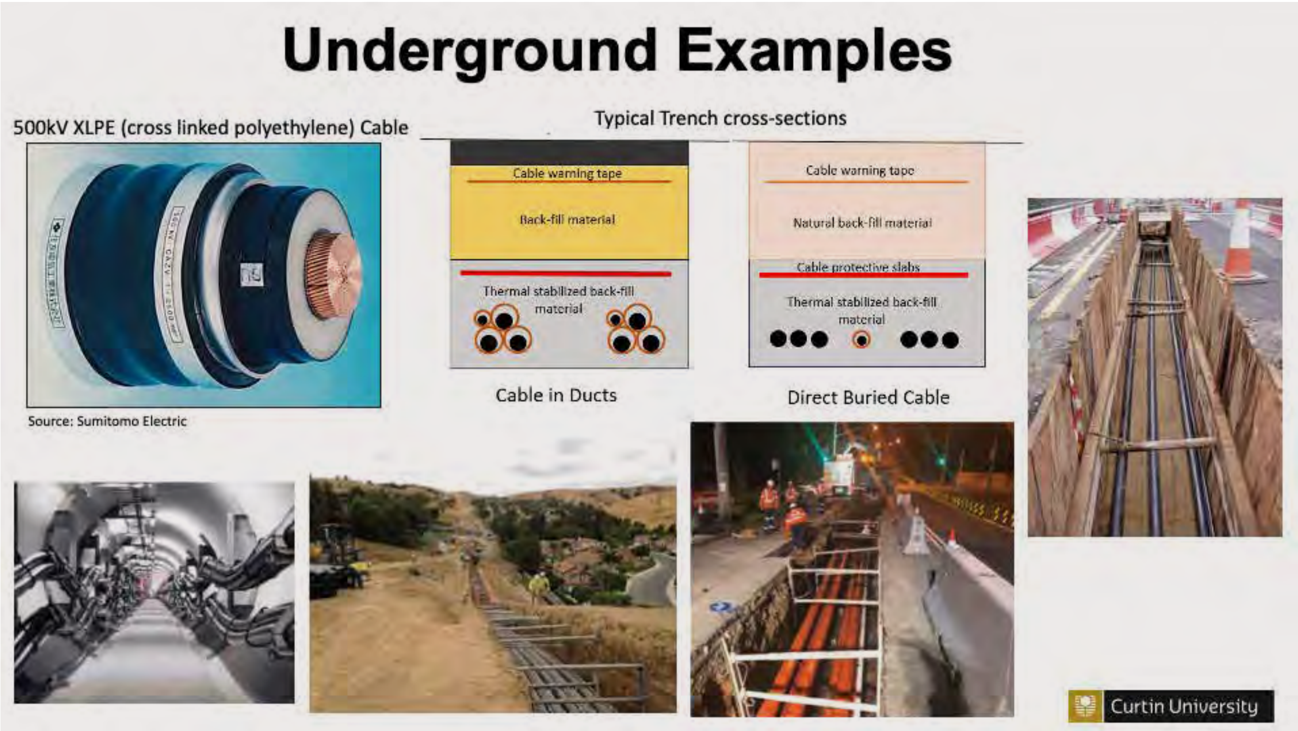

Technical Aspects /1

	Overhead	Underground
Power Transfer Capacity	2000 MW to 3000 MW per circuit (500kV)	1500 MW to 2000 MW per circuit (500kV), (Significantly less than overhead line)
Feasible maximum line route lengths	Up to 1000km. Overhead lines require less **reactive compensation** plant (per km) compared to underground cables.	40km to 60km **Reactive compensation** plant such as shunt reactors or static var compensators at are required to counteract the more significant capacitive effects of cables compared to an overhead line.
Corridor and easements	60 m for 275/330 kV and 70 m for 500 kV	For double circuit 500kV is in the range of 30 to 40m in a rural situation. Trench installation under wide public roads is also feasible. Land requirements for overhead to underground transition stations

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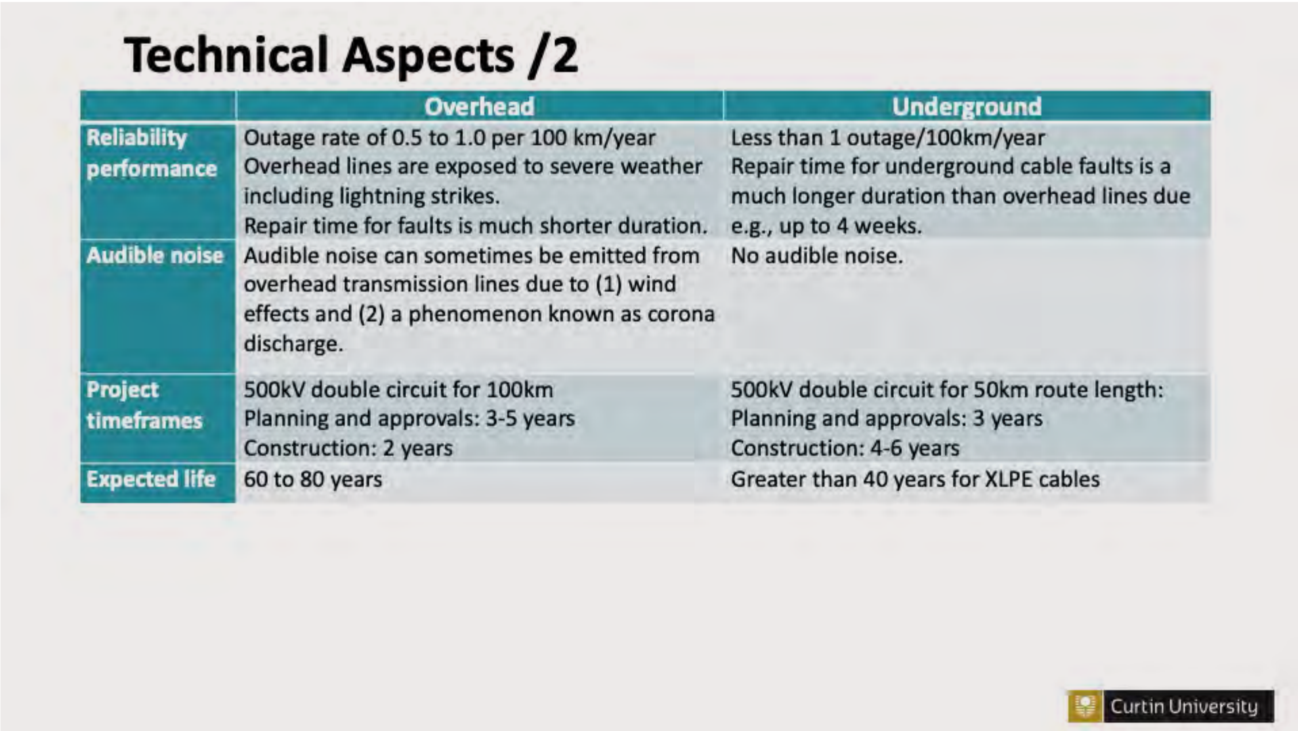

Technical Aspects /2

	Overhead	Underground
Reliability performance	Outage rate of 0.5 to 1.0 per 100 km/year Overhead lines are exposed to severe weather including lightning strikes. Repair time for faults is much shorter duration.	Less than 1 outage/100km/year Repair time for underground cable faults is a much longer duration than overhead lines due e.g., up to 4 weeks.
Audible noise	Audible noise can sometimes be emitted from overhead transmission lines due to (1) wind effects and (2) a phenomenon known as corona discharge.	No audible noise.
Project timeframes	500kV double circuit for 100km Planning and approvals: 3-5 years Construction: 2 years	500kV double circuit for 50km route length: Planning and approvals: 3 years Construction: 4-6 years
Expected life	60 to 80 years	Greater than 40 years for XLPE cables

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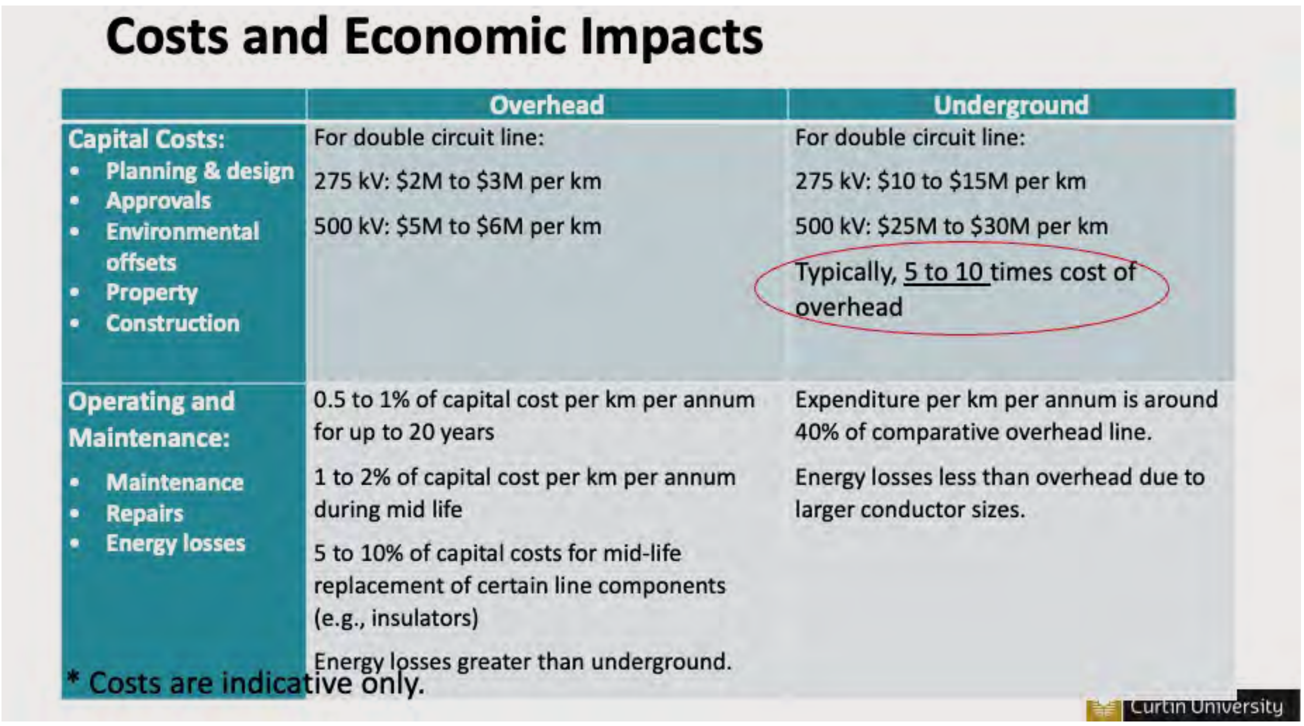

Costs and Economic Impacts

	Overhead	Underground
Capital Costs: • Planning & design • Approvals • Environmental offsets • Property • Construction	For double circuit line: 275 kV: $2M to $3M per km 500 kV: $5M to $6M per km	For double circuit line: 275 kV: $10 to $15M per km 500 kV: $25M to $30M per km Typically, <u>5 to 10</u> times cost of overhead
Operating and Maintenance: • Maintenance • Repairs • Energy losses	0.5 to 1% of capital cost per km per annum for up to 20 years 1 to 2% of capital cost per km per annum during mid life 5 to 10% of capital costs for mid-life replacement of certain line components (e.g., insulators) Energy losses greater than underground.	Expenditure per km per annum is around 40% of comparative overhead line. Energy losses less than overhead due to larger conductor sizes.

* Costs are indicative only.

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HVDC: The Future of Transmission?

DC Transmission Lines
HVDC transmission lines are typically made of overhead lines, underground cables, or a combination of both, and carry the DC power long distances between the converter stations.

AC/DC Converter Stations
These stations are located at the endpoints of the transmission line and are responsible for converting AC power to DC power (rectification) at the sending end and converting DC power back to AC power (inversion) at the receiving end.

More expensive to build
Converter stations and specialized equipment contribute to higher initial costs.

For longer route lengths **HVDC underground** expected to be **3 to 5 times** cost of **HVAC overhead**

Advantages

- Efficient for long-distance transmission
- The most feasible option for long (>50km) off-shore or on-shore transmission cable routes
- Lower Line Losses, however additional losses from converter stations compared to AC
- More compact overhead line structure or towers normally requiring just 2 conductors
- More compact underground cable trench profiles
- Interconnection of asynchronous AC systems
- Controllability and Stability
- Lower Environmental Impact
- EMF generally lower impact than AC for similar voltage

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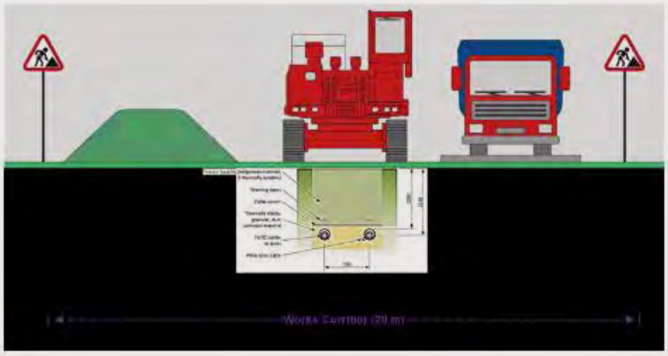
HVDC: The Future of Transmission?



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Electromagnetic Fields (EMF)

EMF - combination of <u>electric</u> and <u>magnetic</u> fields that are generated by electrically energised or charged objects, including power lines, cables, appliances, and electronic devices.

Scientific research on the health effects of EMF from powerlines has occurred since the 1970's.

Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) - *"The scientific evidence does not establish that exposure to extremely low frequency (ELF) EMF found around the home, the office or near powerlines and other electrical sources is a hazard to human health".*

International Commission on Non-Ionizing Radiation Protection (ICNIRP) "*…the currently existing scientific evidence that prolonged exposure to low frequency magnetic fields is causally related with an increased risk of childhood leukemia is too weak to form the basis for exposure guidelines. In particular, if the relationship is not causal, then no benefit to health will accrue from reducing exposure"*

World Health Organization (WHO) – undertakes and sponsors research on the health impacts of radiation including EMF. Considerable information and technical resources are available on their website

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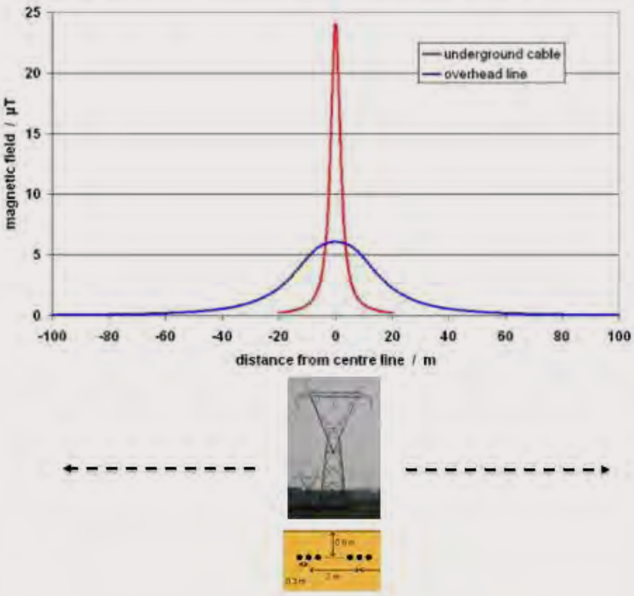
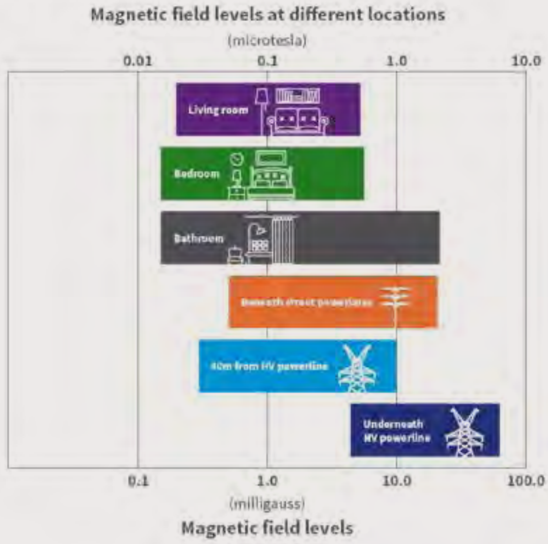
Typical EMF Profiles for Underground and Overhead Lines



Source: emfs.info



Source: arpansa.gov.au

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Environmental Impacts

Habitat loss, fragmentation, and the **alteration of environmentally sensitive areas** are key negative outcomes of the construction of transmission lines on the natural environment.

Clearing of vegetation for easements needed for the construction of both overhead and underground lines is likely to **impact on wildlife habitats** as well as to cause **changes in the microclimate** by restricting the growth of plants and trees.

Effects heightened in **sensitive natural environments** including **watercourses, wetlands and national parks.**

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Environmental Impacts

Overhead: create a barrier effect, where biodiversity is negatively impacted by changes in migrations patterns, collision, electrocution (birds, bats, etc.) but can be mitigated by undergrounding.

Underground: high likelihood of soil degradation and hydrological alterations throughout the lifetime of underground HVAC lines, but likely less than overhead.

Bushfires: of the 32 fires listed in the 2019 NSW Inquiry, two were started by power lines, no distinction was made in the document between distribution or transmission lines. The Royal Commission into National Natural Disaster Arrangements Report 2020 also highlighted the vulnerability of power lines to bushfires and noted that underground power lines were damaged by the fires.

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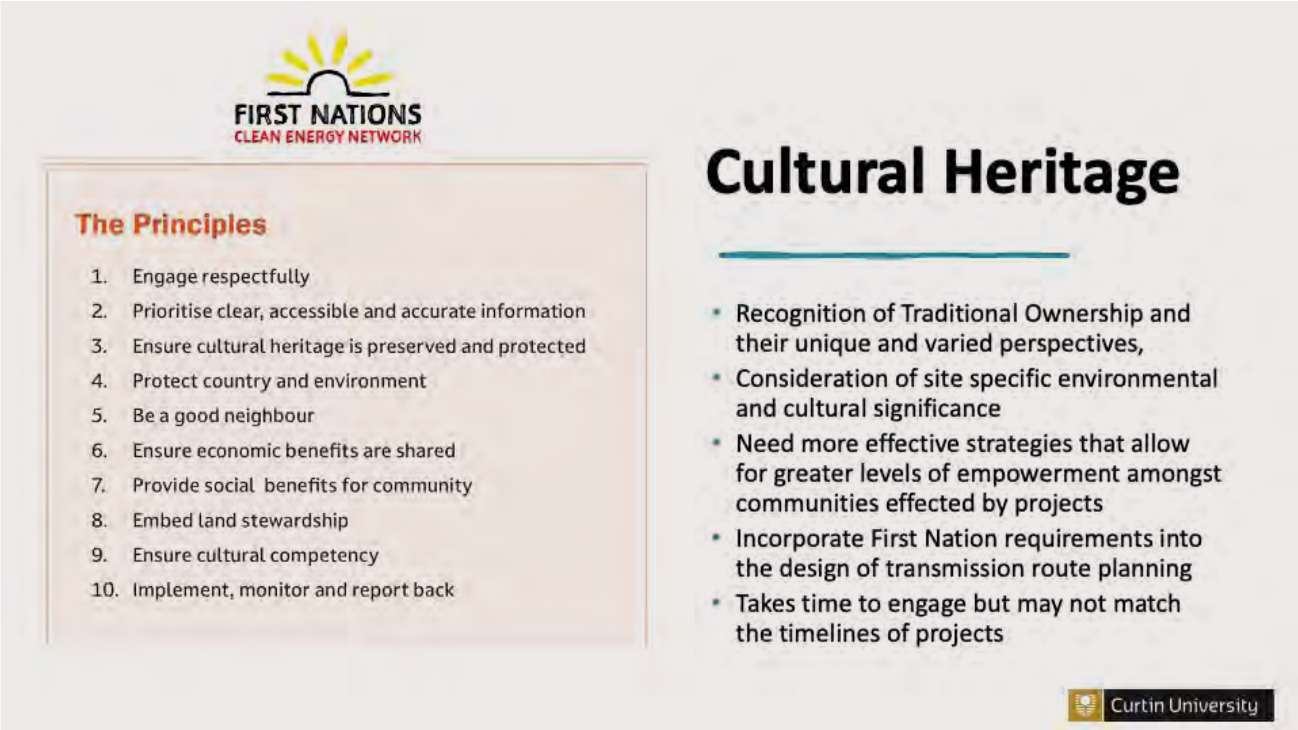
FIRST NATIONS
CLEAN ENERGY NETWORK
The Principles
1. Engage respectfully
2. Prioritise clear, accessible and accurate information
3. Ensure cultural heritage is preserved and protected
4. Protect country and environment
5. Be a good neighbour
6. Ensure economic benefits are shared
7. Provide social benefits for community
8. Embed land stewardship
9. Ensure cultural competency
10. Implement, monitor and report back
Cultural Heritage
Recognition of Traditional Ownership and their unique and varied perspectives,
Consideration of site specific environmental and cultural significance
Need more effective strategies that allow for greater levels of empowerment amongst communities effected by projects
Incorporate First Nation requirements into the design of transmission route planning
Takes time to engage but may not match the timelines of projects
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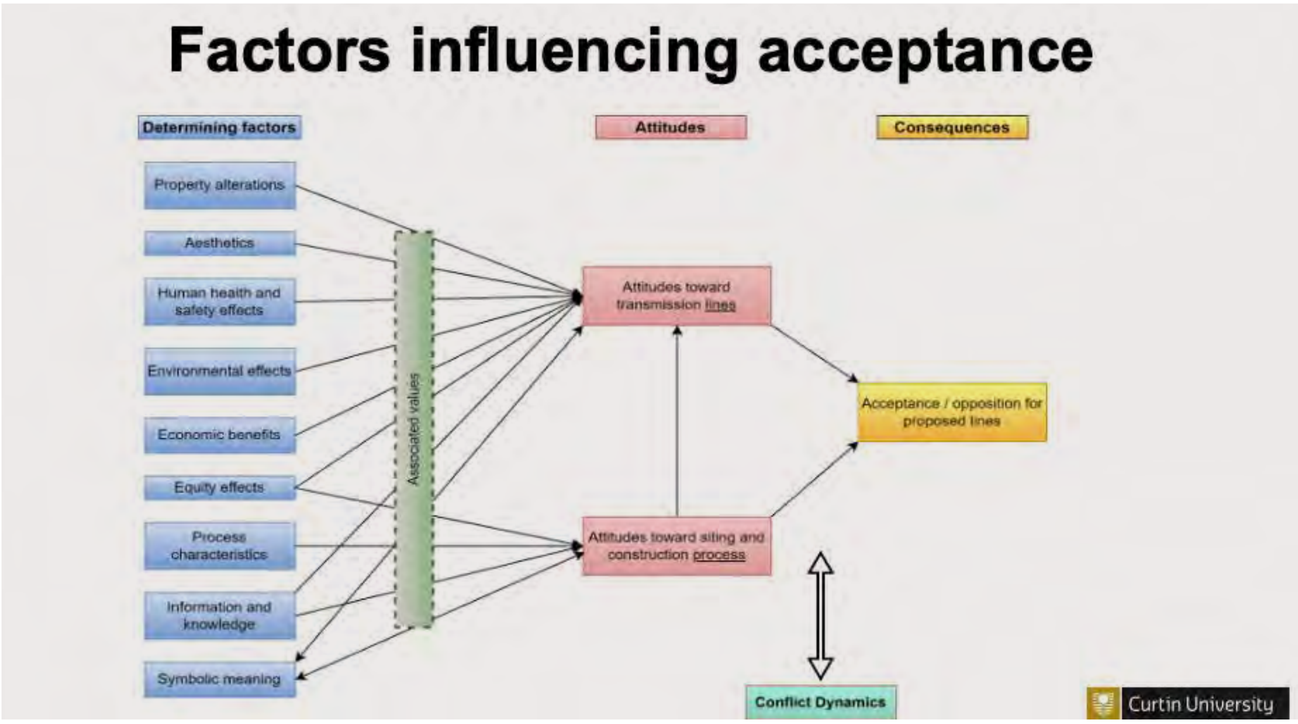
Factors influencing acceptance
Determining factors
Attitudes
Consequences
Property alterations
Aesthetics
Human health and safety effects
Environmental effects
Economic benefits
Equity effects
Process characteristics
Information and knowledge
Symbolic meaning
Associated values
Attitudes toward transmission lines
Attitudes toward siting and construction process
Acceptance / opposition for proposed lines
Conflict Dynamics
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Social impacts

Distributive justice – benefits/burdens
- Visual impacts
- Conflicts with agricultural practices, tourism etc.
- Compensation beyond the landholder

Procedural justice
- Respectful, fair, and transparent
- Flexibility in route decision making
- Adequate time to engage

Context matters
- Historical and current
- Place attachment
- Cumulative impacts

Adequate information to inform decision making
- Trusted expert
- Capacity to engage (time and resources)

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Questions?

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