Network Modelling Report

ElectraNet-AEMO Joint Feasibility Study

South Australian Interconnector Feasibility Study

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ElectraNet electricity transmission

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1. Introduction

ElectraNet Pty Ltd and the Australian Energy Market Operator (AEMO) have conducted a joint feasibility study of transmission development options that could economically increase interconnector transfer capability between South Australia and other National Electricity Market (NEM) load centres.

This report describes the input assumptions and modelling methodology of the joint feasibility study (JFS) from a network modelling perspective.

This report accompanies the following reports:

- South Australian Interconnector Feasibility Study Report – providing an overview of the feasibility study along with discussion of the results and conclusions from the study.
- South Australia Interconnector Feasibility Study Market Modelling Report – providing details of the assumptions, approach, methodology and results of the market modelling work undertaken for this feasibility study.
- Feasibility Study Estimates for Transmission Network Extensions – cost estimate report prepared by Sinclair Knight Merz (SKM).

All reports are available at:

- www.electranet.com.au
- www.aemo.com.au

1.1. Approach

The purpose of the network analysis process was to identify and develop transmission augmentation options that could be required over the next 20 years, under a range of different market development scenarios[1].

The augmentation options developed include:

- incremental augmentations to the existing interconnectors
- new high-capacity interconnectors to provide significantly enhanced transfer capability between the different regions of the NEM
- new transmission augmentation projects across the entire NEM to support the enhanced transmission capability of the new high-capacity interconnector options

The overall approach to developing the augmentation options and assessing the feasibility of those options involved a number of different stages of work, as follows:

- assessment of the performance and limitations of the existing interconnectors
- development of new transmission augmentation options, including:

[1] See the detailed market modelling report (JFS Market Modelling Report) for more details on the market development scenarios used in the JFS

  - a range of incremental augmentations
  - a range of high-capacity interconnector augmentations that would be viable to support a range of different generation scenarios
  - a range of intra-regional and inter-regional network support projects that would be required to support the new incremental and high-capacity interconnectors

- development of cost estimates for each of the identified augmentation options
- development of a reduced network model for the market modelling processes (in order to assess the benefits of the augmentation options)
- validation of the market modelling outcomes, including:

  - validating the reduced market model output with detailed power system analysis
  - identifying all supporting transmission projects needed to support each of the interconnector options in the different scenarios

2. Existing network performance and limitations

The two existing interconnectors between South Australia and the rest of the NEM are:

- the Heywood interconnector, with a dispatch limit of 460 MW
- the Murraylink HVDC interconnector with a rating of 220 MW

2.1. Heywood interconnector

The Heywood Interconnector comprises of a 275 kV double circuit transmission line from South East in South Australia to Heywood in Victoria (Victoria). At Heywood, two 275/500 kV transformers step-up the voltage to 500 kV and connect to the Heywood to Melbourne 500 kV transmission system.

The South East substation is located at the southern end of the 275 kV transmission system in South Australia. Traditionally, power was imported from Victoria to meet the peak demand in South Australia. However, over the last few years there has been a shift from net import to net export on this interconnector due to an increased level of wind generation in South Australia.

The existing import and export capabilities of the Heywood interconnector for system-normal conditions are summarised in the following:

- For flows from Victoria to South Australia, the Heywood transfer limit can vary between 0 MW and 460 MW in response to local network thermal ratings, voltage/reactive power limits, system demand and generation in south east South Australia.
- For flows from South Australia to Victoria, the Heywood transfer limit can vary between 150 MW and 460 MW in response to local network thermal ratings, voltage/reactive power limits, system demand and generation in south east South Australia.

Further details on the historical performance of the Heywood interconnector can be found in Appendix A.

2.2. Murraylink interconnector

The Murraylink HVDC interconnector, with a capacity of 220 MW, involves a high voltage DC link connected between the Red Cliffs 220 kV substation in Victoria and the Monash 132kV substation in South Australia.

The existing import and export capabilities of Murraylink for system-normal conditions are summarised in the following:

- In the South Australia to Victoria direction, thermal limits on the 132 kV transmission system in South Australia's Riverland region, restrict flows on Murraylink to less than 180 MW (with runback schemes in place).
- In the Victoria to South Australia direction at times of low Victorian demand, Murraylink flows can be limited by transient stability constraints in Victoria, or by thermal limits on the South Morang 500/330 kV transformer. At times of peak demand, Murraylink flows can be limited to less than 50 MW by voltage collapse constraint equations applied to Victoria.

Further details on the historical performance of Murraylink can be found in Appendix A and information on the Murraylink runback schemes can be found in Appendix B.

2.3. Combined Heywood and Murraylink limits

In the market dispatch systems there are multiple constraint equation sets that limit the combined transfer capability of the Heywood and Murraylink interconnectors.

Oscillatory stability limit

An oscillatory stability constraint equation limits power transfer from South Australia to Victoria on both Heywood and Murraylink to a total of 580 MW[2]. For the purposes of this feasibility study this limit was ignored[3] and the thermal capacity of the interconnectors was considered as fully available.

Transient stability limit

The Victorian transient stability export limit restricts power transfer from Victoria to New South Wales and South Australia, with the export limit to New South Wales increasing as export to South Australia decreases and vice versa. This transient stability limit restricts flows to New South Wales and South Australia from Victoria (limits may be raised economically by increasing flow on Basslink into Victoria or increasing dispatch of Victorian hydroelectric generation). The transient stability limit was not included in this feasibility study. AEMO is currently reviewing this limit as part of its annual planning process.

Transformer thermal limit

The South Morang 500/330 kV transformer thermal constraint equation can limit flows from South Australia to Victoria when demand in Victoria is low and power transfer to New South Wales is high. The impact of this constraint equation is to increase Victorian generation (and potentially the Victorian spot prices). The requirement to upgrade this transformer was assessed as part of the feasibility study.

2 This limit was increased from 420 MW on 6 January 2011.

3 Addition of new interconnectors, particularly between New South Wales and South Australia, would require significant review of constraint equations currently applied to the NEM. Stability constraint equations may no longer apply in their present form.

3. Incremental augmentation development and assessment

This section describes the development and assessment of incremental transmission augmentation options for the joint feasibility study.

The purpose of the incremental augmentation option assessment was to identify the augmentations that would be required to incrementally augment the existing interconnectors between South Australia and Victoria. Incremental options are relatively inexpensive augmentations that allow the full thermal capability of existing assets to be used without requiring construction of new transmission line circuits.

3.1. Incremental augmentation options for the Heywood interconnector

A third 500/275 kV transformer at the Heywood terminal station and associated minor works in South Australia would allow increased transfers to and from South Australia as the existing transformer capacity is currently the limiting factor on this interconnector.

This option has previously been identified by ElectraNet and AEMO as a low-cost interconnector augmentation which will release additional transfer capacity on the Heywood interconnector.

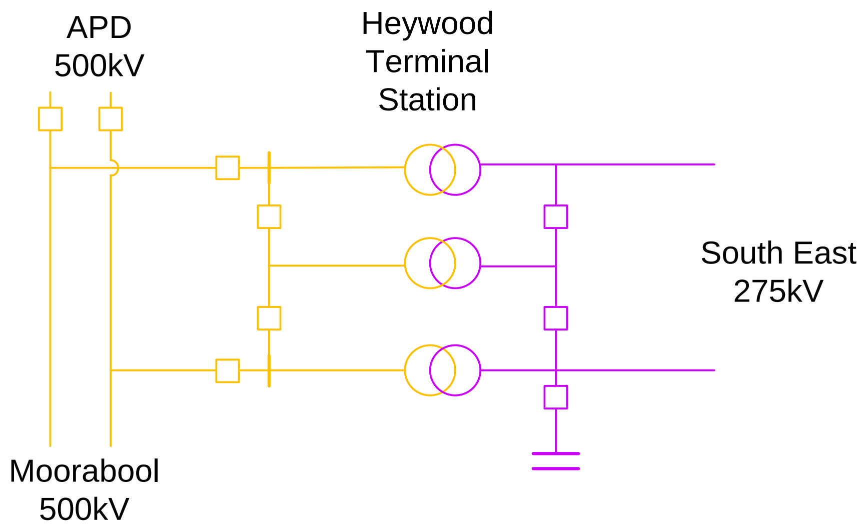
Power flow through the Heywood transformers, in the absence of broader system transient stability, voltage collapse or oscillatory constraints, is limited by the N-1 post-contingent rating of a single transformer. Each transformer is rated at 370 MVA for continuous operation, and limited to 460 MW for post-contingent short term operation.

Addition of a third 370 MVA (continuous) transformer increases the total N-1 post-contingent rating to a sum of the post-contingent rating of the two remaining transformers, or a dispatch limit of 920 MW. This increase brings the post-contingent rating of the transformer bank to a value above the post-contingent transfer capability of the South East-to-Heywood 275 kV lines, which have a maximum winter rating of 675 MVA. These lines then become the limiting factor for the interconnector, meaning that the interconnector's capability can be increased from 460 MW to 650 MW (the post-contingent transfer capability of the 275kV lines).

The cost for the third Heywood transformer used in the JFS was supplied by SP AusNet for the 2010 Victorian Annual Planning Review (VAPR).

An indicative view of the proposed arrangement at Heywood is shown in Figure 1.

Figure 1 Heywood substation layout with third transformer



3.1.1. South Australia to Victoria export study results

A third identical transformer at Heywood would raise the transformer limits to approximately 920 MW. However, the South Australia to Victoria transfer capacity will then be limited by the capacity of the South East-to-Heywood 275 kV lines, which have thermal limits of 591 MVA in summer and up to 675 MVA in winter.

Heywood interconnector export capability of up to 650 MW (the maximum design rating of the South East-to-Heywood 275 kV transmission lines) could potentially be achieved, without any new transmission lines, with the following network augmentations:

- installation of real-time dynamic line rating equipment for the South Australian South East regional 132 kV transmission system and the 275 kV lines from Tailem Bend-to-South East-to-Heywood
- installation of 1 x 100 MVAr capacitor bank at South East 275 kV terminal station

Additionally, export capability beyond 650 MW could potentially be achieved without any new transmission lines, under favourable operating conditions, with the following network augmentations:

- addition of 40% series compensation on the South East-Tailem Bend lines
- installation of 1 x 100MVAr capacitor bank and 1 x +/-80MVAr static var compensator (SVC) at Tailem Bend
- installation of a programmable logic controller (PLC) based voltage control system to switch capacitor banks at South East and at Tailem Bend

To achieve South Australia export capability beyond 650 MW, all the main 275kV backbone transmission lines would need to be operated at higher than design current ratings (with real-time ratings) depending on the location of wind and other generation sources that needs to be exported. Therefore, an assessment of these lines is required to assess whether operating at higher than design current ratings is a possibility and if any additional work will be required in order to achieve these higher ratings.

All secondary system limitation such as the current transformer (CT) ratio, over-load protection and line traps were ignored in the incremental support studies. These secondary limitations were assumed to be fixed as and when required. Table 1 shows the identified augmentations required to increase the export capability from South Australia on Heywood.

Table 1 Augmentations for South Australia to Victoria export limit

Case	Augmentation required	Export limit (MW)	
		Thermal limit[4,5]	Stability limit
(1)	Third 500/275 kV transformer at Heywood and dynamic line rating of Tailem Bend-to- South East lines	>650	550
(2)	(1) + 100 MVAr capacitor bank at 275 kV South East substation	>650	700
(3)	(2) + 40% series compensation of Tailem Bend-to-South East lines, + 80 MVAr SVC at Tailem Bend and reactive support at Tailem Bend	>650	>700

On the Victorian side of the network, the South West 500 kV corridor is operated well within its thermal capabilities, and it is unlikely that thermal limits will be an issue for this part of the network. Long term plans under the VAPR are to build a third Heywood-to-Moorabool 500 kV line if significant levels of generation are connected on the existing Heywood-to-Moorabool 500 kV lines. The JFS has not assessed timing for a third Heywood-to-Moorabool 500 kV line in detail.

3.1.2. Victoria to South Australia import study results

The addition of a third transformer at Heywood will increase the import transfer from Victoria to South Australia, and the import limit can be increased up to 650 MW under favourable transmission line ratings, generation and demand patterns and other operating conditions. However, under the most onerous conditions, the import will be limited to about 490 MW due to thermal limitations of the underlying 132 kV system in the South East. The import capability could be made more firm by either of the following two alternatives:

- decoupling the parallel 132 kV network in the South East from the 275 kV system
- installation of series compensation on the South East–Tailem Bend 275 kV lines

However, decoupling the parallel 132 kV network in the South East from the 275 kV system may also cause a reduction in the South Australia to Victoria export stability limits. Hence, while this option may provide a benefit for import into South Australia, it can potentially cause a reduction in the export capability. Therefore, this matter needs to be investigated further. In the absence of such an investigation, this option was excluded from the JFS.

4 Note that this thermal limit is not firm/continuous, but is subject to generation and demand patterns and achievement of adequate transmission line ratings (including real-time ratings where used).

5 Note that the maximum design (winter) rating of the Tailem Bend-to-South East-to-Heywood transmission lines is 675 MV.A. Any further increase beyond 675 MV.A is subject to a condition assessment of the lines and additional detailed studies.

Table 2 shows the augmentations required to increase the import capability into South Australia on Heywood.

Table 2 Augmentations for Victoria to South Australia import limit

Case	Augmentation required	Import limit (MW)	
		Thermal limit[6,7]	Stability limit
(1)	Third 500/275 kV transformer at Heywood Dynamic line rating of Tailem Bend-to-South East lines	650	665
(2)	(1) + 100 MVAr capacitor bank at 275 kV South East substation	650	685
(3)	(2) + 40% series compensation of Tailem Bend- to-South East lines, + 80 MVAr SVC at Tailem Bend and reactive support at Tailem Bend	650	>800

3.2. Incremental augmentation options for the Murraylink interconnector

The Murraylink HVDC link does not easily allow for incremental augmentations, however the owner of Murraylink, Australian Pipeline Trust (APA), has advised that there is potential to implement a short-term overload capability (an additional 5%), or to build a parallel link. Due to the cost involved with a parallel link, it has not been considered as an incremental upgrade for the purpose of the feasibility study.

The option of a short-term rating increase could be further considered once future reinforcement of the Riverland network in South Australia occurs.

There are extensive runback schemes in place which extend the range of Murraylink's operation, and there is little scope to further increase the Murraylink's transfer capability without transmission lines upgrades, particularly in the regional areas of Victoria. The 2010 VAPR has identified that the Ballarat-Bendigo 220 kV and Ballarat-Moorabool 220kV line upgrades will be assessed under a RIT-T application within the next five years.

Installation of dynamic line rating for the Robertstown-Monash 132 kV lines, along with some reactive support at Monash in South Australia, has been identified by ElectraNet as an augmentation option to allow for increased South Australia to Victoria flows up to thermal capability of the interconnector (220 MW),, under favourable environmental conditions. The cost of the augmentation (installation of Monash 132 kV 30 MVAr shunt capacitor bank and installation of weather stations and dynamic line rating of Robertstown-Monash 132 kV lines) was estimated at $5 million by ElectraNet.

6 Note that this thermal limit is not firm/continuous, but is subject to generation and demand patterns and achievement of adequate transmission line ratings (including real-time ratings where used).

7 Note that the maximum design (winter) rating of the Tailem Bend-to-South East-to-Heywood transmission lines is 675 MV.A. Any further increase beyond 675 MV.A is subject to a condition assessment of the lines and additional detailed studies.

3.3. Summary of incremental augmentations

The assessment showed that with the help of static and dynamic reactive support—including series compensation of lines—it is possible to maximise the utilisation of the transmission network to support the incremental augmentation option of a third Heywood transformer.

Table 3 shows the incremental augmentations options included in the JFS. The relatively low-cost Murraylink incremental upgrade was included in the base case of the feasibility study, as well as all upgrade scenarios. As such the feasibility study did not assess the benefits of the Murraylink incremental upgrade, but treated it is a committed project.

The Heywood augmentation, on the other hand, was only allowed in the upgrade scenarios (and not the base case) so that the benefits of this augmentation could be assessed in the study.

Table 3 JFS incremental augmentations

Interconnector	Augmentation required	Augmented capacity (MW)	Indicative cost ($ million in 2010 $)
Heywood	3rd transformer at Heywood + 100 MVAr capacitor bank at South East 275 kV + dynamic line rating of Tailem Bend to South East to Heywood 275 kV lines	650[8]	38
Murraylink	Monash 132 kV 30 MVAr shunt capacitor bank + weather stations and dynamic line rating of Robertstown-Monash 132 kV lines	220	5

[8] Note that this ultimate Heywood capability is not firm/continuous, but is subject to generation and demand patterns and achievement of adequate transmission line ratings (including real-time ratings where used).

4. Greenfield Options Development

The new high-capacity augmentation options assessed under this feasibility study were identified at a workshop with ElectraNet, AEMO and a representative from TransGrid. At this workshop, analysis of the existing interconnector capability was combined with the potential location of future generation developments to identify the suitable locations and sizes of new high-capacity augmentation options.

The potential location of future generation was based on based on ElectraNet's and AEMO's current connection activity, AEMO's 2009 National Transmission Statement and the Commonwealth Government's National Energy Scenarios Modelling[9].

A significant driver in the identification of new high-capacity augmentation options was potential generation and demand locations in the South Australian power system. Although the north and south regions of the state both have quite significant renewable generation development potential, the central region is where demand is concentrated.

By selecting an interconnector option originating from each of the three regions within South Australia (i.e. the north, south and central regions), the desired outcome was to ensure that the transmission requirements due to different generation locations could be compared.

Another consideration in selecting the route for the four new augmentation options was which regions would be likely to require additional import capability. Under the market development scenarios, it appeared likely that additional generation in South Australia would be able to compete with generation in either Victoria or New South Wales.

As such, the new high-capacity augmentation options were developed so that:

- the northern option would supply directly into New South Wales
- the southern option would supply into Victoria
- the central option would pass through Victoria into New South Wales

Mt Piper was chosen as a connection point in New South Wales due to ongoing 500 kV network developments providing a strong connection to load centres in New South Wales[10].

The central option was chosen by taking into consideration possible future 500 kV network developments in regional Victoria, and allowing for the future connection of renewable generation in this region[11].

Given the high level nature of a feasibility study, detailed assessment of easement availability was not undertaken; however the location of existing national parks was taken into consideration. Figure 2 shows indicative paths for each of the new high-capacity augmentation options assessed in this study.

[9] See www.ret.gov.au

[10] See TransGrid Strategic Network Development Plan: http://www.transgrid.com.au/aboutus/pr/Documents/Strategic Development Network Plan 2008.pdf

[11] See VenCorp Vision 2030 document: http://www.aemo.com.au/planning/2030.html

Figure 2 Proposed new high-capacity augmentation options

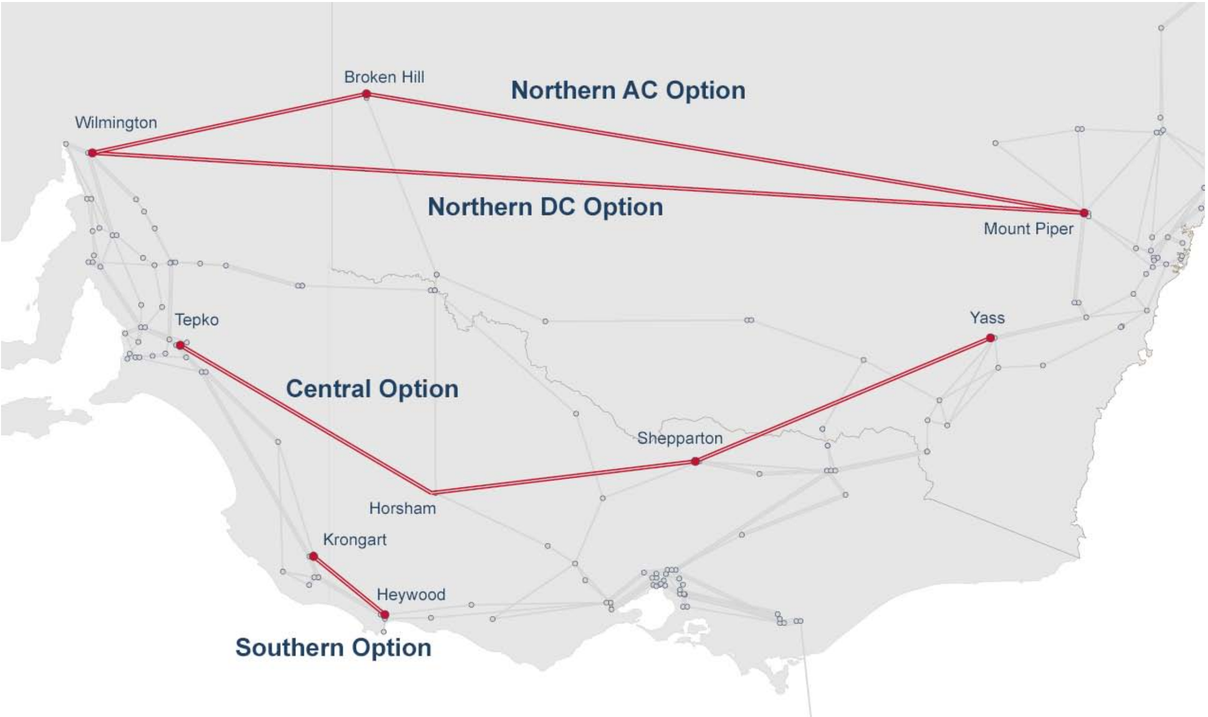


Table 4 contains a summary of the new high-capacity augmentation options assessed in the JFS.

Table 4 Proposed new high-capacity augmentation options

Option	Description	Ultimate Capacity (MW)	Length (km)
Northern AC	Wilmington (near Davenport in South Australia) to Mt Piper (New South Wales) – 500 kV AC double-circuit line	2,000	1,100
Northern DC	Wilmington (near Davenport in South Australia) to Mt Piper (New South Wales) - ±500 kV HVDC bi-pole	2,000	1,100
Central AC	Tepko (near Tungkillo in South Australia) to Yass (New South Wales) routed via Horsham and Shepparton (Victoria) – 500 kV AC double-circuit line	2,000	1,050
Southern AC	Krongart (near Penola in South Australia) to Heywood (Victoria) – 500 kV AC double-circuit line	2,000	125

4.1. HVDC options

A review of previous studies on HVDC projects[12,13] indicated that for the distance and capacity being considered in the JFS, a HVDC link operated at +/-500 kV DC would be an economically feasible choice. The advantages that a HVDC transmission system can deliver include:

- lower cost than AC as distances increase
- lower transmission losses
- easier to control the flow of power
- assists in power oscillation damping
- lower footprint for the transmission lines
- frequency control
- runback schemes to prevent voltage collapse or thermal overloads
- integration with other special protection schemes

One of the main limitations with conventional point-to-point HVDC transmission is the inability to tap into the line along its route, unlike an AC interconnector.

While the AEMO and ElectraNet are aware of the developments in multi-terminal HVDC technologies to support multiple connections along the length of the transmission lines, these technologies were not included in the JFS due to the additional costs involved and to limit the number of options under assessment.

The benefits of being able to stage the HVDC link capacity were investigated by initially constructing one pole with half the ultimate capacity (monopole) and then adding another pole (to provide the ultimate capacity) when required.

For the HVDC option, there would be the potential for the loss of 1,000 MW in interconnector capacity if a contingency occurs when operating the line as a single pole. This potential loss of capacity could lead to restrictions on the existing Heywood interconnector, or the requirement for a co-ordinated load and generation tripping scheme. These restrictions could be reduced to some extent, under bi-polar operation, as the overload capability of one pole can be utilised.

The JFS modelling did not assess in detail the impacts of these contingences, but assumed instead that a suitable control scheme would be implemented to cater for such a contingency.

4.2. HVAC options

An AC interconnector will allow for connection of generation projects or the integrating of existing networks along the route. However, long interconnectors, such as those under consideration in the JFS, require significant reactive support (including series compensation), leading to higher costs.

[12] "Impacts of HVDC lines on the economics of HVDC project" CIGRE Technical Brochure 388 JWGB2/B4.C1.17

[13] Network Extensions to Remote Areas : Part 2 Innamincka Case Study

500 kV was selected as a feasible AC voltage to be used when taking into account required capacity and acceptable losses. An optimisation of voltage level, losses, capacity and costs has not been undertaken for the JFS.

1,000 MVA transformer banks have been selected as a way to provide secure capacity, and also to stage the interconnector capacity. It is likely that the ultimate transformer ratings and connection arrangement could be optimised to suit the final requirement e.g. two higher rated transformers with appropriate overload ratings instead of three may be an option.

Given the variability in transmission line costs, and the relatively small cost for the transformers compared to the line costs, this level of design development has not been pursued further for the JFS.

The requirement for active series compensation has not been assessed in the JFS but would be expected to be taken into account in any future detailed studies.

4.3. Other issues for potential future study

4.3.1. Fault level issues

The HVDC option in particular may require further analysis of expected fault levels during low-demand periods.

The ability of an HVDC link to operate in a stable manner following a network fault generally requires that the fault level at the converter station be at least twice the HVDC power level.

Dispatch constraints or synchronous condensers could be used to mitigate this fault level issue during low-demand periods. Although stability limits have not been studied in detail for the JFS, a minimum inertia constraint has been used in the load flow and market model studies.

Based on preliminary assessment, it was assumed that approximately 500 MW of conventional generation would be required online in South Australia under high-wind generation and low-demand conditions.

4.3.2. Transient and dynamic stability

Further transient and dynamic stability analysis will be required if any of the interconnector augmentation options are assessed further at a later date. It is expected that the addition of new generation, network upgrades, SVCs and high-capacity interconnectors would have a significant impact on the stability limits currently experienced in the NEM, which would then need to be assessed and suitably mitigated.

4.3.3. Reactive optimisation

More detailed analysis of the reactive requirements with the new interconnector augmentations in place would also be necessary under any future detailed studies.

4.3.4. Maximum acceptable interconnector size

The new high-capacity interconnector options have been developed to ensure secure network operation is maintained under system normal conditions. However, there would still be a need to be able to cater for a complete loss of the new interconnector without risking collapse of the power system[14].

With a new high-capacity interconnector in parallel with the smaller capacity existing interconnector (the Heywood interconnector) loss of the new interconnector would create a complex contingency to deal with.

A high-speed tripping scheme may be necessary to reduce the post-contingent flow on the remaining interconnector to acceptable levels.

For example: a trip of the new high-capacity interconnector when importing 2,000 MW into South Australia could require 1,500 MW of load tripping in South Australia, and 1,500 MW of generation tripping in New South Wales/Victoria, depending on the flow on the Heywood interconnector.

Any future detailed studies into a new high-capacity interconnector would need to assess the operational impacts under the loss of the entire interconnector.

4.4. Supporting options development

A number of supporting transmission augmentations would be required to support the addition of new generation in the system and to support the increased flows caused by the new high-capacity interconnector options.

This section details the supporting options developed for each of the high-capacity interconnector options.

4.4.1. Northern new high-capacity interconnector option

For the new northern option, Mt Piper was chosen as the connection point in New South Wales due to ongoing 500 kV network developments providing a strong connection to load centres in New South Wales.

Given the utilisation of the 500 kV networks around the Mt Piper substation, and the planned further development of the 500 kV ring, additional support projects in this part of the network were not

14 S5.1.8 Stability In planning a network a Network Service Provider must consider non-credible contingency events such as busbar faults which result in tripping of several circuits, uncleared faults, double circuit faults and multiple contingencies which could potentially endanger the stability of the power system. In those cases where the consequences to any network or to any Registered Participant of such events are likely to be severe disruption a Network Service Provider and/or a Registered Participant must install emergency controls within the Network Service Provider's or Registered Participant's system or in both, as necessary, to minimise disruption to any transmission or distribution network and to significantly reduce the probability of cascading failure.

considered. Additional 500/330 kV transformer capacity and the impact on other 330 kV networks were considered as part of the JFS.

In South Australia, the upgrading of the existing Davenport-to-Brinkworth-to-Para 275kV lines may be required to allow for additional transfer to the Adelaide load centre, or to provide export capacity on the new interconnector if new generation was not located in northern South Australia.

4.4.2. Southern new high-capacity interconnector option

The 500 kV lines from Heywood-to-Moorabool in Victoria currently have considerable spare thermal capacity to be able to accept or supply additional interconnector capacity.

Given the high level of interest shown for new generation connections in this part of the network over the next few years, it is expected that there will be a number of network augmentations in this area of the network. These augmentations were considered as part of the JFS.

In South Australia, the upgrading of the existing Davenport-to-Para line and a new 275kV line from Tepko to the new Krongart 275kV substation may be required to allow for additional transfer to the Adelaide load centre, or to provide export capacity on the new interconnector if generation was not located in southern South Australia.

With the southern augmentation option, additional export from South Australia at times of low demand in Victoria could create a requirement for an upgrade to the existing Victoria-New South Wales interconnection.

The selected upgrade comprised a third South Morang-Dederang line, an additional Dederang-Jindera line, an additional Jindera-Wagga line, and finally a Wagga-Bannaby section. This upgrade would allow for the bypassing of congestion around the Snowy and Canberra networks.

The South Morang-Dederang-Jindera section is as per current VAPR proposals, and the TransGrid APR notes potential for interconnection with Victoria from the Wagga area. TransGrid has noted that this option would require the replacement of some existing single- circuit lines with double-circuit lines, and that a greenfield site could be required for the Jindera substation works.

For the purposes of this study the environmental impact of these developments has not been assessed, and TransGrid has advised that a similar development further west may be a more feasible route.

Given this uncertainty, sensitivity studies were also undertaken with higher costs for this support option, and these studies showed that the increased costs did not have a material impact on the results.

TransGrid have also advised that a larger capacity 500 kV link from Wagga-to-Yass-to-Bannaby may be a more likely development than the 330kV developments, and this was taken into consideration when converting the linear upgrades selected by the market modelling into discrete projects.

4.4.3. Central new high-capacity interconnector option

The route of the central option was chosen taking into consideration possible future 500 kV developments in rural Victoria, and to allow for the future connection of renewable generation in this region. For these reasons a HVDC option was not considered.

Increased flows under the new high-capacity central option could cause network congestion around the Yass area 330 kV networks. For this reason a 500 kV connection from Yass-to-Bannaby was allowed for in the JFS.

In order to allow for additional transfer to the Adelaide load centre, or for export of other new generation from the north and/or south of South Australia, additional circuits from Davenport-to-Para and Tepko-to-Krongart 275 kV substations were allowed for in the JFS.

Any requirement to upgrade parts of the regional Victoria network to 500 kV operation was assessed as part of the JFS network upgrade studies.

A connection from the proposed new Shepparton 500kV bus to the existing Sydenham 500kV bus, allowing for a Sydenham-Shepparton-Yass 500kV link between Victoria and New South Wales which would bypass the congested 330kV network, was also proposed.

A connection to Sydenham was chosen as it is a terminal station near to significant load, and the substation site has room to be expanded.

4.4.4. Summary of major supporting augmentations

Figure 3 shows the major new supporting projects included in the JFS.

Figure 3 Major new supporting augmentation options

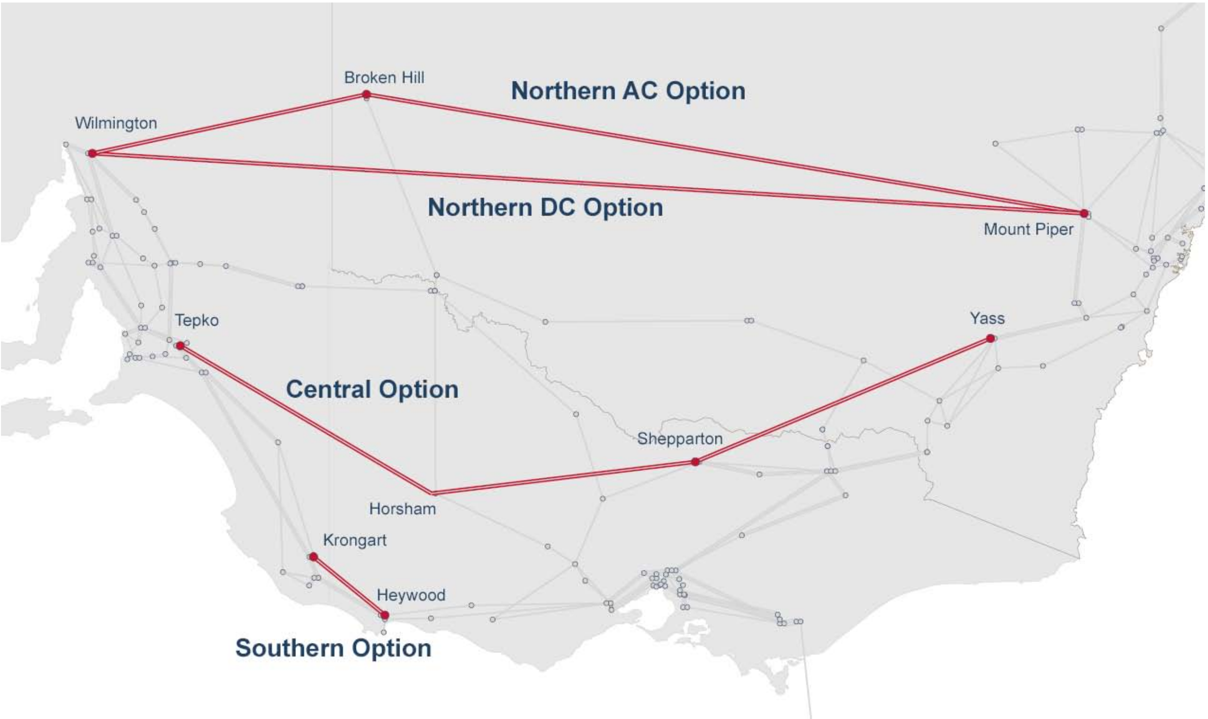


Table 5 Major new supporting augmentation options

No.	Region	Description	Ultimate capacity (MW)	Distance (km)
1	South Australia	Rebuild Davenport-Brinkworth-Para 275 kV line as a double-circuit line with twin conductors	1,200	280
2	South Australia	Krongart - Tepko 275 kV double-circuit line with twin conductors	1,200	340
3	New South Wales	Bannaby-Yass 500 kV double-circuit lines	3,000	120
4	Victoria	Sydenham-Shepparton 500 kV double-circuit line	3,000	170
5	Victoria-New South Wales	South Morang-Dederang-Jindera-Wagga-Bannaby 330 kV single-circuit line	900	660

4.5. Development and costing of options

ElectraNet and AEMO, with assistance from TransGrid, developed technical scopes for each of the new high-capacity augmentation options, including transformer requirements and static and dynamic reactive power requirements including series compensation. These technical specifications were developed with requirements for secure and reliable operation of the network taken into account. The design for the northern AC option was based on previous studies undertaken by TransGrid.

SKM was engaged to provide the cost estimates for each of the new high-capacity augmentation options.

To allow a consistent comparison between the options the following standard design blocks were adopted:

- Breaker and a half bus arrangements
- Quad Orange conductors for 500 kV lines
- Twin Sulphur conductors for 275 kV lines
- Twin Olive conductors for 330 kV lines
- Quad Sulphur conductors for HVDC lines
- Duplicate high-speed communication paths were allowed for
- SVCs to assist with voltage stability and stability
- 50% series compensation where applicable
- 1,000 MVA transformers

Dividing of the new interconnector capacity into two stages was allowed for in the augmentation design, with a first 1,000 MVA stage followed by a second 1,000 MVA stage. This staging was achieved as follows:

- for the AC options, the first stage consisted of a new double-circuit 500 kV line. The second stage involved the installation of additional transformer capacity and series compensation needed to achieve the maximum design capacity of the interconnector.

- for the DC option, the first stage is a twin-conductor line, operated as a HVDC monopole. The second stage involves the installation of extra converters to convert the monopole into a bi-pole.

The cost for the incremental option (the Heywood interconnector) was based on the 2010 VAPR and the costs for the four new high-capacity options were supplied by SKM.

Table 6 Indicative cost estimates for the augmentation options

Option	Description	Ultimate capacity (MW)	Distance (km)	Cost estimate ($ million in 2010 $)
Incremental (Heywood)	Add a third 500/275 kV transformer at Heywood in Victoria plus associated minor works in South Australia	650[15]	N/A	38
Northern AC	Wilmington (near Davenport in South Australia) to Mt Piper (New South Wales) – 500 kV AC double-circuit line	2,000	1,100	3,750
Northern DC	Wilmington (near Davenport in South Australia) to Mt Piper (New South Wales) - ±500 kV HVDC bi-pole	2,000	1,100	3,000
Southern AC	Krongart (near Penola in South Australia) to Heywood (Victoria) – 500 kV AC double-circuit line	2,000	125	530
Central AC	Tepko (near Tungkillo in South Australia) to Yass (New South Wales) routed via Horsham and Shepparton (Victoria)– 500 kV AC double-circuit line	2,000	1,050	3,500

Table 7 shows the cost estimates for the supporting options included in the JFS. These cost estimates were supplied by SKM.

Table 7 Supporting augmentation options and indicative costs

Region	Description	Ultimate capacity (MW)	Distance (km)	Cost estimate ($ million in 2010 $)
South Australia	Rebuild Davenport-Brinkworth-Para 275 kV line as a double circuit line with twin conductors	1,200	280	250
South Australia	Krongart - Tepko 275 kV double circuit line with twin conductors	1,200	340	305
New South Wales	Bannaby-Yass 500 kV double circuit lines	3,000	120	380
Victoria	Sydenham-Shepparton 500 kV double circuit line	3,000	170	530
Victoria-New South Wales	South Morang-Dederang-Jindera-Wagga-Bannaby 330 kV single circuit line	9,00	660	490

[15] Note that this ultimate Heywood capability is not firm/continuous, but is subject to generation and demand patterns and achievement of adequate transmission line ratings (including real-time ratings where used).

4.6. Generic augmentation options

Although ElectraNet and AEMO attempted to identify specific transmission augmentations that would be required under the different new high-capacity augmentation options, it was recognised that such work would depend heavily on where new generation would be located under the market modelling.

For example, while the 500 kV lines from Heywood-to-Moorabool currently have considerable spare thermal capacity to accept or supply the new southern augmentation option, a number of additional transmission augmentations will be required if there are a large number of generation connections in this part of the network.

To account for this need for additional transmission investment, a set of generic augmentation costs were developed as input to the market model. These costs allowed the market model to select lines or transformers for augmentation when it was economic to do so.

The generic costs used in the JFS are shown in Table 8. These costs were developed by AEMO.

Table 8 Generic transmission augmentation costs

Augmentation option	Estimated costs ($ million in 2010 $)
500 kV double-circuit transmission line (capacity per circuit 2500 MVA)	2.5 per km
220 kV, 275 kV or 330 kV double-circuit transmission line (capacity per circuit 800 MVA, 1100 MVA, 1300 MVA)	1 per km
220 kV double-circuit transmission line (capacity per circuit 500 MVA)	0.75 per km
132 kV double-circuit transmission line (capacity per circuit 150 MVA)	0.5 per km
1500 MVA 500/275 kV or 500/330 kV transformer with associated switchgear	45
1000 MVA 500/220 kV transformer with associated switchgear	36
400 MVA 330/220 kV transformer with associated switchgear	20
700 MVA 330/220 kV transformer with associated switchgear	25
375 MVA 275/110 kV transformer with associated switchgear	18

5. Development and benchmarking of the market model

5.1. Reduction of electrical network into the nodal model for market studies

The JFS utilised a reduced nodal model to represent significant load and generation centres and transmission links. The nodal representation was developed using a pre-existing model as a starting point, with revisions provided by ElectraNet, AEMO and TransGrid.

The key assumptions used in developing the reduced nodal model include:

- the reduced network model represents the electricity grid backbone, as follows:
  - South Australia (SA) – 275 kV and 132 kV nodes only
  - Victoria (VIC) – 500 kV, 330 kV and 220 kV nodes only
  - New South Wales (NSW) – 500 kV, 330 kV and 220 kV nodes only
  - Queensland (QLD – one 330 kV node only
  - Tasmania (TAS) – one 220 kV node only
- reductions within the model include:
  - the South Australian 275 kV network around Torrens Island has been reduced due to the meshed nature of this part of the network
  - the radial 132 kV transmission systems in the Eyre Peninsula and the Yorke Peninsula in South Australia have been reduced
  - the Victorian network has a lot of parallel circuits in the 220 kV network feeding the Melbourne area load, therefore in order to reduce the network further some parallel 220 kV lines and transformers have been reduced to a number of single equivalent elements
  - generation located within lower voltage networks are represented as connected to the nearest node
- new nodes and buses have been created in the model to cater future substations and generation connection points
- series compensation (capacitors and reactors) have been modelled as in service via the line parameters used
- ratings assumptions include:
  - seasonal and time-of-day line ratings have been applied to lines in South Australia based on advice from ElectraNet
  - seasonal and time-of-day line ratings have been applied to lines in Victoria based on advice from AEMO
  - static summer ratings have been applied in New South Wales based on advice from TransGrid
  - post-contingent ratings have also been used where provided (some lines and transformers in Victoria and New South Wales)

  - in the South Australia networks, thermal ratings of the conductors have been used on the assumption that any other limiting equipment can be upgraded if required
  - in Victoria where up-rating of circuits is planned to occur within the next 5 years, these new ratings have been incorporated
  - TransGrid supplied conductor ratings for circuits where they are higher than the current operational ratings, and these ratings have been utilised prior to the requirement of additional network upgrade
  - short-term ratings have not been utilised

- in Victoria, a number of parallel lines or transformers have been equivalenced into single elements:

  - thermal limits have been calculated instead of just summing individual ratings, i.e. the rating used is the maximum total flow through these elements which does not cause a rating violation on any of the elements, taking into account contingencies
  - automatic contingency analysis is not applied to these equivalent elements as the thermal rating used already represents the maximum flow
  - where it has been anticipated that significant network changes in the future could impact on the validity of the equivalences, these elements have remained as separate network

- where control schemes are present to deal with post contingent overloads, these control schemes have been assumed to be in place and the post-contingent ratings used reflect the additional headroom

An overview diagram of the nodal model can be found in Appendix C.

5.2. Projects in the 2015 base model

The nodal model was developed to represent the state of the network in 2015. As such a number of committed projects or advanced projects were included in the base network model.

5.2.1. Victoria

In Victoria, the projects included in the base model include the following:

- Mortlake terminal station (committed)
- Tarrone terminal station (committed)
- uprating of Geelong-Moorabool 220 kV lines
- uprating of Ballarat-Moorabool no.1 220 kV line
- uprating of Ballarat-Terang 220 kV line
- uprating of Bendigo-Kerang 220 kV line
- uprating of Ballarat-Waubra-Horsham-Redcliffs 220 kV line
- uprating of Rowville-Ringwood-Thomastown 220 kV line

5.2.2. South Australia

In South Australia, the following projects (all of which are currently under construction) were included in the base model:

- Adelaide Central Reinforcement: TIPS-to-City West 275 kV
- Templers 275/132 kV injection
- Mount Barker 275/66 kV injection
- North Brown Hill, Waterloo and The Bluff wind farms

5.2.3. New South Wales

In New South Wales, the projects included in the base model include the following:

- Bannaby–Mt Piper 500 kV conversion project (recently completed)
- transfer of the Bayswater no.3 unit to the Bayswater 500 kV bus (recently completed)
- Wollar-Mt Wellington 330kV connection (recently completed)
- Dumaresq-Lismore 330kV line (planned)
- uprating of Tamworth-Armidale no.86 line (committed)

5.3. Benchmarking of the market modelling outcomes

The market modelling makes use of a network impedance model and automatically generates N and N-1 thermal constraint equations to ensure a security-constrained generator-dispatch in the market modelling.

Some limitations of the market modelling process include:

- only thermal aspects of the existing transmission capacity are taken into account, not issues like voltage control and stability issues
- areas with significant parallel lower voltage networks are less accurate with reduced network models

For the JFS, the aim was to ensure that the model was accurate enough to highlight areas of congestion in the network, particularly major transmission bottlenecks.

To determine the level of accuracy of the market model, snapshots from the market modelling were benchmarked with full power system analysis.

These benchmarking studies showed that the market modelling outcomes were fairly accurate. 500 kV and 330 kV network flows were shown to generally have less than 20 MW difference, and for networks at 275 kV and below network flows less than 30 MW difference was found.

Some differences are to be expected due to:

- differences in loss calculations
- differences in some bus arrangements

- impacts of parallel lower voltage networks

5.4. Intra-regional augmentations

In the JFS, the new high-capacity interconnector augmentations were entered into the market at pre-defined times. The market model then optimised when to build the incremental augmentation options and the support options.

Over the 20-year outlook period it was recognised that a number of intra-regional augmentations would also be required. The approach used for implementing intra-regional augmentations in the JFS involved both market modelling analysis and power system analysis.

The market model used a least-cost algorithm to optimise generation and transmission optimisation over the 20-year outlook period.

The least-cost optimisation in the market model used generic network upgrades costs ($/MW/km) for each existing line in the network as shown in Table 8.

These generic costs allowed the market model to compare the costs and benefits of building an intra-regional transmission upgrade with the costs and benefits of developing generation closer to a demand centre.

The least-cost optimisation used in the market model was a linear model. This linear model allowed the model to build new intra-regional transmission and generation in continuous blocks.

As transmission augmentations are in reality built in discrete steps rather than continuous blocks, the market modelling outputs were then converted to discrete projects with specific timings. These discrete intra-regional projects and timings were then used in the detailed time-sequential market modelling runs.

Conventional power system analysis was performed to identify suitable intra-regional upgrade projects to deliver the increase in network capacity required. Where possible, the upgrade projects were based on information published in the Jurisdictional Planning Bodies' (JPBs') Annual Planning Reports (APRs)

5.4.1. References for choice of intra-regional projects

The following documents were used to identify possible intra-regional projects for the JFS:

- AEMO National Transmission Statement (NTS) http://www.aemo.com.au/planning/nts2009.html
- AEMO Victorian Annual Planning Review (VAPR) http://www.aemo.com.au/planning/apr.html
- TransGrid Annual Planning Review http://www.transgrid.com.au/network/np/Pages/default.aspx
- ElectraNet Annual Planning Review http://www.electranet.com.au/network_planning_review.html

Appendix A. Historical network performance

A.1. Heywood interconnector

The AEMO Constraint Report 2009[16] and AEMO 2009 National Transmission Statement[17] data highlight the following for the Heywood interconnector:

- a trend of increasing flow from South Australia to Victoria
- increasing constraint binding hours for the South Australia to Victoria direction
- Heywood interconnector is mainly unconstrained within the ranges from -280 MW to 340 MW , flows above these levels can cause system-normal constraints to bind
- for flows from South Australia to Victoria, limits are mainly due to thermal ratings of the network on both sides of the interconnector
- South Australia to Victoria thermal constraints can be caused by the South East 275/132kV transformers in South Australia and the 500/330kV transformer at South Morang in Victoria
- for flows into South Australia from Victoria, limits are mainly due to voltage stability in South Australia and transient stability in Victoria

Table 9 shows the binding system-normal constraint equations setting the South Australia to Victoria limit on the Heywood interconnector for the calendar year 2009.

Table 9 Binding constraints for Heywood - South Australia to Victoria (2009)

Constraint equation ID	Binding hours	*Description*/Notes
V>>V_NIL_2A_R & V>>V_NIL_2B_R & V>>V_NIL_2_P	493.0	*Out = Nil, avoid pre-contingent overloading the South Morang 500/330kV (F2) transformer, for Radial/Parallel modes and Yallourn W1 on the 500 or 220kV*
S>>V_NIL_SETX_SETX	67.7	*Out= Nil, avoid overloading the remaining South East 275/132z kV transformer on trip of one South East 275/132 kV transformer, feedback* This constraint equation binds when there is export from South Australia to Victoria and high generation from the wind farms and gas turbines in the south-east of South Australia
SV_300	35.2	*South Australia to Victoria on Heywood, upper transfer limit of 300 MW* Oscillatory limit
S_V_NIL-300	18.7	*Out= Nil, limit South Australia to Victoria to reduce time and amount exceeding 300 MW due to non-conformance or FCAS raise regulation flows*

Table 10 shows the binding constraint equations setting the Victoria to South Australia limit on the Heywood interconnect for the calendar year 2009.

[16] http://www.aemo.com.au/electricityops/0200-0006.pdf

[17] http://wwww.aemo.com.au/planning/nts2009.html

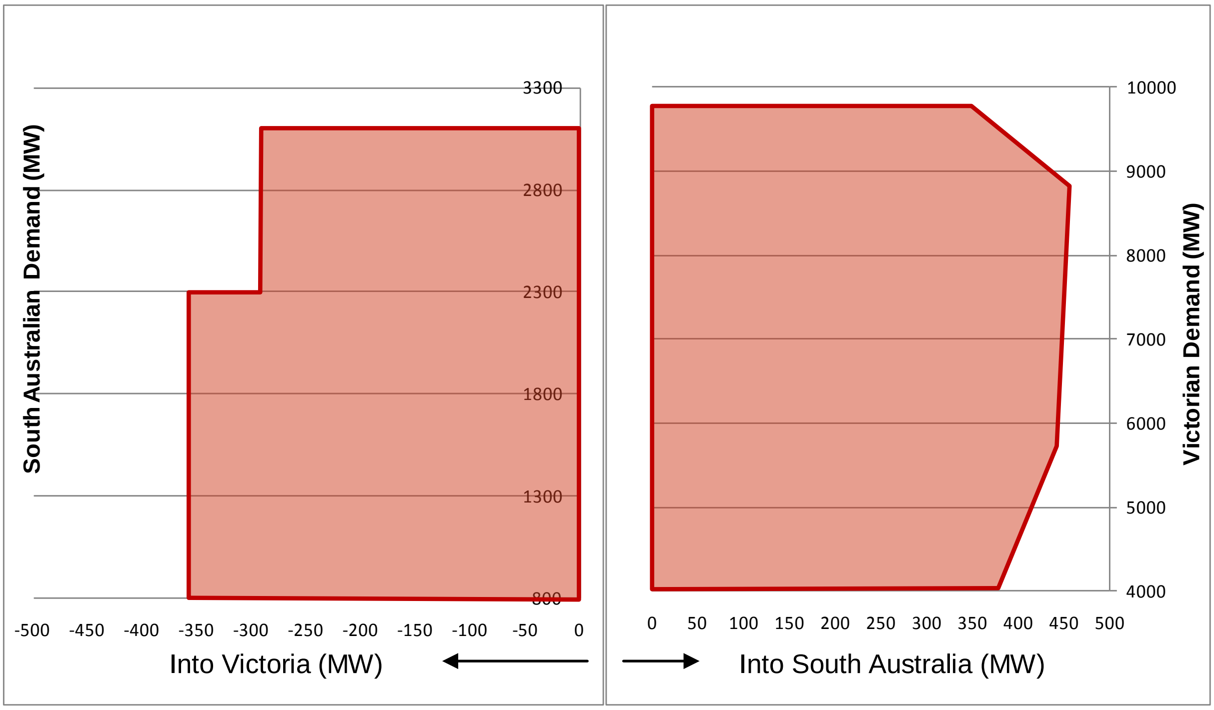
Table 10 Binding constraints for Heywood - Victoria to South Australia (2009)

Constraint equation ID	Binding hours	*Description*/Notes
V^^S_NIL_NPS_SE_OFF & V^^S_NIL_NPS_SE_ON & V^^S_TBCP_NPS_SE_OFF & V^^S_TBCP_NPS_SE_ON & V::S_NIL	624.4	*Out = Nil, Vic to South Australia long-term voltage stability limit for loss of one Northern unit, South East cap bank on/off, Tailem Bend cap bank on/off*
V::N_NILVxxx & V::N_NILQxxx	190.1	*Out = Nil, avoid transient instability for fault and trip of a Hazelwood-to-South Morang 500kV line, radial or parallel modes in Victoria*

Figure 4 shows the range of flows on the Heywood interconnector over the period from November 2009 to October 2010.

The step change in values (at 300 MW to 350 MW into Victoria) is due to the recent oscillatory limit changes (SV_300 removed). Even though this limit was removed, the combined Murraylink and Heywood oscillatory limit for flows into Victoria can still limit flow on Heywood to less than 460 MW.

Figure 4 Range of Heywood operation (Nov 2009 to Oct 2010)



A.1.1. Victoria to South Australia long-term voltage stability limit

Historical data shows that the Victoria to South Australia limit is often set by voltage stability requirements in South Australia in the range of 200 MW to 460 MW. This limit is dependent on demand and generation in the south-east region of South Australia. Similarly the voltage stability export limit can range from 250 MW to 460 MW, again as a function of the south-east region system demand and generation.

A.2. Murraylink interconnector

The AEMO Constraint Report 2009 and AEMO 2009 National Transmission Statement data highlights the following for the Murraylink interconnector:

- a trend of increasing flow from South Australia to Victoria
- the interconnector is mainly unconstrained within the ranges from 110 MW to 80 MW and above these flow levels system normal constraints start to bind
- for flows from South Australia to Victoria, limits are mainly due to thermal ratings of the network in South Australia
- South Australia to Victoria thermal constraints can be caused by the North West Bend-to-Robertstown 132 kV line, and the Waterloo-MWP4 132 kV line
- for flows into South Australia from Victoria, limits are due to thermal ratings of the Victorian network as well as transient stability issues in Victoria
- Victoria to South Australia thermal constraints can be caused by binding constraints the South Morang 500/330kV transformer
- a trend of reduced Murraylink interconnector capability as Victorian regional demand increases

Table 11 shows the binding system-normal constraint equations setting the South Australia to Victoria limit on Murraylink for the calendar year 2009.

Table 11 Binding constraints for Murraylink - South Australia to Victoria (2009)

Constraint equation ID	Binding hours	*Description*/Notes
S>V_NIL_NIL_RBNW	200.3	*Out=Nil, avoid overloading North West Bend-to-Robertstown 132 kV line on no line trips*
S>>V_NIL_RBTX_WTMW4	53.3	*Out=Nil, avoid overloading Waterloo - MWP4 line for trip of one Robertstown transformer*
SVS_420	35.3	*South Australia to Victoria on Heywood and Murraylink upper transfer limit* *of 420 MW oscillatory limit*
V>>V_NIL_1B	16.2	*Out = Nil, avoid overloading Dederang-to-Murray no.2 330 kV line for loss of the parallel no.1 line, 15-minute line ratings*

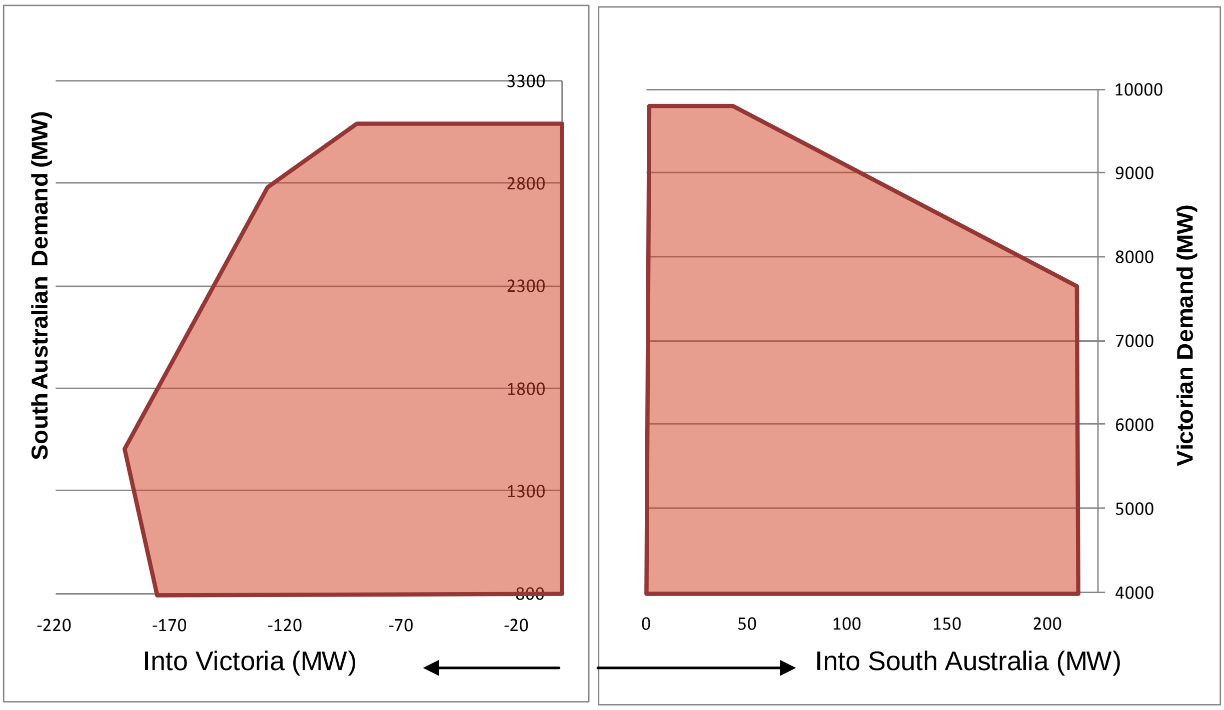
Table 12 shows the binding system-normal constraint equations setting the Victoria to South Australia limit on Murraylink for the calendar year 2009

Table 12 Binding constraints for Murraylink - Victoria to South Australia (2009)

Constraint equation ID	Binding hours	*Description*/Notes
V>>V_NIL_2A_R & V>>V_NIL_2B_R & V>>V_NIL_2_P	488.2	*Out = Nil, avoid pre-contingent overloading on the South Morang 500/330 kV (F2) transformer, for radial/parallel modes and Yallourn W1 on the 500 kV or 220 kV*
V::N_NILVxxx & V::N_NILQxxx	204.1	*Out = Nil, avoid transient instability for fault and trip of a Hazelwood-to-South Morang 500 kV line, radial or parallel modes in Victoria*
V^SML_NSWRB_2	56.3	*Out = New South Wales Murraylink runback scheme, limit Victoria to South Australia on Murraylink to avoid voltage collapse for loss of Darlington Pt-to-Buronga (X5) 220 kV line*
V>>N-NIL_HA	34.4	*Out= Nil, avoid Murray-to-Upper Tumut (65) overload on Murray-Lower Tumut (66) trip*

Figure 5 shows the range of flows on Murraylink over the period from November 2009 to October 2010

Figure 5 Range of Murraylink operation (Nov 2009 to Oct 2010)



Appendix B. Murraylink Runback Schemes

A number of runback schemes have been implemented for Murraylink in order to allow for higher transfers on this interconnector. These schemes allow higher pre-contingency flows on Murraylink due to automatic post-contingency action returning the network to a secure state.

A fast runback scheme was also installed for some network elements in New South Wales; however this scheme has not yet been placed into service because of problems with communications. Without the New South Wales runback scheme enabled, Murraylink transfer to South Australia may be limited to near zero under high demand conditions in New South Wales. Investigations are ongoing into getting this runback scheme into operation.

B.1. Murraylink automatic slow runback control (Victoria)

This automatic slow runback control scheme is required to prevent power flows exceeding the thermal limits in the Victorian transmission system for contingent loss of one of a number of critical 220 kV circuits. The scheme continuously monitors the loading of critical circuits within Victoria and will reduce Murraylink transfer if overloads become apparent.

The monitored circuits are (dynamic line ratings are used for all lines):

- Shepparton-to-Bendigo 220 kV line
- Moorabool-to-Ballarat no.1 220 kV line
- Ballarat-to-Bendigo 220 kV line
- Dederang-to-Shepparton 220 kV line
- Dederang-to-Glenrowan no.1 220 kV line
- Dederang-to-Glenrowan no.3 220 kV line

If the scheme is triggered it will reduce Murraylink flow by 110 MW in order to relieve the overloaded transmission circuit.

B.2. Murraylink very fast runback scheme (Victoria)

The very fast runback scheme (VFRB) allows higher transfers on Murraylink by initiating rapid reduction in Murraylink power flow following critical contingencies within Victoria.

Murraylink transfer is reduced to zero virtually immediately following the trip of any of the following monitored transmission elements:

- Shepparton-to-Bendigo 220 kV line
- Bendigo-to-Kerang 220 kV line
- Kerang-to-Red Cliffs 220 kV line
- Ballarat-to-Horsham 220 kV line
- Horsham-to-Red Cliffs 220 kV line
- Ballarat-to-Bendigo 220 kV line

- Moorabool-to-Ballarat no.1 220 kV line
- Moorabool-to-Ballarat no.2 220 kV line
- Moorabool 500/220 kV no.1 transformer (VFRB not enabled for MLTS no.2 transformer)
- Dederang 330 kV bus tie

B.3. Automatic sever trip (South Australia)

As the existing North West Bend (NWB) and Murraylink Berri substations are supplied through a radial system, it is possible for the system to be “severed” from the South Australian grid, either momentarily or permanently. The automatic sever trip scheme is required to identify the “islanding” of the NWB, Monash and Murraylink Berri substations from the South Australian grid, and to trip the connecting circuit breakers to the Berri converter. This prevents the possibility of one part of the radial network being supplied by Murraylink and the other part supplied by the South Australian grid.

B.4. Automatic runback scheme (South Australia)

This runback scheme permits increased power flow across Murraylink through supervision of selected network conditions and automatic control of power flow to prevent network thermal overload conditions. When a contingency occurs, runback will not only reduce the real power flow through Murraylink but will also increase the reactive power capability of Murraylink. Such increased reactive capability is especially useful in improving voltage stability following network contingencies. The automatic runback control scheme is designed to prevent exceeding the thermal limits in the South Australian transmission system.

The scheme reduces the import/export of Murraylink to a secure operating condition within 5 seconds from receipt of the runback signal.

The following lines are monitored by the automatic runback control scheme:

- Robertstown-NWB no. 1 132 kV transmission line
- Robertstown-NWB no. 2 132 kV transmission line
- NWB – Monash no. 1 132 kV transmission line
- NWB – Monash no. 2 132 kV transmission line
- Each of the two 275/132 kV transformers at Robertstown, monitoring on the 132 kV side

Appendix C. Reduced nodal model

Figure 6 Reduced nodal model diagram