Investigation of HVDC Trans-Australian Interconnections

By

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Abstract

This paper presents the findings of an investigation into a new electricity transmission interconnector linking Western Australia to the National Electricity Market including the eastern states of Australia. The proposed interconnector would capture the economic and security benefits from the time and weather diversity across Australia, both the three hour differences in timing of the peak demands for electricity as well as the differences in timing of power generation. The later includes the traditional sharing of generation reserves between the western and eastern power systems as the diversity of power station breakdowns which rarely coincide, and also the diversity in the timing of solar and wind power generation – or put simply that solar power is still strong in Western Australia when the sun has set along the east coast and needle-peak power demands are driving huge investments in energy storage or load shedding. This paper presents the findings of investigations by the author into the optimum technology for the East-West interconnector, being HVDC-VSC, configured as a single bipole with a capacity of around 1000MW, its optimal voltage of around +- 500KV, and the optimal transmission line design being guyed cross-rope structures as well as indicative transmission line routes and preferred connection points for the interconnections. Preliminary estimates are presented of the capital costs and life-cycle costs and benefits of the East-West interconnector that demonstrate that it may be economically justified under the Australia's Regulatory Investment Test for Transmission. The other benefits of the East-West interconnector to Western Australia are examined including the potential economic and social benefits to the Collie community otherwise facing an early closure of the region's energy infrastructure and an associated economic downturn and high unemployment levels. It is concluded that East-West HVDC interconnector should be fully investigated as strategic, nation building infrastructure to underpin the delivery of affordable, reliable and sustainable electricity to Australia's industry and society and to support Australia's transitions to progressively higher levels of renewable electricity generation.

***Index Terms*—trans-Australian interconnection, HVDC, VSC, renewables**

Introduction

As illustrated in Fig.1, the Eastern Australian national Electricity Market (NEM) transmission system is one of the world's longest alternating current (AC) power systems stretching 5,000kms from North Queensland to South Australia, over a relatively weak transmission system passing sequentially through Qld, NSW, Victoria and SA. The grid experiences high congestion and high transmission losses, which restrict and distort the free flow and interstate trade of bulk electricity in the NEM. There are also serious concerns for the security of the SA power system due the closure and sidelining of conventional synchronous power stations due to the rapid growth in renewable generation and high gas prices resulting in low system strength and synchronous inertia. The state-wide SA blackout on 28th September 2016 demonstrated that the SA power system lacks the electrical strength to withstand the tripping of the single SA-Victoria interconnector due to the severe voltage swings that then tripped the remaining SA synchronous generators before the SA frequency eventually collapsed.

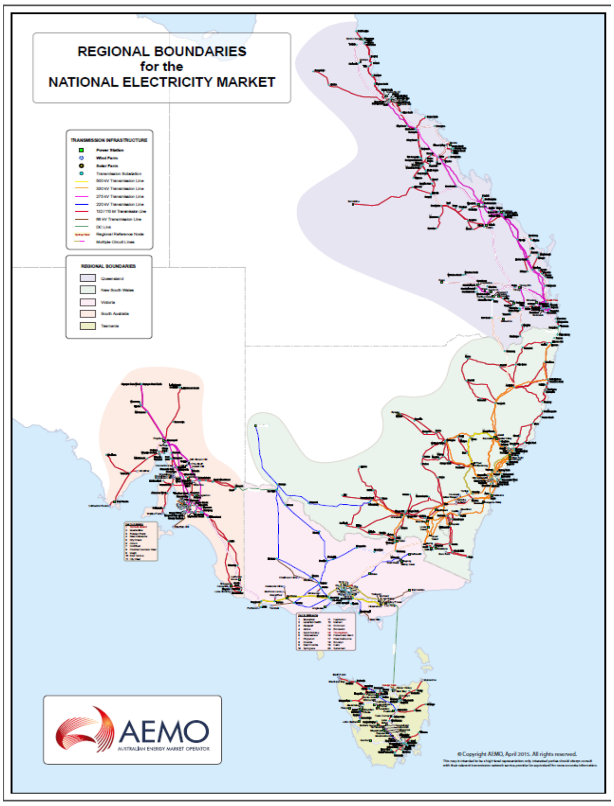
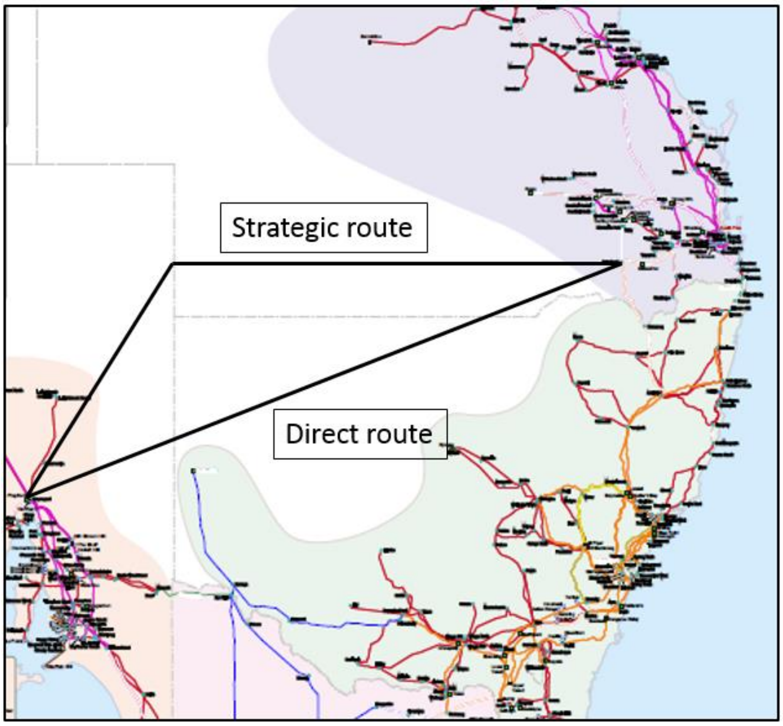


Fig 1 Australian National Electricity Market (11)

Meshing the NEM



As illustrated in Fig. 2, it would be feasible to directly connect the existing South Australian and Queensland electricity grids with a new interconnection, forming a secure NEM meshed grid, that would be inherently more reliable and secure that the current flawed linear NEM interconnection design. This would significantly improve the grid security for SA and Qld, providing both states with redundant interconnectors to two other NEM states, as is currently enjoyed by only NSW and Victoria.

Had such an interconnector been in place, it would have eliminated the very serious load shedding that has recently occurred on three separate occasions across the NEM: being the South Australian blackout in 2016, the

Figure 2 Meshing the NEM by a direct SA to Qld Interconnector

NSW/Victorian blackouts in 2017 caused by a single lightning strike knocking out the single Qld-NSW interconnection and the Victorian-SA load shedding in 2019 caused by severe constraints on the NSW-Victorian interconnector coinciding with high loads and the tripping of Victorian generators. A new interconnection directly between Qld and South Australia, would have immediately re-routed power across the NEM to support the southern states ensuring that none of these three recent events would have resulted in load shedding. Market studies undertaken by the author confirm that such a meshed NEM design would fundamentally change the dynamics of the current high pool prices when the existing single interconnectors between the states reach their limits as well as eliminating the unacceptably high risks of load shedding due to the currently flawed NEM interconnector design.

A direct interconnection between SA and Qld would also halve the transmission distance between SA and Queensland, bypassing the high transmission losses and congestion on the existing grid which passes through Victoria and NSW. This would increase the efficiency of the entire NEM

Technology for Interconnections

A comparison has been made of HVAC, HVDC-LCC (line commutated converter) and HVDC-VSC (voltage source converter) technologies for the Eastern interconnector. Between Queensland and NSW

Given the long transmission distance of around 1,600km for the Eastern interconnection and 2,400km for the East-West interconnection between South Australia and Western Australia, it is unquestionable that HVDC is economic compared with HVAC, delivering a savings of up to 40% in capital costs as well as lower transmission losses.

Both HVDC-LCC and HVDC-VSC are technically feasible technologies for voltages up to 500KV based on extensive world-wide experience with HVDC. Australian interconnector typically discount HVDC due to Australian utilities lack of experience and understanding of HVDC technology, There are only three HVDC interconnection in Australia and all are owned and operated by small private companies and not by the large state-based Australian transmission companies. Both HVDC-LCC and HVDC-LCC are now mature technologies widely used overseas especially HVDC-VSC which is the interconnector technology of choice for large power systems being weakened by the increased penetration of variable solar and wind power renewable generation technologies, that are displacing conventional synchronous generation. HVDC VSC has now considerably closed the gap to HVDC-LCC technology in terms of capital cost and efficiency and has very substantial power system security advantages very relevant to the Australian situation. [1].

The last decade has seen the development and successful application of high capacity HVDC-VSC technology suited to flexible, multi-terminal transmission to support weaker power systems and connections to large scale renewable energy generation. Since 2010, more than twenty HVDC-VSC schemes have been installed or committed in more than ten countries with voltages up to 500kv, capacities up to 2000MW and transmission distances up to 1000km [2]. It is the interconnector technology of choice for long distance integration of renewables across the existing HVAC grid in Europe and China.

In 2012 the CIGRE HVDC working group B4.46 undertook a comparison of HVDC-VSC transmission with other AC and DC technologies from a technical and economic perspective [3],[4]. Table 1 summaries some of their technical findings which highlights the additional VSC capabilities that make VSC the preferred option for these Australian interconnections given the growing power system security concerns and the benefits of increasing the capacity of the existing NEM interconnected network and connecting Western Australia to the NEM.

	HVAC w/o FACTS	HVAC with FACTS	LCC-HVDC	VSC-HVDC
Fast active power flow control	-	Available	Available	Fast control
Fast reactive power flow control	-	Available	-	Fast control
Transient stability improvement	Inherent	Available	Available	Available
Damping Control	-	Available	Active Power Modulation	Active and reactive power control
Black-start / island supply	-		-	Full support
System loss reduction	-	Depending on situation by means of reactive power control	-	Depending on situation by means of reactive power control

Table 1 CIGRE B4 Comparison of Technologies [3]

Given the materiality and relevance of these additional benefits and the ability of HVDC VSC to connect additional terminal stations along the interconnector routes for future renewable generation developments, HVDC-VSC is the preferred technology for these applications.

Route for Eastern Interconnection

A study by the author considered two alternative routes for the Eastern interconnector as illustrated in Fig. 2, being: the Direct route from SA to Qld passing through north-west NSW over a distance of 1,400kms and the Strategic route via the undeveloped renewable energy resources in central Australia over some 1,600kms.

Consideration was given to much better access for the Strategic route which follows the existing gas pipelines between Queensland and South Australia as well as the Strategic routes potential to facilitate the future development of some of Australia's best renewable energy resources. by providing for a future connection for renewable energy generation which could be transmitted to both South Australia and Queensland depending on their needs at the time.

Unlike HVDC-LCC technology, HVDC-VSC can accomodate multiple terminals along the interconnector, an example being the Zhoushan VSC scheme in China which has five multi-terminals with capacities of 400MW, 400MW, 100MW, 100MW and 100MW [7].

As illustrated in Fig. 3, the Strategic route passes through undeveloped geothermal energy resources in Central Australia and well as areas of much higher solar energy potential. There are also better wind power resources along the southern end of the Strategic route and substantial natural gas and undeveloped LNG resources in western Queensland.

The estimated cost of installing a new HVDC converter connections along the route could enable the development of more efficient, lower cost renewable generation with a net present value estimated to well exceed that additional cost, thereby delivering a net benefit attributed to the Strategic route.

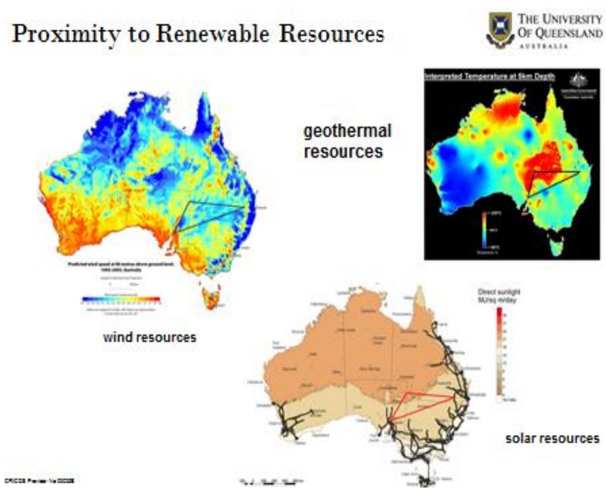


Figure 3 - Australia's Best Renewable Energy Resource

Access and existing land uses along the Strategic route are more suitable for efficient transmission line construction and maintenance than along the Direct route which passes though intensely cultivated land in Queensland and northern NSW and also passes through remote and challenging channel country in north-western NSW. The land use along the Strategic route is compatible with the use of innovative transmission line designs such as guyed cross-rope structures (figure 5) which have been proven internationally to reduce both cost and construction time by up to 40% and have better lightning and high wind performance than conventional line designs used elsewhere in Australia.

A preliminary evaluation of alternative connection points for the Eastern interconnector concluded that the best Qld connection would be at Bulli Creek 330kv substation and the SA connection at Davenport 275kV substation. Studies have indicated that the Bulli Creek connection would additional benefit of substantially increasing the capacity of the existing Qld to NSW interconnection if HVDC-VSC technology is adopted. Davenport substation is a strong point on the SA grid, and a "springboard" for the East-West HVDC interconnector to Western Australia. It is close to undeveloped wind-power and solar PV resources and the transmission supply point for the Olympic Dam mine area.

Preliminary Design and Estimated Costs

Fig. 4 illustrates the findings of the CIGRE Joint Working Group B2/B4/C1.17 "Impacts of HVDC Lines on the Economics of HVDC Projects dated August 2009 [5]. It summarizes how interconnector total annualized costs vary with interconnector length and capacity, as well as the optimum interconnector voltage.
The costs include transmission line and terminal station annualized capital costs as well as transmission losses and annual operation and maintenance costs.

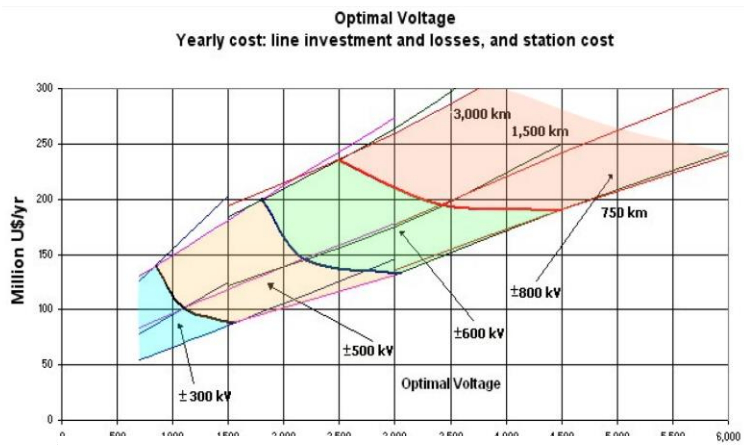


Figure 4 Optimum Voltage vs capacity and distance (5)

Based on this CIGRE working group analysis, the optimal voltage for the Eastern 1600km interconnector, transmitting up to 1000MW would be around 400kv whilst the East-West interconnector, being some 2,100km long may suit a 500KV HVDC voltage to optimize capital and operating costs and transmission losses. HVDC-VSC is already being installed globally at voltages up to 500KV.

Providing a second interconnector to SA with a total capacity of 700MW to 1,000MW, would duplicate the existing AC interconnection and provide a total interconnection capacity equivalent to the total average SA state-wide demand. It would enable new renewable generation (both wind power and solar power) to be installed and operated in SA and alleviate interconnection congestion and SA security concerns.

Cost comparisons confirmed that an interconnector voltage of 400kV would require two sulphur conductors per bi-pole or triple Term conductors which was found to be optimal from a capital cost, transmission loss and corona viewpoint. The East-West HVDC interconnector would require the operating voltage to be increased to around 500KV but could achieve an efficient interconnector capacity of around 1,000MW using triple Tern conductors which would help to reduce corona losses. The interconnector voltage drop and conductor losses for the eastern interconnector would be around 10% and around 15% for the longer east-west interconnector. This demonstates that the interconnector design would be an efficient balance between initial capital costs and transmission losses over its operating life.

Estimated Interconnection Capital Costs

Table 1 Estimated Capital Cost Trans-Australian Interconnectors

	Eastern Interconnector	**East-West Interconnector**
Transmission Lines	$ 900m	$1,500m
Easements	$ 70m	$ 130m
Converters stations	$500m	$ 900m
HVAC connection costs	$30m	$ 50m
TOTAL COST	$1,500m	$2,580m

The estimated capital cost of the Eastern interconnector and East-West Interconnector are summarised in Table1 based on converter cost estimates advised by the three European manufactures of HVDC-VSC converters. Transmission line cost estimates are based on guyed cross-roped tower design costs estimates from by an international transmission line consultant adjusted for Australian labor costs and the remote location. The estimated transmission line costs assume that both interconnector routes generally avoid cultivated land to enable the construction of highly efficient guyed cross-rope transmission towers and that their routes are alongside existing gas pipelines and the trans Australian railway which both provide excellent access for line construction and maintenance.

Operation and maintenance costs over the asset life-cycle of the interconnectors have been estimated to be $15mpa and $26mpa respectively (ie 1% of the capital cost) capitalized at $210m and $360m respectively over their asset lives. This covers the cost of routine inspections, line patrols, easement and access track maintenance, scheduled maintenance, as well as corrective and emergency repairs.

Transmission losses including conductor resistive losses, corona losses and HVDC-VSC converter losses are have been estimated assuming CIGRE B4 VSC converter loss figures [3] and balanced power flows between SA and Qld and between western and eastern Australia The capitalized cost of losses over the asset lifecycle of the interconnector has been estimated to be $460m and $750million respectively for the two interconnectors.

Summating the capital costs, operation and maintenance and transmission loss estimates gives total estimated life-cycle costs of $2,170m for the Eastern interconnection and $3,690m for the East-West Interconnection.

Potential Benefits

Indicative financial benefits of the Eastern interconnector have been estimated from high level analyses and the results of previous interconnector studies. The categories of benefits considered and quantified in NPV financial terms are shown in Table 2.

Table 2 Estimated Potential Benefits of Eastern Interconnection

Item	Estimated Potential Benefit
Rectify South Australian Security Risks	A$ 900m
Facilitate Renewable Generation in SA	A$ 300m
Facilitate Renewable Generation in Central Australia	A$ 300m
Qld and NEM Reliability Benefits	A$ 400m
Improvements to NEM Efficiency	A$ 700m
TOTAL Benefits Eastern Interconnection	A$2,600m
TOTAL Life cycle Costs Eastern Interconnection	A$2,170m
Net Benefits and benefit/cost ratio	$430million 20%

Indicative financial benefits of the East-West interconnector have been estimated from high level analyses and the results of previous interconnector studies. The categories of benefits considered and quantified in NPV financial terms are shown in Table 3.

Table 3 Estimated Potential Benefits of East-West Interconnection

Item	Estimated Potential Benefit
Reduction in Overall generation reserves in Western and Eastern network, assuming 500MW savings both at $1,000/KW	A$ 1,000m
Economic benefits from extending the cost-effective life of Western Australian power stations including Collie power stations	A$ 600m
Economic benefits from extending the cost-effective lives of Australia's most efficient coal fired power stations (all five in Qld) and the economic benefits to Western Australia from gaining access to their lower cost, cleaner electricity	$A1,000m
Benefits from utilising diversity of the timing of peak loads and renewable power generation between east and west Australia – valued at the avoided cost of installing 500MW of battery storage in each of Western Australia and Eastern Australia at a cost of	A$ 900m

$900/MW	
Improved operational efficiency including dispatch costs and reduction in transmission losses assuming $20/MWh, 25% ACF	A$ 600m
TOTAL Benefits East-West Interconnection	A$4,100m
TOTAL Life cycle Costs Eastern Interconnection	A$3,690m
Net Benefits and benefit/cost ratio	$410million 11%

Both interconnectors would also deliver further unquantified benefits such as: -

1. Helping achieve Government renewable energy targets.
2. Creating additional employment opportunities.
3. Stimulating and preserving the economics of regional communities.
4. Proving the viability of low-cost, long distance HVDC –VSC transmission
5. Increasing the competitiveness and security of the NEM and reducing wholesale electricity price volatility.

East – West Interconnection

Preliminary investigations of the East-West Interconnection have indicated that the best interconnector route is to run alongside the Great Australian railway line from the Davenport substation to the Kalgoorlie area due to the direct route and excellent access provided by the railway and its associated road access. The sparce land use is also ideal to the use of extremely cost effective guyed cross rope transmission line structures

The interconnector must continue westwards beyond Kalgoorlie as the existing 220kv AC transmission line supplying Kalgoolie from the Muja Power station have insufficient capacity to support a 1,000MW east-west interconnection. The benefits on installing a HVDC-HVSC terminal station at Kalgoolie have not been assessed but would have to justify the cost of the required converter station.

Alternative routes for the HVDC interconnector running west from Kalgoolie have been assessed and it was concluded that the route to the Perth or Muja regions would pass through intensely cultivated land which is likely to necessitate much greater cost conventional free-standing transmission towers as well as having much greater social and economic impacted on existing land users along the route.

A better and lower cost route is for the HVDC interconnector to run north-west-west from Kalgoorlie to the northern end of the existing 330kV network at the Three Springs substation in the Geraldton area. This would enable the new interconnector to import and export sufficient power via the Western Power 330kV power system and also be well placed to enable: the future development of the renewable energy resources in the Geraldton area In the longer term the HVDC grid could be extended northwards to the Pilbara region to support the future expansion of mining and minerals processing as well as the future development of the renewable energy potential of the Pilbara region.. Ultimately, it may become technically and economically feasible to export Australian electricity to Indonesia and South-east Asia via HVDC undersea cables

Benefits to the Collie Region in Western Australia

The Collie region is an important Western Australian energy resources centre due to is extensive coal mines and existing electricity generation facilities. The viability of the region is increasingly being threatened by the progressive development of intermittent renewable generation is the relatively small and isolated Western Power electricity market which will drive the early closure of the Collie power stations and their associated coal mines. This will have serious consequences for the local economy and community with flow-on implications for Western Australia's economy.

The connection of the Western Australian power system to Australia's much larger eastern states NEM power system, via the proposed East-West HVDC interconnector will substantially increase the size of the wholesale electricity market in which the Collie power stations operates. This will provide the Collie power stations with a significantly increased opportunity to continue to generate cost effective electricity which could be utilized both locally in Western Australia or exported via the new East-West HVDC interconnector to the NEM and eastern states of Australia.

This will alleviate the otherwise increasing economic pressures on the Collie Power Station and provide increased opportunities for it to continue to operate and utilize the full technical life of its existing power plant and coal mine. It will provide additional time to develop new local industries in the Collie area, retrain the existing highly skilled workforce and to invest in new industries and technologies that provide ongoing employment and continue to support the Collie community.

THE BIGGER PICTURE – ACROSS AUSTRALIA AND BEYOND

The NEM states of Australia are already operating as a large interconnected power system with an interconnected transmission network spanning Queensland through to South Australia, albeit over the longest, weakest HVAC interconnection in the world . There is some level of security offered through the existence of the interconnections which derive benefits from the generation and load diversity within the eastern states, although the interconnections are frequently constrained. With the construction of the eastern HVDC interconnecttor between Queensland and South Australia, to MESH the NEM, current power system security risks will be reduced. The nation may more safely move towards it's renewable energy targets[1] through the development of more efficient renewable generation via a more efficient HVDC grid. MESHing the NEM will cost effectively and reliably integrate the further development of renewable generation and improve power system efficiency. There is also an opportunity to interconnect Western Australia, via the East-West Interconnection and in the longer term, potentially the Northern Territory.

CONNECTING TO WESTERN AUSTRALIA

There are several benefits of interconnecting WA (starting with Western Power's 330kV transmission network), with one such benefit being that WA would be able to participate in interstate trade of electricity with the NEM. Currently, WA has a generating capacity of just over 6000MW, however the typical daily electricity demand is only some 2200MW. After allowing for generation outages, there is sufficient surplus generating capacity in Western Australia to export up to 1500MW across to the East-West interconnector to the eastern states (refer to figure below) of unused generation capacity.

State	**Summer**	**Winter**
NSW	14,100	0
QLD	10,600	0
VIC	9,400	0
SA	2,600	0
TAS	0	1,900
WA	4,100	0

Table 4 Maximum demand forecast in 2016
AEMO National Electricity Forecast Report

This would represent only 5% of NSW, QLD, and VIC's total peak demand of 33,700MW which could be supplied by affordable electricity from existing WA power stations and sustainable electricity from the development of WA's high quality renewable energy sources..

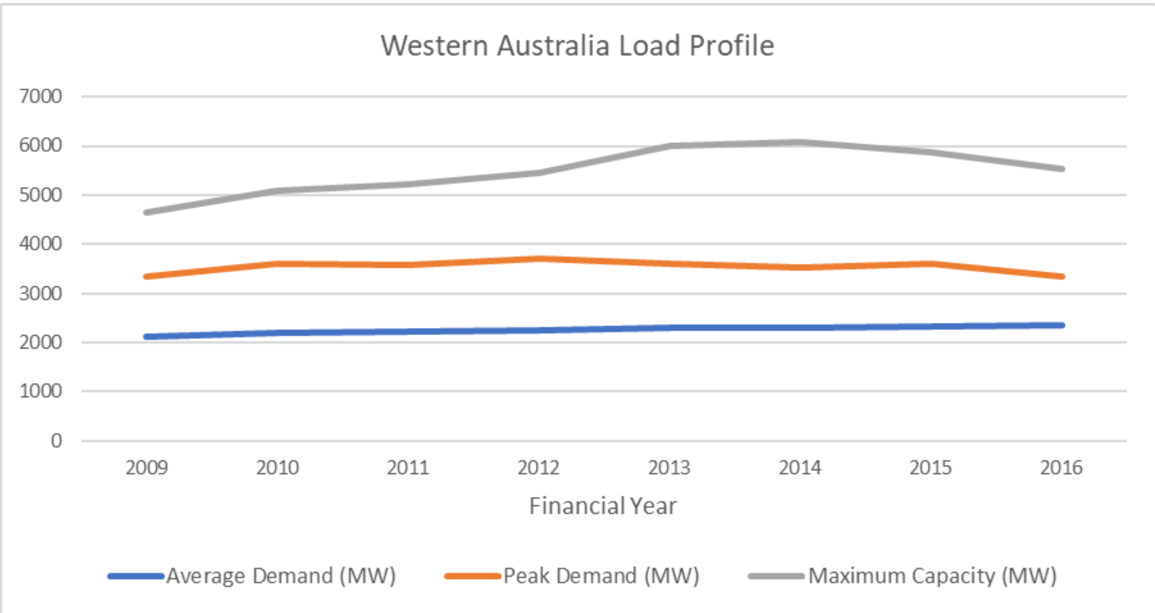


Figure 6 : WA load profile from 2009 to 2016

The development of the East-West HVDC interconnector to WA to the NEM would allow the NEM to benefit economically and contribute to increased reliability and security from WA power supplies. It would enable WA to increase its renewable energy generation without jeopardizing WA power system security and threatening the ongoing viability of its existing efficient and reliable coal and gas power stations. At present only approximately 10% of WA generation comes from renewables (primarily wind) – refer to figure 7, yet this is already threatening the viability of existing WA power stations such as Collie Power station.

Figure 7 : AEMO Data Dashboard for Fuel Mix in the WEM

Additional to this existing generating capacity, there is an estimate 1664MW of additional renewable energy potential, 880MW of which are existing committed and proposed projects, and a further 716MW of additional inferred potential.[2] There has been further interest for the development of more solar and wind generation sources up in the North Country load area (close to the existing Walkaway Wind Farm) and also in the Muja load area towards the south of the South West Interconnected Network (SWIN). These can be supported by the existence of current wind farm locations and high solar exposure areas within WA.

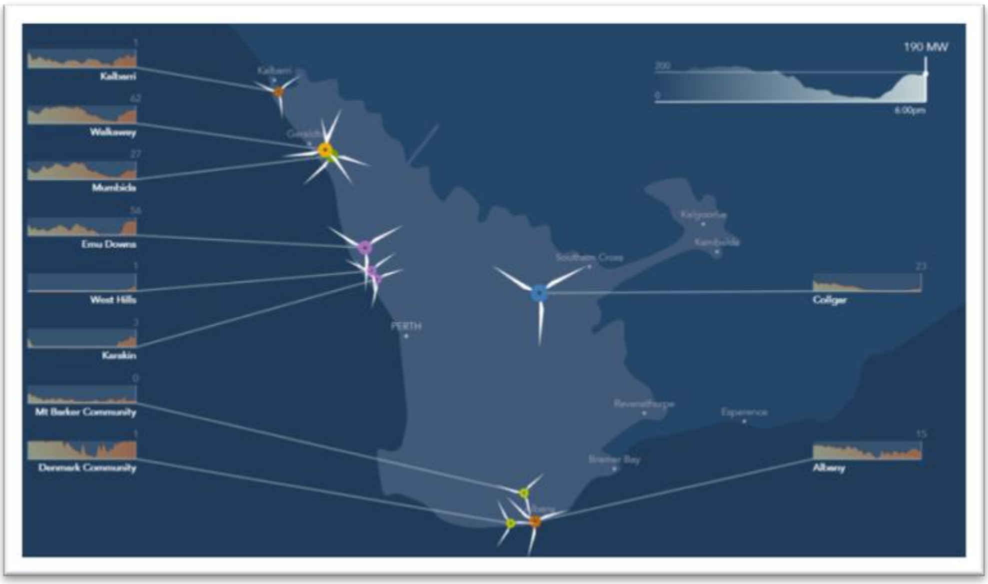


Figure 8 : AEMO Wind Generation location map

[2] Australian Climate Institute figures.

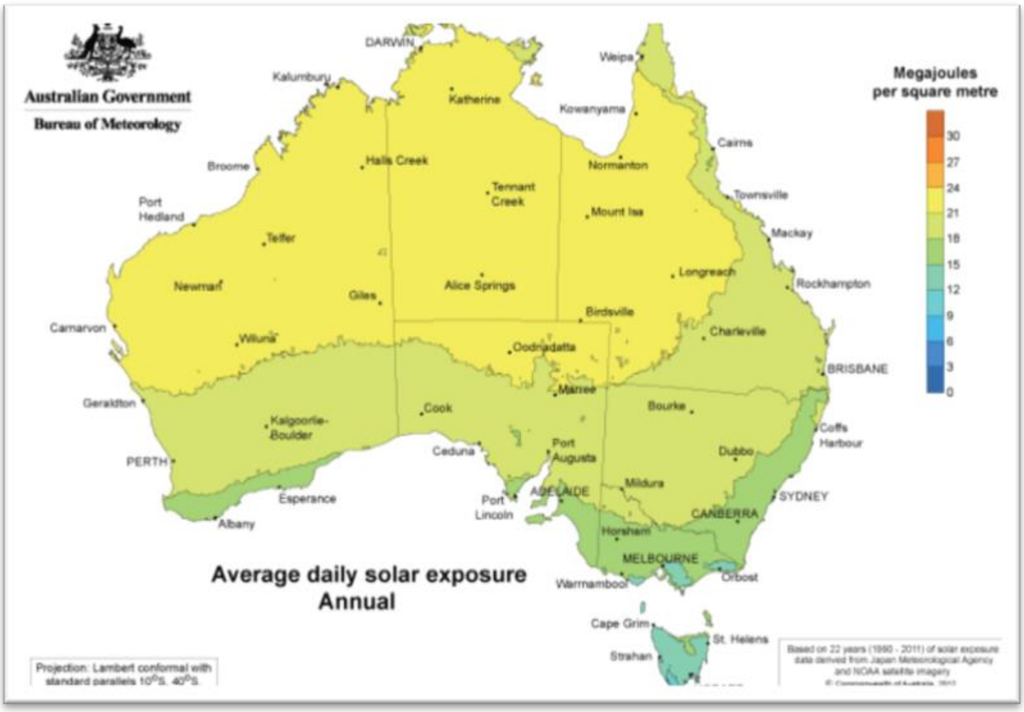


Figure 9 : Bureau of Meteorology (BOM) Solar Exposure Map

A third benefit for the construction of the East-West interconnector would be to strengthen the WA power system in the case of a major network event. The existing network supplying the Kalgoorlie and Geraldton areas is a low capacity 220kv or 132kv network that may need strengthening to maintain power sytem security as the penetration of VRE increases in WA. Reinforcing those transmission network could cost ~$1billion due to the long distances involved. This could supplement the benefit from the participation of WA in the NEM market. in terms of renewable contribution and electricity trade. The estimated cost of installing an intermediate HVDC-HVSC terminal station at Kalgoorlie would be only some $200million, a much lower investment that reinforcing the existing 220kv grid supplying the Kalgoorlie region.

Three potential routes have been considered for the interconnection between South Australia to Western Australia in order to complete the Trans-Australian interconnection. These can be summarized as the following:

Option	Route	Overview of option(s)	Length (km)
1	Davenport (SA) to West Kalgoorlie (WA)	• Insecure network with only a single 220kV circuit supply • No new renewable generation potential in the area	1,865
2	Davenport (SA) to Three Springs (WA)	• Good predicted availability of new renewable generation • Recently reinforced at Three Springs with new double circuit 330kV line via the Mid-West Energy Project (MWEP) • Relatively accessible region to gain easements	2,400
3	Davenport (SA) to Muja (WA)	• Good predicted availability of new renewable generation • Well interconnected and secure 330kV network at Muja • Accessibility problems due to mines and agriculture for easements	2,444

Based on the considerations provided, Option 2 would be the preferred option for a transmission interconnector to WA. This is based on the following reasons:

- The interconnection to Three Springs is onto a strong double circuit 330kV transmission network
- The North Country load area is expected to attract a number of new renewable generation which the interconnection can take advantage of

- The route for this interconnection traverses a lengthier path, but is relatively open for easements to be obtained for the overhead line and ideal for the construction of much lower cost guyed, chainette HVDC transmission towers.

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Figure 10 : Proposed Eastern and East-West Interconnector routes

Further expansion of the 330kV network at Eneabba is also expected in the future to cater for anticipated load growth in the area[3]

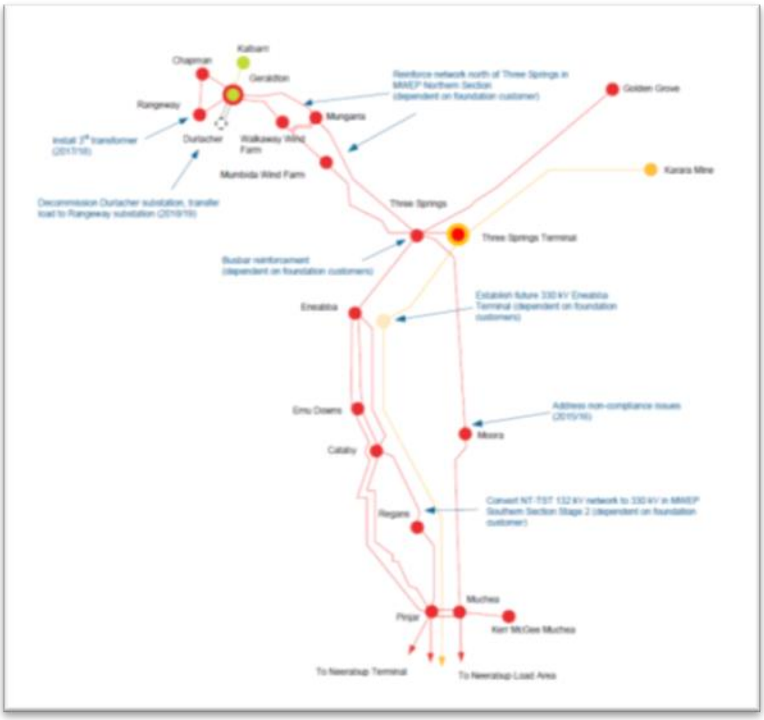


Figure 11 - Western Power Grid Expansion Plans – Planning Report

[3] Western Power Annual Planning Report 2015-16

EAST-WEST INTERCONNECTOR SCOPE AND COSTING

An HVDC link is two rectifier/inverter stations connected by an overhead line or DC cables. A bipolar HVDC line uses only two insulated sets of conductors (one is positive and one is negative) rather than three (in the case of a single circuit HVAC line), or six (in the case of a double circuit HVAC line). This reduces the easement width and smaller transmission towers providing an overall cost benefit. For a given cable conductor area, the line losses with HVDC cables are about 50% of AC cables.

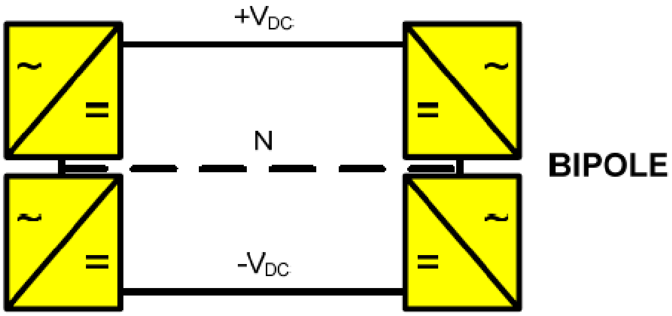


Figure 12 : Simplified HVDC bipolar system topology (4x converter stations)

Referring to Figure 13, it is evident that HVDC becomes the more economical alternative for very long transmission line.

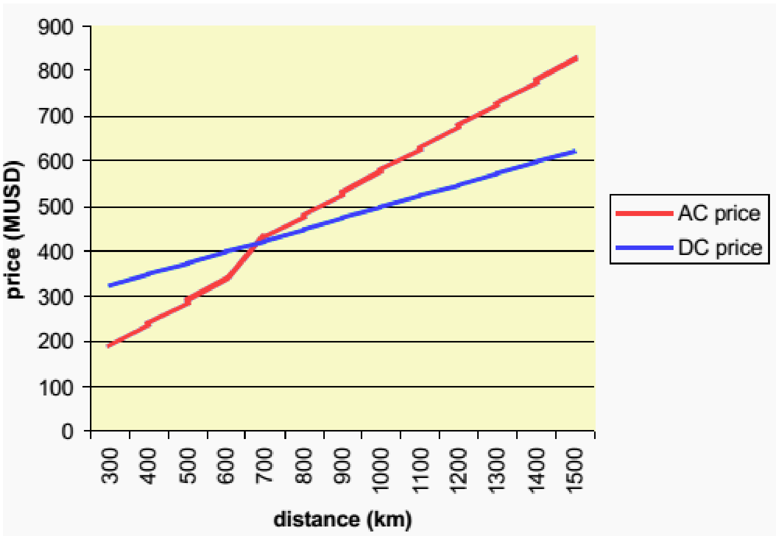


Figure 13 : Comparative HVDC and HVAC Transmission Costs for a 1000MW Line[4]

In a HVDC system the capital cost will consist of the following:

- DC Converters Stations (LCC or VSC)
- AC Step Up/Down Substations
- Transmission line (2400km with a 1000MW capacity)
- Environmental Conditions
- Safety and regulatory requirements

Optimal HVDC Transmission Voltage

[4] http://electrical-engineering-portal.com/analysing-the-costs-of-high-voltage-direct-current-hvdc-transmission

Figure 4 guided the selection of the most economical voltage for long HVDC interconnection. Based on this a ~2400km transmission line with a 1000MW (2000 Amps) capacity should be built at 500kV to achieve optimal balance between cost and efficiency.

Converter Station Technology Selection

There are two converter technologies available in the market today that will be evaluated, these include Line Commutated Converter (LCC) & Voltage Source Converters (VSC). The differences in converter technologies are summarised in table 6.

HVDC – Line Commutated Converters	HVDC – Voltage Source Converters
Uses thyristors as switching element	Uses IGBTs as switching element
50-60Hz switch frequency produces large harmonics resulting in larger filters but have lower losses (1-2%)	1000-2000kHz switching frequency produces smaller harmonics but results in more losses (2-3%)
Thyristors are cheaper than IGBTs	IGBT's are more expensive than thyristors
Cannot be used to connect to weak AC grids or to black-start a dead power system	Can be connected to blacked-out networks and re-energies them
Experience commutation failures	Do not experience commutation failures
Does not have fast voltage control capability	Supports the grid with fast voltage control capability
The control of active and reactive power is not independent	PMW controls active and reactive power independently without extra compensation equipment
Cannot operate at zero power	Can operate at a very low power, even at zero power, just transmitting reactive power
Nil	Reactive power generation and consumption of a HVDC-VSC converter is advantageous (in terms of grid support) when connecting to a weak grid as the voltage can be controlled
Not suitable for isolated operation	The VSC can create its own AC voltage at any predetermined frequency without the presence of rotating machines, suitable for isolated operation
Are not robust with respect to AC faults	Are robust with respect to AC network faults, can contribute to the short circuit current if needed and act as a firewall to limit the spread of system disturbances

Table 6 : Technical and economic cost comparison between LCC & VSC HVDC converters

Although more expensive, VSC is the more favorable technology to implement HVDC between WA and SA as it provides the many benefits detailed above. The largest benefits include its ability to maintain system stability by limiting the effects of system disturbances. Particularly when the power system in contains an increasing amount of intermittent renewable energy generation.

Transmission Line and Tower Selection

Compared to self-supporting steel lattice towers, Guyed cross rope suspension towers are much cheaper, are more light weight and have a faster construction time. They however require 45% more easement area. It is much cheaper to purchase additional easement area than to build self-supporting steel lattice towers.

The estimated Right of Way for a 500kV HVDC transmission line built with guyed cross rope suspension towers will need to be 80m wide at the tower locations and 40m wide between tower spans. Tower spans are estimated to average 550m long as such 100m of this will need to be 80m wide and 450m will need to be 40m wide.

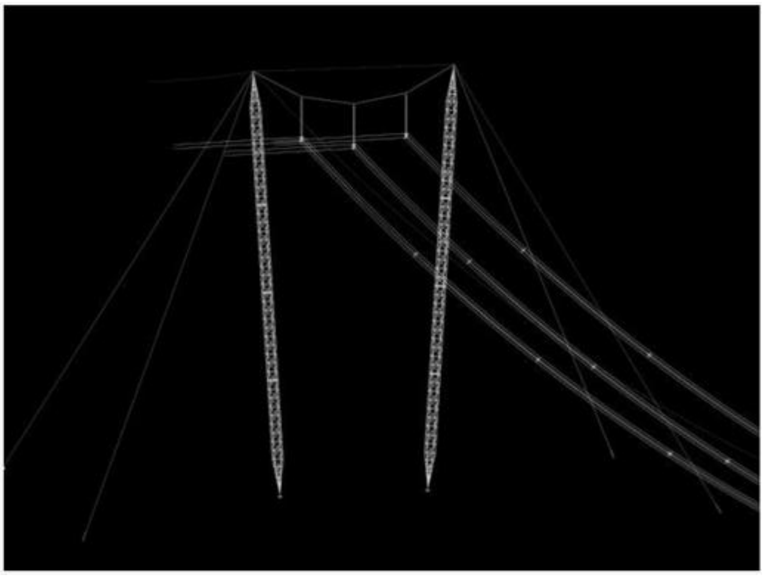
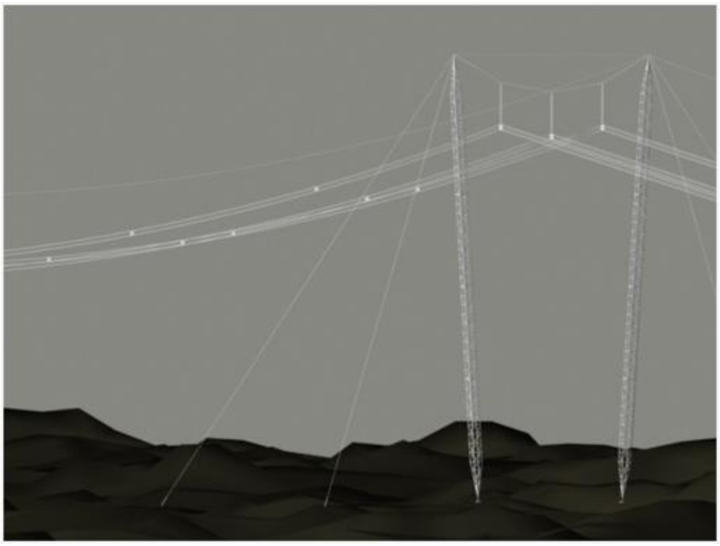


Figure 14 Guyed Cross-rope Transmission Structure



In addition to the above guyed cross rope suspension towers have the following benefits:

- Excellent shielding is provided from lightning strikes
- Improved earthling with 6 connections over a large area
- Low weight allowing for faster erection (up to 10 towers a day)

When selecting the conductor for guyed cross rope suspension tower one must take conductor weight into consideration. Referring to the table below when compared to ACSR, ACCC has an exceptionally higher strength and has a much lighter weight which allows the incorporation of up to 30 percent more aluminum without a weight/diameter penalty. This effectively reduces conductor resistance by of ACCC conductors between 25 to 40 percent compared to ACSR.

	Peak Amps	Temperature at peak amps (C°)	Load Factor	MVA	Annual Line Losses (MWh)	Line Loss Reduction	Value of Reduction (at $50/MWh)	Value of Reductio per lineal conduct (meter)	(foot
ACSR	1,000	95	53%	398	76,917	----	----	----	----
ACCC®	1,000	82	53%	398	56,588	20,329	$1,016,450	$3.39	$1.03
ACSS	1,600	194	53%	637	251,998	----	----	----	----
ACCC®	1,600	156	53%	637	179,022	72,976	$3,648,800	$12.16	$3.71

Figure 16 : Economic comparison between ACSR and ACCC considering line losses for 100km line [5]

Price Summary for East West HVDC Interconnector

Component	Guyed Crossrope	Suspension Tower
Transmission Lines 2400km - 1200MW	$ 1,500m	$ 2,600m
Easements 2400km x 40m – 80m	$ 130m	$ 110m
Converter Stations	$ 900m	$ 900m
Step Up/Down AC Substation Connections	$ 50m	$ 50m
Total	$ 2,580m	$ 3,660m

For the guyed cross-rope transmission tower solution, the estimated operation and maintenance costs for the preferred option (assuming 1% of capital costs pa) is $26Mpa.

COST BENEFIT ANALYSIS

The following cost benefit analysis was undertaken by a syndicate group of engineers at the API Summer School and is a different approach to that adopted earlier in this assessment by the author, none-the-less the results are similar and deliver a similar net benefit of around $400million.
See table below for the assumptions used:

SA - WA Interconnector Assumptions	Assumptions	Unit
VCR	$33.46	per kWh
Outage Duration	8	hrs

[5] https://www.ctcglobal.com/ftp/ACCC_Field_Experience.pdf

Probability of Statewide Blackout	5%	per year
Avg Peak Demand WA, SA	3600	MW
Peak Demand Reduction Factor	30%	
Interconnector Capacity	1200	MW
Loss	12%	
Initial Utilisation (One Way)	35%	
Utilisation Growth	1%	per year
Avg Wholesale Price Differential	$20	per MWh
Jobs Created Interconnector Construction	250	per year for the first 3 years
Jobs Created Renewables	20	per year for 50 years
Avg Salary	$120,000	per year
Salary Inrease	2%	per year
Discount Rate	7%	per year
Total Interconnector Construction Cost	$2,960,000,000	over 3 years
Maintenance Cost	1%	per year (capital cost)
Battery Cost	$100,000	per MWh

The VCR, blackout outage duration is consistent with our analysis for the SA-QLD interconnector. However, due to the reserve requirement in WEM and lower renewable generation penetration in WA, WA and SA will both have a lower probability of blackout of once every 20 years, or 5% per year. We also assume 3600MW of average peak demand for SA or WA and 8 hours blackout duration with 30% reduction factor due to system peak typically only lasts for 1-2 hours.
The interconnector will have a total energy loss of 12% and one-way (as energy can be transferred both ways between WA and SA) utilisation of 35%. The utilisation will improve by 1% per year. Due to the 3 hour time zone difference between WA and the eastern states, we assume an average of $20/MWh price differential can be achieved by utilising this interconnector.
The design, construction, and commissioning of the interconnector and the renewable energy generators will also help create jobs that support Australia's economy. That will be 250 FTE for the interconnector in the first 3 years and 20 FTE in the renewable energy sector for the next 50 years. The average annual salary is assumed to be $120,000 per year in 2030 and will grow by 2% per year. The discount rate used in our analysis is 7%.

The table below summarises the NPV of the benefits and costs of this interconnector project over the next 50 years.
To assess the economic benefits of this project, we grouped the benefits into the following 4 key areas.

Security: Due to the increasing penetration of renewable energy, we believe each state, especially WA and SA will experience reduced system strength and security by 2030. Although the SA-QLD interconnector addressed some of the immediate security issues in SA, by 2030, WA and SA will be subject to once in 20 year statewide backout. Much of this risk can be mitigated by having this interconnector.
Renewable generation: This is the combined benefit that allows 1200MW of renewable energy that can be transferred and traded between WA and the eastern states. This includes improvement to the market efficiency and reduction in congestion and spot price volatility. All benefits are assumed to be averaged to a $/MWh value and the benefits will increase as the interconnector utilisation improves over time.
Avoided need for battery construction: Having the interconnector meant that renewable energy can be transferred to supply other states rather than stored. There will be significant benefit in having to avoid this cost altogether.
Economic benefits: We see major benefit in sustained job creation from the interconnector construction as well as those required to develop renewable generators across Australia.

SA - WA Interconnector Benefits/Costs	**NPV**
Security - Avoided Unserved Energy from Blackout	$ 466,537,229
Renewable Generation Differential between WA and the Eastern States	$ 2,437,071,221
Avoided Battery Costs	$ 56,074,766
Economic Benefits from Jobs Creation	$ 124,061,925
Interconnector Construction Costs	-$2,589,325,164
Interconnector Maintenance Costs	-$ 144,885,727
Total	$ 349,534,250
ROI	13%

Based on the NPV analysis above, there is a total net benefit of $350m over the next 50 years with 13% ROI.

INTERCONNECTION TO DARWIN

There are two options to connect to Darwin from the rest of the NEM, these are from either South Australia (Davenport – approximately 2600km) or Queensland (Ross (Townsville) via Mount Isa – approximately 2000km). This will enable the NEM to be connected to the future global energy market. Based on the cost assessment used for the East-West Interconnector, assuming a 1200MW the approximate capital cost of construction is approximately $2 to $2.5B. Though further investigation into route options and potential constraints around transmission through central Australia is required, based on the reduced distance to Townsville and the benefits of connecting Mount Isa , the Northern Territory to Ross (Townsville) Interconnector option is preferred.

SECURING A GLOBAL ENERGY FUTURE

The International Energy Agency (IEA) launched its ‘Large-Scale Electricity Interconnection: Technology and Prospects for Cross-regional Power Networks’ in April 2017, aiming to deliver policy and recommendations for the global power sector for a future vision of integrated power systems.[6] The document outlines the future vision of national and then global interconnection. For the Association of Southeast Asian Nations (ASEAN), the objective is to enhance energy security by developing and investing in regional power interconnections between those countries with surplus power generation capacity and those facing potential deficit. The illustration below shows the current and proposed interconnector infrastructure for the ASEAN region.[8]

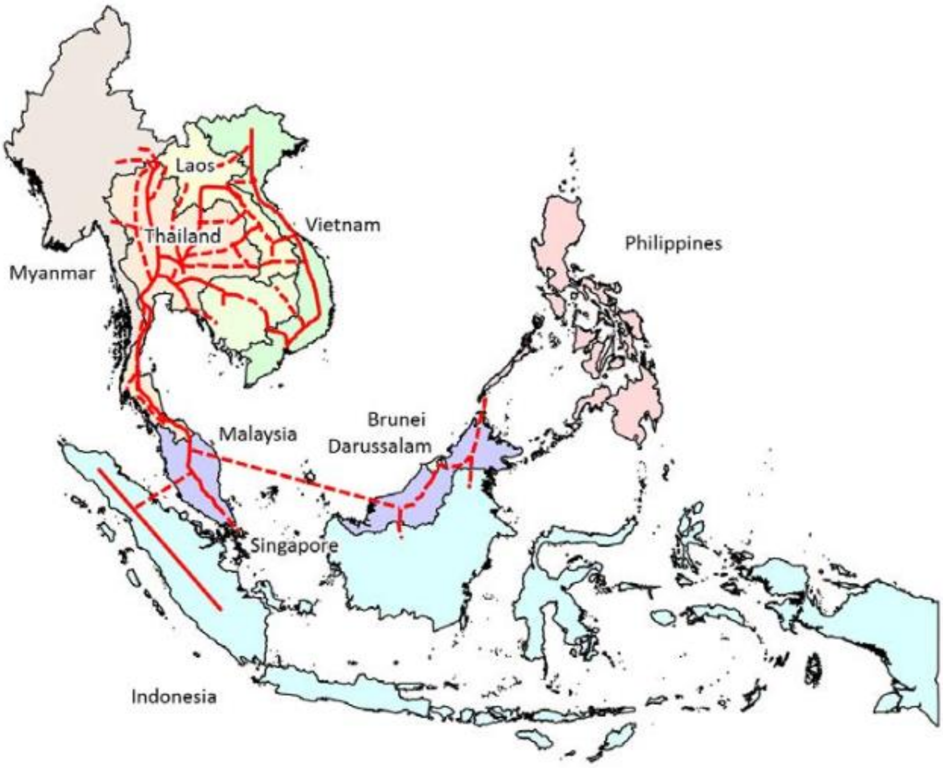


Figure17 - Proposed Interconnection of ASEAN Countries

Further to this, State Grid Corp. Charmain China has put forth a proposal for a global smart ultra-high-voltage (UHV) grid that transmits only "clean energy". This includes a connection between Darwin and Timor, through to Indonesia and South East Asia. In the first instance, State Grid are investigating options to connect the northern parts of Asia into the south easterly parts of Asia, and encouraging countries to develop national grids.

The Northern Territory Government in 2013[7] reviewed the potential for connection between Darwin and West Timor, then Java via HVDC subsea cable, estimating a cost of $US8B (based on current technologies). The proposed route is shown in the figure below:

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[6] OECD/IEA 2016: Flyer for Large-Scale Electricity Interconnection Technology And Prospects For Cross-regional Networks

[7] Blanch, S. Law, R. Campbell, A. Halawa, E. & Eiritz, C. (2013) Scoping Workshop on Australia-South East Asia grid connec on to catalyse regional genera on and distributed on of renewable energy, 29-30 July 2013, Environment Centre NT & Centre for Renewable Energy, Charles Darwin University, Darwin.

Existing, planned and proposed HVDC cables

While the cost of this project today makes the project a less attractive investment, IEA notes that as more global interconnection projects are proposed, the demand for this technology will increase, bringing with it larger scale production and inherent efficiency leading to cost reduction.
The effective implementation and use of a globally interconnected market requires significant work in negotiating and agreeing to regulatory frameworks, network transfer capacities and allocation of that capacity to market participants.
Whilst the immediate global focus is on more localised energy interconnection, the long term view should be to enable a global energy network, in order to ensure strategic spending in network advancement.

OVERALL OPTIONS ANALYSIS

SUMMARY OF OPTIONS REVIEWED

The table below describes a range of new interconnector options considered in recent studies. These options should not be considered in isolation from each other, as the end to end solution is a combination of the below.

Option	Route	Length (km)	Indicative capex ($m)	Increase in capacity (M
1	Central SA to Victoria interconnector (nominally Tungkillo to Horsham, and beyond)	350 – 600	500 - 1,000	300 - 650
2	Mid North SA to NSW interconnector (nominally Robertstown to Buronga, and beyond)	300 – 800	$1,400m	700MW
3	Northern SA to NSW interconnector (nominally Davenport to Mt Piper)	1,100 – 1,300	$1,500m	1,000 MW
4	Northern SA to Queensland interconnector	1,450 - 1,600	$1,500m	1,000MW

	(nominally Davenport to Bulli Creek)			
5	Davenport (SA) to West Kalgoorlie (WA)	1,865	$2,200m	1000MW
6	Davenport (SA) to Three Springs (WA)	2,400	$2,580m	1000 - 1200
7	Davenport (SA) to Muja (WA)	2,444	$3,000m	1000 - 1200
8	Davenport (SA) to Darwin (NT)	2,600	$3,100m	1000 - 1200
9	Ross (QLD) to Darwin (NT)	2,000	$2,300m	1000 - 1200

FEASIBILITY

Option	Description	Meets identified needs	Technically feasible	Economically Feasible	Improves System Security
1	Base Case: Do nothing	No	No	No	No
2	SA to NSW interconnector	Yes	Yes		
3	SA to QLD Interconnector	Yes	Yes	Yes	Yes
4	WA via SA to QLD interconnector	Yes	Yes	No	Yes
5	WA – SA – QLD – NT interconnector	Future	Future	Future	future

FUTURE CONSIDERATIONS

- DC Circuit Breaker being developed which would greatly enhance an HVDC Grid.
- Cheaper rectifier technologies are required to make interconnector technologies more economical viable.
- Regulatory testing does not suit national interconnector projects, as it is currently reliant on state specific needs.
- Government policy required or non regulated intervention (private investors) to make funding available for the project.
- Benefits: market benefits highly uncertain but sensitive to NPV
- Protection: no DC breaker yet
- Easement: terrain, ownership, access
- Rapid adoption of new transmission technologies
- Multi-Terminal HVDC system to enable teeing of renewable resources along the route

IMPLEMENTATION STAGING STRATEGY

Due to the significant investment required to realise the full Trans- Australian Interconnector network, the following staged approach is recommended:

1. South Australia to Queensland Interconnector – meeting the immediate needs for system reliability and security of supply to South Australia, subsequently benefitting Queensland,

circumventing the forecast future reliability issues for that state, and allowing – 18 – 24 months (Construction phase)

2. Western Australian Interconnector – to connect WA to the NEM, enable Western Australia's progression towards achieving renewable energy targets and increase opportunities for investment into significant untapped renewable energy potential in the central western regions of Australia.
3. South Australia to Northern Territory interconnector – enable the global energy market connection to the rest of Australia's National Electricity Market
4. Darwin to East Timor and Indonesia – providing opportunity to export Australia's Renewable Energy Resources to the global market.

CONCLUSIONS

A preliminary assessment has been made of the Eastern and Western trans-Australian interconnectors to connect South Australia to Queensland and Western Australia. The Eastern Interconnector would mesh the NEM, rectifying a fundamental design weakness of the existing National Electricity Grid that is unnecessarily increasing wholesale electricity prices in South Australia and Queensland by some 30% and threatening their power system reliability and security as renewable energy generation increases over time. Alternative technologies for the Eastern interconnector were compared and HVDC-VSC was found to be the most suitable choice for this application and is proven globally at the voltage levels required for the interconnection. Technical parameters such as capacity, voltage, and number and size of conductors were selected to enable interconnector cost and performance to be assessed. Alternative routes were compared, along with the best connection points to the existing grid in SA, Qld and WA. It was concluded that the most financially beneficial route would be the Strategic route. The Eastern Interconnection and the East-West Interconnection is more suitable for innovative, lower cost transmission line structures. It would also enable the future development of Australia's best renewable energy resources in Central Australia. Interconnector transmission losses were estimated to be 10% and 15% for each interconnector on average. This indicates that the preliminary design is prudent and efficient, balancing lower capital cost against life cycle transmission losses, whilst consistent with proven international practice for similar interconnectors using HVDC-VSC technology.

Based on the cost-benefit estimates, the eastern interconnector's esimated capital cost of $1,500m could justified by its benefits, delivering a significant 20% net benefit over its operating life.

The preliminary assessment of the east-west interconnector indicated that its estimated capital cost of $2.68 billion is justified and delivers an 15% net benefit from the economic and reliability benefits of diversity in electricity consumption and renewable energy generation across Australia

RECOMMENDATIONS

It is recommended that for the long term benefit of Australian electricity users, a Trans Australian Interconnected transmission network using HVDC VSC technology should be considered to create a truly national Australian energy market that helps enable renewable energy targets to be safely achieved, and enhances the competition in Australia's wholesale electricity markets whilst maintaining power system reliability and security.

Based on the high level analysis completed, this could involve the staged development of firstly the SA – QLD eastern interconnection followed by the east-west interconnection from Davernport io SA to Three Springs in WA. The eastern interconnection was rejected by ElectraNet in February 2019 who instead are proposing to invest $1,400million in an AC interconnector between SA and NSW. It is believed that the ElectraNet assessment is flawed and that the better option from an AER Regulated Test perspective is the Eastern HVDC Interconnection between Queensland and South Australia. The Eastern Interconnector would also provide very significant strategic benefits leading to the ultimate development of the HVDC grid outlined in this paper.

It is recommended that:

(a) The ElectraNet proposal to develop an AC interconnection between SA and NSW at a total estimated cost of $1,400m be "put on hold" until the Australian Energy Regulator has fully considered objections to ElectraNet economic assessment including ElectraNet;s assessment of the Eastern Interconnector being HVDC between Queensland and South Australia

(b) And that Western Australian and Federal Government funding be approved for a detailed evaluation of the East-West Interconnector

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