Inter – Area Transmission Capacity

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Revision Table

Revision	Issue Date	Description
Draft Rev 5	10 August 2006	• First draft sent to Electricity Commission • Still awaiting information on line construction from Transpower. In the meantime we have assumed construction data for a number of lines.
Draft Rev 6	15 August 2006	• Add Appendix 3 to summarize line construction assumptions • Add option for Pole 1 upgrade with no new cables
Draft Rev 7	28 August 2006	• Added loss coefficients for each inter-area transfer.
Draft Rev 8	29 August 2006	• Editorial changes
Draft Rev 9	21 September 2006	• Update analysis with line construction information from Transpower

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Executive Summary

This report describes the transmission capacity and loss coefficients between different areas in the New Zealand power system.

The N – 1 system transmission capacity and N system loss coefficients are estimated for the committed system (present system plus committed projects) and for a number of possible transmission augmentations. Indicative cost estimates are provided for the augmentations.

The information in this report is intended to help the Electricity Commission develop future generation scenarios by providing an indication of the additional cost required to transmit power from new generation to the load. (It should be noted that these costs are not sufficiently accurate for use as budgetary estimates for projects).

1. Introduction

The generation scenarios for the Initial Statement of Opportunities in 2005 [1] (Initial SOO) were based on the likely cost of new generation but did not take into account the likely cost of associated transmission augmentation. The Electricity Commission intends that the next SOO will take some account of the cost of transmission augmentation in the development of new generation scenarios.

This report is intended to identify the major constraints on inter-area transmission capacity in the committed system (existing system + committed projects) and to provide an estimate of the cost of increasing the transmission capacity. This information will then be used by the Commission to help develop new generation scenarios.

2. Analysis Assumptions

2.1 Accuracy of Analysis

This analysis is of a very approximate nature and is only intended to be used to help in the development of generation scenarios.

The costs associated with transmission augmentations are merely intended to differentiate between the relatively low cost of a transmission upgrade and the much higher cost of building a new line.

We do not consider that these costs are sufficiently accurate for budgetary purposes and should not be used when estimating the costs of transmission projects.

2.2 Construction of Existing Lines

Transpower provided the Commission with information on the construction of existing transmission lines. We used this construction information to help us make assumptions about future upgrades. This is described in Appendix 3.

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[1] 'Initial Statement of Opportunities', Electricity Commission, July 2005.

2.3 Cost Estimates for Transmission Augmentation

We have derived our cost estimates for transmission augmentations from :

a) Transpower Annual Planning Report 2006 [2]

b) Previous work on the Commission's Draft Decision on Transpower's Auckland 400 kV Grid Investment Proposal, in particular the PB Associates Costs Report [3]

Where possible, our cost estimates were taken directly from these reports for specific projects. Where costs for specific projects were not available we have used the costs for similar projects, scaled for line length.

We have included easement costs for new lines, although no allowance was made for differences in terrain or property values around the country. On the other hand, we have excluded easement costs for line upgrades because of the uncertainty surrounding easements.

Table 1 lists the estimated unit costs that we used for transmission augmentations.

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[2] 'Annual Planning Report 2006', Transpower New Zealand Ltd, 31 March 2006.

[3] 'Transmission Augmentations into Auckland : Capital Cost Estimates for Short-Listed Alternatives to Transpower's 400 kV Transmission Line Proposal', Parsons Brinckerhoff Associates, 26 March 2006.

Table 1. Unit Cost Estimates

Augmentation	Cost	Source
300 MVAr SVC	$ 32 m	Cost in 2010 dollars from PBA Costs Report
100 MVAr Capacitor bank	$ 4 m	Cost in 2010 dollars from PBA Costs Report
Thermal upgrade for a 220 kV circuit	$ 0.03 m/km	Cost in 2006 dollars from TTU 12 'Thermal Upgrade of 220 kV BPE – TKU' [4]. $ 8.5 m for 2 x 170 km single circuit lines.
Upgrade a single circuit 220 kV line from simplex to duplex conductor	$0.21 m/km	Cost in 2010 dollars from PBA Costs report for upgrading 200 km OTA – WKM A and B lines. Excludes easement costs.
New 220 kV double circuit line	$1.4 m/km	Cost in 2010 dollars from PBA Costs report for new 200 km double circuit 220 kV line OTA – WKM. Duplex Zebra. 765/695 MVA per circuit. Includes easement costs.
New 400 kV double circuit line	$ 1.9 m/km	Cost in 2010 dollars from PBA Costs report for new 200 km double circuit 400 kV line OTA – WKM. 1200 MVA per circuit. Includes easement costs.
220 kV cable	$ 4 m/km	Cost in 2010 dollars from PBA Costs Report for 10 km 220 kV 400 MVA cable
HVDC Upgrade	$ 657 m OR $742 m	Cost in 2010 dollars from Transpower Proposal for HVDC Upgrade [5]. (0 new cables) (1 new cable)
New 1400 MW HVDC Bipole Southland - Auckland	$ 2,180 m	Cost in 2010 dollars 1400 MW +/- 350 kV

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[4] The TTU projects were 'Tactical Transmission Upgrades' proposed before the process for approving Grid Upgrade Plans was finalized.

[5] 'HVDC Inter-Island Link Upgrade Project Investment Proposal', Transpower New Zealand Ltd, 2005.

2.4 Inter – Area Network

We have assumed that most of the cost of transmission augmentations will be associated with inter – area transmission and that the cost of intra – area augmentations will be relatively small.

Figure 1 shows the inter-area network that we considered. The choice of these areas was based on geographic separation with major transmission connections between areas. (Appendix 1 lists the GXP's in each area).

Figure 1 also shows the inter – area transmission capacity for the present system in the form of an N - 1 winter/summer capacity and a scaled graphical indication of the N – 1 winter capacity (the thickness of the inter-area link representing the N – 1 winter capacity).

2.5 Transmission Capacity Limits

We based the inter-area transmission capacity limits in this report on an N – 1 criterion which allows for one circuit to trip without subsequent cascade failure.

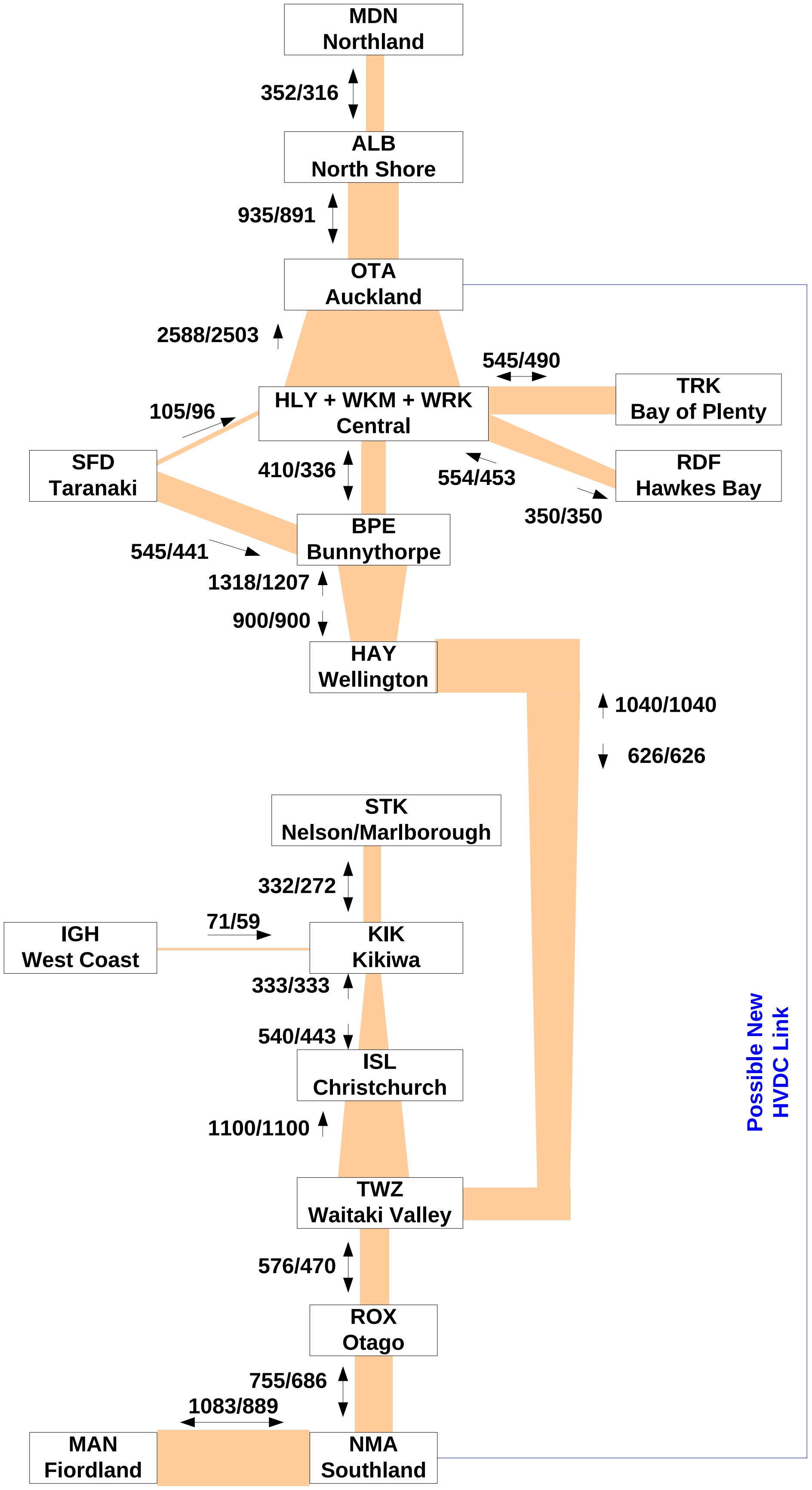
In most cases we found the N – 1 capacity limit by tripping the worst case inter-area circuit and finding the maximum power that could be transferred on the remaining circuits. There were 2 exceptions to this method:

a) The HVDC capacity limit is equal to the continuous bipole rating. In the event of a pole trip we assumed that the power loss will be compensated by a combination of reserves and overload capability on the healthy pole.

b) The HAY – BPE thermal capacity limit is equal to the capacity with all circuits connected. In the event of a circuit tripping we assumed that the HVDC will runback to prevent overloading on the healthy circuits.

In most cases we found that the N – 1 capacity was determined by the thermal capability of the circuits. However in some cases the capacity was determined by voltage stability (with a 5% margin from the 'nose' of the PV curve). A voltage stability limit is typically shown in Figure 1 as a voltage stability capacity that is less in one direction than the thermal capacity in the other direction.

Figure 1. Inter-Area Network



2.6 Transmission Loss coefficients

The Commission intends to use Inter-area transmission losses to help estimate energy loss (and hence costs) associated with future generation and transmission scenarios.

We estimated the inter-area transmission losses by considering the change in total system loss (on the N system) before and after a perturbation in transfer between the two areas being investigated [6]. We used this information to estimate an inter-area loss coefficient for each inter-area transmission link [7].

The procedure for finding the loss coefficients involved the following steps:

a) Shifting the slack bus to one of the two areas,

b) Solving the load flow and recording the total system loss, $P_{LOSS,TOTAL\ 1}$ in MW, and the inter-area transfer S_{T1}, in MVA.

c) Adding an appropriate change in demand on the other area, typically somewhere between 10 and 100 MW,

d) Solve again and record the new total system loss, $P_{LOSS,TOTAL\ 2}$ and the new inter-area transfer, S_{T2}.

e) Calculating the inter-area loss coefficient (R) with units (MW^{-1}) using the equations below.

$$P_{LOSS,TOTAL1} = S_{T1}^{2}\ R + P_{LOSS,REST} \qquad (1)$$

$$P_{LOSS,TOTAL2} = S_{T2}^{2}\ R + P_{LOSS,REST} \qquad (2)$$

Eliminate $P_{LOSS,REST}$ from (1) and (2), and introduce ΔP_{LOSS} as the change from $P_{LOSSTOTAL1}$ to $P_{LOSSTOTAL2}$:

$$R = \frac{\Delta P_{LOSS}}{S_{T2}^{\ 2} - S_{T1}^{\ 2}}$$

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[6] The transfer perturbation was modelled by increasing / decreasing load in one area with a corresponding decrease / increase in generation in the adjacent area.

[7] It should be noted that these results are a linearization of a non-linear system. To check the non-linearity (caused by reactive power flow and changing power sharing with perturbation magnitude) the results were tested at several different transmission levels and perturbation magnitudes. In most cases fairly consistent results occurred. Where some inconsistency was observed a value closer to that predicted by hand calculations was used. The loss coefficient was usually picked at a medium to high power transfer and perturbations between 10 and 100 MW.

Where appropriate, a rough check was performed for all inter-area loss coefficients. This was done by comparing the values from PSS/E simulation with hand calculations of the parallel sum of transmission line pu resistances.

3. Summary of Inter – Area Transmission Capacity

We have estimated the inter-area capacity and losses for the present system shown in Figure 1. We have also estimated the increase in inter-area capacity and reduction in losses that may be gained by implementing various transmission augmentations.

Table 2 summarizes the present inter-area capacities and losses and the increase in capacity and reduction in loss provided by various transmission augmentations. The analysis for each augmentation is described in Appendix 2.

Transmission augmentations are sequenced by cost. For example the capacity for TWZ – ISL is presently 1100 MW and is constrained by voltage stability. Adding capacitors and an SVC increases the capacity to 1200 MW at a cost of $ 36 m (still constrained by voltage stability). Adding further SVCs at a further cost of $ 64 m increases the capacity to the thermal limit of 1709/1402 MW. The binding constraint is then the thermal limit on the Livingston to Islington circuit. This circuit can be thermally up-rated from 50°C to 70°C at a cost of $8m and increasing the inter-area capacity limit to 1996/1813 MW. Finally, a new 220 kV double circuit line ($322 m) increases the inter-area capacity to 3448/3132 MW.

Table 2. Summary of Inter – Area Transmission Capacity and Loss Coefficients

Inter – Area Transmission	Augmentation	Cost	Winter/Summer N – 1 Capacity	Inter – Area Loss Equation
MAN – NMA	Committed system	$ 0 m	1083 / 889 MW	$0.000029 \times P_{MW}^2$
	Thermally upgrade short Pheasant sections	+$ 3 m	1405 / 1151 MW	$0.000029 \times P_{MW}^2$
	Thermally upgrade entire lines and replace Pheasant sections with Chukar.	+$ 51 m	1760 / 1600 MW	$0.000029 \times P_{MW}^2$
	New 220 kV double circuit line	+$ 189 m	2930 / 2665 MW	$0.000019 \times P_{MW}^2$
NMA – ROX	Committed system	$ 0 m	755 / 686 MW	$0.000080 \times P_{MW}^2$
	2 x 350 MVA 220 kV PSTs on NMA – TMH circuits	+ $ 30 m	1089 / 990 MW	$0.000080 \times P_{MW}^2$
	New 220 kV double circuit line	+$ 182 m	1815 / 1650 MW	$0.000029 \times P_{MW}^2$
ROX – TWZ	Committed system	$ 0 m	576 / 470 MW	$0.000036 \times P_{MW}^2$
	Thermally upgrade ROX – NSY – LIV and 8.6km section between Cromwell and Tarras.	+ $5 m	780/715 MW	$0.000036 \times P_{MW}^2$
	Duplex the ROX – NSY – LIV circuit.	+ $30 m	1171/1073 MW	$0.000030 \times P_{MW}^2$
	New 220 kV double circuit line	+ $210 m	2546/2333 MW	$0.000021 \times P_{MW}^2$

TWZ – ISL	Committed system	$ 0 m	1100 MW	0.000050 x P_{MW}^2
	Addition of capacitors at ASB ($3.5 m) and 1 x 120 MVAr SVC at ISL ($15 m).	+ $ 19m	1200 MW	0.000050 x P_{MW}^2
	Addition of further dynamic reactive support at ISL and ASB, 2 x 300 MVAr SVCs	+ $64m	1709/1402 MW	0.000050 x P_{MW}^2
	Thermal up-rate of LIV – ISL circuit to 70°C	+$8 m	1996/1813 MW	0.000050 x P_{MW}^2
	New 220 kV double circuit line	+ $322m	3448/3132 MW	0.000032 x P_{MW}^2
ISL – KIK	Committed system (Northward) Committed system (Southward)	$ 0 m	333 MW 540/443 MW	0.000095 x P_{MW}^2
	Increase in Northward transfer to thermal limits by addition of 300 MVAr SVC at KIK.	+ $32m	540/443 MW	0.000095 x P_{MW}^2
	Thermal upgrade on the ISL – KIK 1 circuit from 50°C to 75°C (assuming enough reactive support for Northward transfer)	+ $ 8 m	708/643 MW	0.000095 x P_{MW}^2
KIK – STK	Committed system[8]	$ 0 m	332/272 MW	0.000039 x P_{MW}^2
	Thermal upgrade of both 220 kV KIK – STK circuits	+ $4 m	435/396 MW	0.000039 x P_{MW}^2

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[8] The current constraint is a component limiting the transfer to 182 MW. It is assumed this can be upgraded for very little cost and so is not included in the cost of upgrades.

IGH – KIK	Committed system	$ 0 m	71/59 MW	0.000270 x P_{MW}^2
	Thermally up-rate the KIK – MCH – IGH 1 circuit.	+ $3 m	92/85 MW	0.000270 x P_{MW}^2
	Re-conductor the KIK – MCH – IGH 1 circuit from simplex Coyote to simplex Zebra strung at 75°C.	+ $ 25 m	181/165 MW	0.000170 x P_{MW}^2
	Operate IGH – KIK B line at 220 kV and install third circuit (Simplex Zebra) by stringing vacant side of the IGH – KIK B line	+ $32 m	455/412 MW	0.000150 x P_{MW}^2
TWZ – HAY	Committed system (Northward)	$ 0 m	1040 MW	0.000060 x P_{sent}^2
	Committed system (Southward)		626 MW	0.000069 x P_{sent}^2
	Pole 1 replacement with no new cables (Northward)	+ $ 657 m	1200 MW	0.000045 x P_{sent}^2
	Pole 1 replacement with no new cables (Southward)		1000 MW	0.000050 x P_{sent}^2
	OR			
	Pole 1 replacement with additional cable (Northward)	+ $742 m	1400 MW	0.000045 x P_{sent}^2
	Pole 1 replacement with additional cable (Southward)		1000MW	0.000049 x P_{sent}^2

HAY – BPE	Committed system (Northward) Committed system (Southward)	\$ 0 m	1318/1207 MW 900/900 MW	0.000041 x P_{MW}^2
	HVdc upgrade with additional reactive support (C11) on HAY 220 kV bus. Northward Southward	+ \$ 0m	1318/1207 MW 970/970 MW	0.000041 x P_{MW}^2
	Up-rate transmission capacity by duplexing the HAY – BPE 1 and 2 circuits and add 650 MVAr of dynamic reactive support at BPE. Northward Southward	+ \$127 m	2164/1983 MW 1280/1280 MW	0.000027 x P_{MW}^2
	New 220 kV double circuit line Northward Southward	+ \$225 m	3211/2919 MW 1450/1450 MW	0.000018 x P_{MW}^2
BPE - (HLY+WKM+WRK)	Committed system	\$ 0 m	410 / 336 MW	0.000140 x P_{MW}^2
	Thermal upgrade of BPE – TKU 1 & 2 circuits	+ \$10 m	557 / 510 MW	0.000140 x P_{MW}^2
	Duplex BPE – TKU – WKM 1 & 2 and BPE – TNG – RPO – WRK – PPI – WKM circuits	+ \$ 160 m	1152 / 1056 MW	0.000070 x P_{MW}^2
	New 220 kV double circuit line BPE – WKM	+ \$ 336 m	2183 / 2000 MW	0.000036 x P_{MW}^2

SFD – BPE	Committed system	$ 0 m	545 / 441 MW	0.000085 x P_{MW}^2
	Thermal upgrade of BRK – SFD circuits to 120°C.	+ $ 9 m	726/ 659 MW	0.000085 x P_{MW}^2
	New 220 kV double circuit line between BPE – BRK.	+ $ 105 m	950/893 MW	0.000063 x P_{MW}^2
	Duplexing BRK – SFD circuits to twin Zebra and running at 75°C.	+ $ 63 m	1454 / 1321 MW	0.000039 x P_{MW}^2
	Continuation of 220 kV double circuit line from BRK – SFD.	+ $ 126 m	2177/ 1978MW	0.000027 x P_{MW}^2
SFD – (HLY+WKM+WRK)	Committed system	$ 0 m	105 / 96 MW	0.0002 x P_{MW}^2
	No upgrades as these circuits are not loaded to capacity	–	–	–
(HLY + WKM + WRK) – OTA	Committed system	$ 0 m	2588 / 2503 MW	0.000025 x P_{MW}^2
	New 400 kV double circuit line OTA – WKM Followed by additional transformers & reactive support	+ $ 710 m + $ 181 m	2999 / 2818 MW 4053 / 3926 MW	0.0000117 x P_{MW}^2
	OR Intermediate thermal upgrades, phase shifters, and reactive support Followed by new 220 kV double circuit line Followed by reactive support and phase shifters	+ $ 95 m + $ 479 m + $ 285 m	3018 / 2919 MW 3285 / 3209 MW 4116 / 3975 MW	0.000025 x P_{MW}^2 0.0000145 x P_{MW}^2 0.0000145 x P_{MW}^2
	OR Duplex OTA – WKM A and B and reactive support Followed by new 400 kV line.	+ $ 259 m + $ 770 m	3334 / 3281 MW 4222/ / 4078 MW	0.000019 x P_{MW}^2 0.0000098 x P_{MW}^2

(HLY + WKM + WRK) – TRK	Committed system	$0 m	545 / 490 MW	0.000025 x P_{MW}^2
	Duplex ATI – TRK 1 & 2, and thermally up-rate OHK – KAW – EDG circuits ($23m) and add extra reactive support in the form of a 400 MVAr of capacitor banks on the 110 kV system ($ 16 m).	+ $39 m	830 / 830 MW	0.000015 x P_{MW}^2
	Additional reactive support on 110 kV system (600 MVAr of capacitor banks) to reach transmission thermal limits.	+ $24 m	1031 / 936 MW	0.000015 x P_{MW}^2
(HLY + WKM + WRK) – RDF	Committed system (**into** Hawkes Bay[9])	$0 m	350 MW	0.000043 x P_{MW}^2
	Committed system (**out of** Hawkes Bay)	$0 m	554 / 453 MW	0.000043 x P_{MW}^2
	Additional reactive support (300 MVAr SVC on 110 kV system) to assist power transfer **into** Hawkes Bay.	+ $32 m	554 / 453 MW	0.000043 x P_{MW}^2
	Thermally up-rate WRK – RDF circuits from 50°C to 75°C or 764/694 MVA ($9 m) with additional 300 MVAr SVC and 120 MVAr caps on the 110 kV system ($32 m + $3.5 m).	+ $45 m	726/659 MVA	0.000043 x P_{MW}^2
	New 220 kV double circuit line	+ $200 m	2178 / 1977 MW	0.000018 x P_{MW}^2
OTA – ALB	Committed system	$0 m	935 / 891 MW	0.000014 x P_{MW}^2
	New 220 kV PEN – ALB cable	+ $160 m	1556 / 1434 MW	0.0000079 x P_{MW}^2
	Additional 220 kV PEN – ALB cable	+ $160 m	2177 / 1977 MW	0.0000067 x P_{MW}^2

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[9] Without Whirinaki generation.

ALB – MDN	Committed system	$ 0 m	352 / 316 MW	0.000070 x P_{MW}^2
	Duplex HPI – BRB circuit	$ 23 m	703 / 633 MW	0.000058 x P_{MW}^2
NMA – OTA	New 1400 MW +/- 350 kV HVdc link	$2,180 m	1400 MW	0.000093 x P_{MW}^2

Appendix 1. GXP – Area Mapping

Area	GXP's in Area
MAN (Fiordland)	None
NMA (Southland)	Balclutha Brydone Edendale Gore Invercargill North Makarewa Tiwai
ROX (Otago)	Cromwell Clyde Frankton Halfway Bush -1 Halfway Bush -2 Naseby Oamaru Palmerston South Dunedin Studholme Waitaki
TWZ (Waitaki Valley)	Albury Timaru Tekapo A Temuka Twizel

Area	GXP's in Area
ISL (Canterbury)	Addington 11kV -1 Addington 11kV -2 Addington 66kV Addington 66kV Ashburton 33 Ashburton 66 Ashley Bromley 11kV Bromley 66kV Heathcote (off BRY66) Coleridge Culverden Hororata Hororata 66kv Islington 33kV Islington 66kV Halswell (off ISL66) Kaiapoi Kaikoura Papanui 11kV-1 Papanui 11kV-2 Papanui 66kV Southbrook Springston Waipara
KIK (Kikiwa)	Kikiwa
STK (Nelson/Marlborough)	Blenheim Motueka Motupipi Stoke

Area	GXP’s in Area
IGH (West Coast)	Arthur's Pass
	Castle Hill
	Dobson
	Greymouth
	Hokitika
	Murchison
	Orowhaiti (was Robertson Street)
	Westport
	Otira
HAY (Wellington)	Central Park 11kV
	Central Park 11kV
	Central Park 33kV
	Central Park 33kV
	Gracefield
	Greytown
	Haywards 11kV
	Haywards 33kV
	Kaiwharawhara - 1
	Kaiwharawhara - 2
	Melling 11kV
	Melling 33kV
	Masterton
	Pauatahanui
	Paraparaumu
	Takapu Rd
	Upper Hutt
	Wilton

Area	GXP’s in Area
BPE (Bunnythorpe)	Bunnythorpe 33kV Bunnythorpe NZR Brunswick Dannevirke Linton Mangamaire Mangahao Marton Mataroa National Park Ohakune Ongarue Tokaanu Tangiwai 11kV Tangiwai NZR Woodville Wanganui Waipawa
SFD (Taranaki)	Carrington St 11kV Carrington St 33kV Huirangi Hawera Motunui - 1 Motunui - 2 Moturoa (NPL) Opunake Stratford Taumarunui NZR Waverley

Area	GXP’s in Area
HLY+WKM+WRK (Central North Island)	Cambridge Hamilton 11kV Hamilton 33kV Hamilton NZR Hinuera Hangatiki Kinleith 11kV - 1 Kinleith 11kV - 2 Kinleith 11kV - 3 Kinleith 33kV Kopu Lichfield Ohaaki Te Awamutu Western Rd Waihou Whakamaru Waikino Wairakei

Area	GXP’s in Area
TRK (Bay of Plenty)	Edgecumbe Kawerau BOP Kawerau T4 Kawerau T9 Kawerau T6 Kawerau T7 Kawerau T8 Kawerau T11 Kawerau T14 Mt Maunganui 11kV Mt Maunganui 33kV Owhata Rotorua 11kV Rotorua 33kV Tauranga 11kV Tauranga 33kV Tarukenga 11kV Te Kaha Te Matai Waiotahi
RDF (Hawkes Bay)	Fernhill Gisborne 50kV Redclyffe Tuai Whirinaki 11 kV Bus A Whirinaki 11 kV Bus B Whirinaki 11 kV Bus C Wairoa 11kV Whakatu

Area	GXP's in Area
OTA (Auckland)	Bombay 33kV Bombay 110kV Glenbrook NZ Steel Glenbrook Counties Meremere (BOB_33B) Mangere 33kV Mangere 110kV - 1 Mangere 110kV - 2 Otahuhu Pakuranga Penrose 22kV Penrose 33kV Penrose 110kV - LST Penrose 110kV - KING Mt Roskill 22kV Mt Roskill 110kV - LST Mt Roskill 110kV - QUAY Takanini Wiri
ALB (North Shore)	Albany 33kV Albany 110 (Wairau Rd) Henderson Hepburn Rd Silverdale Wellsford
MDN (Northland)	Bream Bay Dargaville Kensington Kaikohe Kaitaia Maungatapere Maungaturoto

Appendix 2. Derivation of Capacity Limits

A2.1 MAN – NMA

The MAN to NMA transmission is made up of two double circuit 220 kV lines. The conductors are mostly Duplex Goat at 50^{o}C (493/404 MVA) with a short section on each line (13 km and 34 km) of Simplex Pheasant at 50^{o}C (380/312 MVA). This gives an overall rating 380/312 MVA per circuit:

1. MAN – NMA 1	(380/312 MVA)
2. MAN – NMA 2	(380/312 MVA)
3. MAN – NMA 3	(380/312 MVA)
4. MAN – INV 1	(380/312 MVA)

Assuming that the MW capacity of a circuit is about 0.95 of the MVA capacity, the N – 1 MW capacity of the 4 circuits is 3 x 0.95 x the MVA capacity of a single circuit:

Winter Capacity = 3 x 0.95 x 380 MW
= 1083 MW

Summer Capacity = 3 x 0.95 x 312 MW
= 889 MW

The capacity could be increased by first thermally upgrading the short simplex Pheasant sections from 50^{o}C to 75^{o}C. This would increase the rating of the Pheasant sections to over that of the 50^{o}C Duplex Goat sections giving an overall rating of 493/404 MVA for each circuit. This would cost about $3 m (based on unit costs in Table 1) and increase the N – 1 capacity to:

Winter Capacity = 3 x 0.95 x 493 MW
= 1405 MW

Summer Capacity = 3 x 0.95 x 404 MW
= 1151 MW

The capacity could then be further increased by thermally upgrading the Duplex Goat conductors to 75^{o}C and replacing the simplex Pheasant with simplex Chukar running at 75^{o}C to give an overall rating of 617/561 MVA per circuit. Around 93km of simplex Pheasant would require replacement with simplex Chukar (2 x 12.5km + 2 x 34 km) at around $37.2 m (assuming $0.4 m/km). Thermal up-rating of the remaining 4 circuits (135km in length) would cost about $13.4 m (based on unit costs in Table 1) giving a total cost of around $51 m and increasing the N – 1 capacity to:

Winter Capacity = 3 x 0.95 x 617 MW
= 1760 MW

Summer Capacity = 3 x 0.95 x 561 MW
= 1600 MW

The capacity could then be further increased by adding a new double circuit 220 kV line about 135 km in length for about $ 189 m (based on the unit costs in Table 1). This would increase the N – 1 capacity to:

Winter Capacity = 5 x 0.95 x 617 MW
= 2930 MW

Summer Capacity = 5 x 0.95 x 561 MW
= 2665 MW

The loss coefficient was calculated by making the MAN bus slack and placing a 100 MW load on the NMA bus to give a loss coefficient of 0.000029 MW^{-1}. Addition of a new double circuit line reduces this by 2/3rds to 0.000019 MW^{-1}.

A2.2 NMA – ROX

The NMA to ROX transmission is made up of two single circuit lines INV – ROX A & B, a double circuit line NMA – TMH, and a double circuit line ROX – TMH. The NMA – ROX capacity is determined by the following circuits which are all simplex Zebra at 75°C :

1. INV – ROX 1	(382/347 MVA)
2. INV – ROX 2	(382/347 MVA)
3. NMA – TMH 1	(382/347 MVA)
4. NMA – TMH 2	(382/347 MVA)

The MW capacity for a INV – ROX circuit is 363/330 MW [10].

The power sharing for the worst case contingency of an INV – ROX circuit is about 1.00 : 0.54 : 0.54 (INV – ROX : NMA – TMH : NMA – TMH). Hence, the combined N – 1 capacity for the 4 circuits is then (1.00 + 0.54 + 0.54) x the single INV – ROX MW capacity:

Winter Capacity = (1 + 0.54 + 0.54) x 363 MW
= 755 MW

Summer Capacity = (1 + 0.54 + 0.54) x 330 MW

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[10] Assuming that the MW capacity of a circuit is about 0.95 of the MVA capacity.

= 686 MW

The capacity could be increased by adding 2 x 350 MVA 220 kV PSTs on the NMA – TMH circuits to evenly share the loading with the INV – ROX circuits. This would cost about $30 m . The N – 1 capacity would increase to:

Winter Capacity = 3 x 363 MW
= 1089 MW
Summer Capacity = 3 x 330 MW
= 990 MW

We have assumed that these circuits can not be duplexed.

The capacity could be further increased by adding a new double circuit 220 kV line about 130 km in length for about $182 m (based on the unit costs in Table 1).

This would increase the N – 1 capacity to:

Winter Capacity = 5 x 363 MW
= 1815 MW

Summer Capacity = 5 x 330 MW
= 1650 MW

The loss coefficient was calculated by making the ROX bus slack and placing a 50 MW load on the NMA bus. This gives a rough loss coefficient of around 0.000080 MW^{-1}. Addition of a new 220kV twin Zebra double circuit line between NMA and ROX reduces this considerably to around 0.000029 MW^{-1}. In this case the slack was changed to NMA and a 1000MW load added to the ROX 220 kV bus for the initial condition. A further 50MW was then added to the ROX bus and the loss coefficient calculated.

A2.3 ROX – TWZ

The ROX to TWZ transmission is made up of 3 x 220 kV circuits :

1. CYD – CML – TWZ 1 (476/391 MVA)
2. CYD – CML – TWZ 2 (476/391 MVA)
3. ROX – NSY – LIV (247/202 MVA)

The CYD – CML – TWZ circuits are simplex Chukar strung at 75^{o}C with an 8.6 km exception between Cromwell and Tarras strung at 50^{o}C.

The MW capacity for the ROX – NSY – LIV circuit is 235/192 MW .

The power sharing for the worst case contingency of a CYD – CML – TWZ circuit is about 1.00 : 1.45 (ROX – NSY – LIV : CYD – CML – TWZ).

The combined N – 1 capacity for the 3 circuits is then (1.00 + 1.45) x the ROX – NSY – LIV MW capacity:

Winter Capacity = (1 + 1.45) x 235 MW
= 576 MW

Summer Capacity = (1 + 1.45) x 192 MW
= 470 MW

Thermal up-rates on the ROX – NSY – LIV circuit from 247/202 MVA to 335/307 MVA (≈140km x $0.03m/km = $4.2 m) and the 8.6 km section between Cromwell and Tarras 617/561 MVA (≈ 8.6km x 2 x $0.03m/km = $0.5 m) will increase the N – 1 capacity to:

Winter Capacity = (1 + 1.45) x 335 x 0.95 MW
= 780 MW

Summer Capacity = (1 + 1.45) x 307 x 0.95 MW
= 715 MW

The capacity could be further increased by duplexing the ROX – LIV circuit. Duplexing this line would cost approximately $29m (140kms x $0.21m/km) and double the transmission capacity of the 220 kV circuits from 335/307 MVA to 670/614 MVA.

The power sharing for the worst case contingency of an CYD– CML circuit after duplexing[11] is about 1.00 : 0.84 (ROX – LIV : CYD – CML). Hence, the N – 1 capacity is:

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[11] The transmission line impedance from Simplex to Duplex is assumed to reduce by around ½ for the resistance and ¾ for the reactance.

Winter Capacity = (1.00 + 0.84) x 670 x 0.95 MW
= 1171 MW

Summer Capacity = (1.00 + 0.84) x 614 x 0.95 MW
= 1073 MW

The capacity could be further increased by adding a new double circuit 220 kV line about 150 km in length between the Clutha and Waitaki valleys. This would cost roughly $210 m (based on the unit costs in Table 1).

This would increase the N – 1 capacity to:

Winter Capacity = 4 x 670 x 0.95 MW
= 2546 MW

Summer Capacity = 4 x 614 x 0.95 MW
= 2333 MW

The loss coefficient was calculated by making the ROX bus slack and placing a 100 MW load on the TWZ bus. Adding a further 50 MW at the TWZ bus and calculating the loss coefficient gives around 0.000036 MW^{-1}. Duplexing of the ROX – NSY – LIV circuit reduces this further to around 0.000030 MW^{-1}. The addition of a 220kV twin Zebra double circuit transmission line between ROX and TWZ reduces this to approximately 0.000021 MW^{-1}. In this case a 500MW load added to the TWZ 220 kV bus for the initial condition and a further 100MW was then added to the TWZ bus and the loss coefficient calculated.

A2.4 TWZ – ISL

The Upper South Island (USI) is supplied by four 220 kV transmission circuits, one from LIV and three from TWZ, all terminating at the ISL substation in Christchurch. Several projects are currently underway to upgrade the transfer limits into the USI including duplexing of the LIV – ISL circuit and bussing two TWZ – ISL circuits at ASB. These are considered as committed projects in this analysis. After these projects are complete the capacity of the four transmission circuits is :

1. TWZ – TKB – ISL	(620/557 MVA)
2. TWZ – OPI A – ASB – BRY – ISL	(764/694 MVA)
3. TWZ – OPIB – ASB – ISL	(764/694 MVA)
4. LIV – ISL	(492/403 MVA)

The TWZ – TKB – ISL and LIV – ISL circuits are duplex goat running at 70°C and 50°C respectively. The other two circuits form part of the CHH – TWZ A line and are Duplex Zebra running at 75°C.

With this transmission configuration the N – 1 capacity is approximately 1100 MW, constrained by a 5% voltage stability margin. Transpower proposes adding reactive support at ISL and ASB. After these projects, and assuming all USI generation is dispatched, the binding voltage stability constraint becomes 1200 MW (including two new 60 MVAr capacitors at ASB and a 120 MVar SVC at ISL – assumed to cost in the vicinity of $15 million)[12],[13].

Additional dynamic reactive support could increase this voltage stability limit further until thermal limits of the lines become binding. This would require up to two additional 300 MVAr SVCs at ISL and at a total cost of around $64 m.

The MW capacity for the ISL – LIV circuit is 467/383 MW . The power sharing for the worst case contingency (a TKB bus section fault) is around 1.00 : 1.33 : 1.33 (ISL – LIV : TWZ – OPI A : TWZ – OPI B). The combined N – 1 capacity for the remaining 3 circuits is then (1.00 + 1.33 + 1.33) x the LIV – ISL MW capacity:

Winter Capacity = (1 + 1.33 + 1.33) x 467 MW
= 1709 MW
Summer Capacity = (1 + 1.33 + 1.33) x 383 MW
= 1402 MW

The capacity could be further increased by thermally upgrading the LIV – ISL circuit from 50°C to 70°C or (620/557 MVA) at a cost of around $8 m (270km x $0.03/km). With the above power sharing the TWZ – OPI A and TWZ – OPI B lines would then reach their limits. This would hence increase the total capacity to approximately:

Winter Capacity = (0.75 + 1 + 1) x 764 x 0.95 MW
= 1996 MW
Summer Capacity = (0.75 + 1 + 1) x 694 x 0.95 MW
= 1813 MW

Adding a new double circuit 220 kV line from ISL – TWZ (about 230 km in length and rated at 765/695 MVA) would cost around $322 m (based on the unit costs in Table 1).This would increase the N – 1 capacity to:

Winter Capacity = (0.75 + 1 + 1 + 1 + 1) x 764 x 0.95 MW
= 3448 MW

Summer Capacity = (0.75 + 1 + 1 + 1 + 1) x 694 x 0.95 MW
= 3132 MW

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[12] Transpower has proposed 2 x 60 MVar capacitors at ISL, however our voltage stability analysis suggests that dynamic reactive support is likely to be required. We have assumed a 300 MVar SVC will provide this.

[13] The MVAr/MW increase in transmission ratio for these augmentations is around 2.4 MVAr/MW.

The loss coefficient was calculated by making the TWZ bus slack. Placing an additional 100 MW load on the ISL bus and calculating the loss coefficient gives approximately 0.000050 MW^{-1} for the current system. The addition of reactive support to boost the voltage stability limit will have no effect on the loss coefficient. The addition of a 220kV twin Zebra double circuit transmission line between TWZ and ISL reduces the loss coefficient to approximately 0.000032 MW^{-1}. In this case a 500MW load added to the ISL 220 kV bus for the initial condition before a further 100MW was added to the ISL bus and the loss coefficient calculated.

A2.5 ISL – KIK

The ISL – KIK transmission is made from 3 x 220 kV circuits:

1. ISL – KIK 1	(292/239 MVA)
2. ISL – WPR – CUL – KIK – 1	(383/348 MVA)
3. ISL – WPR – CUL – KIK – 2	(383/348 MVA)

These circuits are all simplex Zebra with the ISL – KIK 1 circuit running at 50°C and the ISL – WPR – CUL – KIK 1 and 2 circuits running at 75°C.

The current binding post-contingent constraint is a voltage stability limit of 333 MW[14] (for northward flow). For southward flow the limit is a thermal constraint.

The MW capacity for the ISL – KIK 1 circuit is about 277/227 MW . The power sharing for the worst case contingency of a CUL – KIK 1 circuit is about 1.00:0.95 (ISL – KIK 1 : ISL – WPR 2) and the combined N – 1 capacity for the remaining 2 circuits is then (1.00 + 0.95) x the ISL – KIK 1 MW capacity:

Winter Capacity = (1 + 0.95) x 277 MW
= 540 MW

Summer Capacity = (1 + 0.95) x 227 MW
= 443 MW

An increase in the Northward transmission, from 333 MW up to the thermal limits 540/443 MW could be achieved with a 300 MVAr SVC at KIK providing additional dynamic reactive support. This would cost in the vicinity of $32 m (with a MVAr/MW ratio of around 1).

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[14] This assumes a strong ISL 220 kV bus voltage of 1.05pu and is taken as a 5% power margin from the peak of the PV curve.

Again, under the assumption of enough reactive support at KIK, a further thermal upgrade on the ISK – KIK 1 circuit from 50°C to 75°C (382/347 MVA) would cost around $8m (250km x $0.03 m/km) and increase this to around:

Winter Capacity = (1 + 0.95) x 382 x 0.95 MW
= 708 MW

Summer Capacity = (1 + 0.95) x 347 x 0.95 MW
= 643 MW

The loss coefficient was calculated by making the ISL bus slack. Placing an additional 50 MW load on the KIK bus and calculating the loss coefficient gives roughly 0.000095 MW^{-1} for the current system. The addition of reactive support to boost the voltage stability limit will have no effect on this loss coefficient.

A2.6 KIK – STK

The KIK to STK transmission is made up of 2 x 220 kV circuits and 2 x 110 kV circuits :

1.	KIK – STK 1	220 kV	(292/239 MVA)
2.	KIK – STK 2	220 kV	(292/239 MVA)
3.	KIK – STK	110 kV	(68/56 MVA)
4.	KIK – ARG – BLN	110 kV	(68/56 MVA)

The KIK – STK 1 and 2 circuits are simplex Zebra strung at 50°C. The 110 kV circuits are simplex Coyote strung at 50°C.

The MW capacity for the KIK – STK 220 kV circuits are 277/227 MW . The power sharing for the worst case contingency of a KIK – STK 220 kV circuit is about 1.00 : 0.1 : 0.1 (KIK – STK 220 kV : KIK – STK 110 kV : KIK – ARG – BLN). The combined N – 1 capacity for the remaining 3 circuits is then (1.00 + 0.1 + 0.1) x the single KIK – STK 220 kV MW capacity:

Winter Capacity = (1 + 0.1 + 0.1) x 277 MW
= 332 MW

Summer Capacity = (1 + 0.1 + 0.1) x 227 MW
= 272 MW

Thermal re-tensioning of the two 60 km KIK – STK circuits from 50°C to 75^{oC} would increase the MVA rating to 382/347 MVA and would cost around $3.6 million (based on the unit costs in Table 1).

The combined N – 1 capacity is then (1.00 + 0.1 + 0.1) x the single KIK – STK 220 kV MW capacity:

Winter Capacity = (1 + 0.1 + 0.1) x 382 x 0.95 MW
= 435 MW

Summer Capacity = (1 + 0.1 + 0.1) x 347 x 0.95 MW
= 396 MW

The loss coefficient was calculated by making the KIK bus slack. Placing an additional 50 MW load on the STK bus and calculating the loss coefficient gives roughly 0.000039 MW^{-1} for the current system. The addition of reactive support to boost the voltage stability limit will have no effect on this loss coefficient.

A2.7 IGH – KIK

The IGH to KIK transmission is made up of a 220 kV line (IGH – KIK 2) strung on one side and operated at 110 kV, and a single circuit 110 kV line. There is also a low capacity 66 kV connection through APS. The capacities of each circuit are as follows:

1.	IGH – KIK 2	110 kV	(191/174 MVA)
2.	IGH – MCH – KIK 1	110 kV	(68/56 MVA)
3.	OTI – APS	66 kV	(2 x 32/27 MVA)

The IGH – KIK 2 circuit is simplex Zebra strung at 75°C but currently component limited to 58 MVA. The IGH – MCH – KIK 1 circuit is simplex Coyote strung at 50°C but also component limited to 59 MVA and the OTI – APS circuit is hard drawn copper conductor (7/3.5).

When the West Coast is exporting with a generator at Westport, the power sharing for the worst case contingency of a IGH – KIK 110 kV circuit is about 1.0 : 0.1 (IGH – MCH – KIK : OTI – APS).

Ignoring the component constraints the N – 1 capacity is then about:

Winter Capacity = (1.0 + 0.1) x 68 x 0.95 MW
71 MW

Summer Capacity = (1.0 + 0.1) x 56 x 0.95 MW
= 59 MW

Thermally up-rating the 100 km IGH – MCH – KIK 1 circuit from 50°C to 75°C (we assume that this would increase the capacity to around 88/81 MVA[15]) will

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[15] Based on the average percentage increase in MVA rating (from 50°C to 75°C) of other transmission conductor types.

cost roughly \$3 million (based on the unit costs in Table 1). This would increase the N – 1 capacity to about :

Winter Capacity = (1.0 + 0.1) x 88 x 0.95 MW
92 MW

Summer Capacity = (1.0 + 0.1) x 81 x 0.95 MW
= 85 MW

Re-conductoring the 100 km IGH – MCH – KIK 1 circuit from simplex Coyote to simplex Zebra conductor strung at 75°C and running at 110 kV will increase the line rating to around 191/174 MVA. This would cost around \$25 million (assuming \$0.25 m / km) and increase the N – 1 inter-area capacity limit to around 181/165 MW.

Upgrading the IGH – KIK B line from 110 kV to 220 kV and stringing the second circuit would increase the rating to 383/347 MVA per circuit. This gives an N – 1 power sharing ratio of 1:0.25 (IGH – KIK B : IGH – MCH – KIK) and would likely cost around \$7 million for the establishment of a 220 kV switchyard[16] plus \$ 25 m for stringing the second circuit .

Ignoring the 66 kV Arthur's Pass circuits, the N – 1 capacity is then about:

Winter Capacity = (1.0 + 0.25) x 383 x 0.95 MW
455 MW

Summer Capacity = (1.0 + 0.25) x 347 x 0.95 MW
= 412 MW

The loss coefficient was calculated by making the KIK bus slack. Placing 50 MW of generation on the IGH bus and calculating the loss coefficient gives roughly 0.000270 MW^{-1} for the current system. Re-conductoring the KIK – MCH – IGH 1 circuit from Coyote to Zebra gives an improved loss coefficient of 0.000175 MW^{-1}. Further upgrading the system voltage from 110kV to 220kV and adding an extra simplex Zebra circuit lowers the loss coefficient to 0.000150 MW^{-1}.

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[16] Based on Transpower costs for new 220kV interconnections at Waipara and Culverden under the Tactical Transmission Upgrade (TTU) projects, TTU16 and TTU17.

A2.8 TWZ – HAY

The TWZ to HAY transmission consists of the existing HVdc link.

Under N – 1 conditions the lost capacity is made up by reserves, therefore the N capacity is used for this analysis.

TWZ to HAY (winter and summer) = 1040 MW

HAY to TWZ (winter and summer) = 626 MW (stability constraint)

Upgrading Pole 1 converters without any additional cables will cost $657 m and will increase the capacity to:

TWZ to HAY (winter and summer) = 1200 MW

HAY to TWZ (winter and summer) = 1000 MW

Transpower has proposed to replace Pole 1 at a cost of $ 742 m (one new cable) which will provide a capacity of :

TWZ to HAY (winter and summer) = 1400 MW

HAY to TWZ (winter and summer) = 1000 MW

The current HVdc configuration has 2 cables on Pole 1 and 1 cable on Pole 2. This equates to a total resistance of 10.908 ohms on pole 1 and 11.143 ohms on pole 2. Pole 1 is rated at 270 kV northwards, 250kV southwards. Pole 2 is rated at 350kV northwards and 333kV southwards.

The HVdc loss can be calculated with the following formula :

$$\text{HVDC Loss} = (R_{dc1} / (2 \times V_{dc1})^2 + R_{dc2} / (2 \times V_{dc2})^2) \times P_{sent}^2$$

A2.9 HAY – BPE

The HAY to BPE transmission is made up of 4 x 220 kV circuits:

1. HAY – BPE 1	(335/307 MVA)
2. HAY – BPE 2	(335/307 MVA)
3. HAY – WIL – LTN – BPE	(765/695 MVA)
4. HAY – LTN – BPE	(765/695 MVA)

The HAY – BPE 1 and 2 circuits are simplex Goat conductor having recently been thermally up-rated from 50^{o}C to 80^{o}C (247/202 MVA to 335/307 MVA). The HAY – WIL – LTN – BPE and HAY – LTN – BPE circuits are duplex Zebra running at 75 ^{o}C.

Power flow in the Northerly direction is constrained by thermal limits while power flow south is constrained by voltage stability. The capability of the HVdc link to runback means the northward flow thermal constraint can be regarded at N capacity.

The voltage stability limit for southward flow is currently 900 MW. SSG analysis shows that the HVdc Pole 1 upgrade (with extra reactive support at Haywards) will increase the southward voltage stability limit to 970 MW[17].

If runback is assumed then the power sharing between the four circuits is 1 : 1 : 1.43 : 0.71 (HAY – BPE 1 : HAY – BPE 2 : HAY – LTN – BPE : WIL – LTN – BPE) giving an N capacity limit of :

Winter Capacity = (1 + 1 + 1.43 +0.71) x 335 x 0.95 MW
= 1318 MW

Summer Capacity = (1 + 1 + 1.43 +0.71) x 307 x 0.95 MW
= 1207 MW

Duplexing the 150 km HAY – BPE 1 and 2 circuits to 670/614 MVA will cost in the vicinity of $31.5 m per circuit, or around $63 m (based on unit cost data in Table 1). Another $ 64 m is assumed for 650 MVAr of dynamic reactive support at BPE (most likely in the form of one or more SVCs). This gives an N capacity thermal limit for northward flow of:

Winter Capacity = (1 + 1 + 1 +0.4) x 670 x 0.95 MW
= 2164 MW
Summer Capacity = (1 + 1 + 1 +0.4) x 614 x 0.95 MW
= 1983 MW

With the extra reactive support at BPE, southward flow is further increased to 1280 MW .

The capacity could be further increased by adding a new double circuit 220 kV line about 150 km in length between Haywards and Bunnythorpe. This would cost roughly $225 m (based on unit cost data in Table 1).

This would increase thermal northward N capacity to :

Winter Capacity = (1 + 1 + 1 + 1 + 1 +0.4) x 626 x 0.95 MW
= 3211 MW

Summer Capacity = (1 + 1+ 1 + 1 + 1 + 0.4) x 569 x 0.95 MW
= 2919 MW

SSG analysis shows that an extra line raises the southward voltage stability limit to 1450 MW .

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[17] This is taken from PV analysis with a 5% power margin from the nose of the PV curve.

The loss coefficient was calculated by making the HAY bus slack and placing an initial 1000 MW load on the BPE bus. Adding a further 100 MW at the BPE bus and calculating the loss coefficient gives around 0.000041 MW^{-1}. Duplexing of both HAY – BPE 1 and 2 circuits reduces this further to around 0.000027 MW^{-1}. The addition of a 220kV twin Zebra double circuit transmission line between HAY and BPE further reduces this to approximately 0.000018 MW^{-1}.

A2.10 BPE – (HLY+WKM+WRK)

The BPE to (HLY+WKM+WRK) transmission consists of three 220 kV circuits.

1.	BPE – TKU 1	(246/202 MVA)
	TKU – WKM 1	(335/307 MVA)
2.	BPE – TKU 2	(246/202 MVA)
	TKU – WKM 2	(335/307 MVA)
3.	BPE – TNG – RPO	(292/239 MVA)
	RPO – WRK	(397/364 MVA)
	WRK – PPI – WKM	(448/421 MVA)

The BPE – TKU – WKM 1 and 2 and BPE – TNG – RPO are simplex goat with the BPE – TKU sections strung at 50^{o}C (due for thermal up-rate to 80^{o}C in 2008) and the TKU – WKM sections strung at 80^{o}C.

The BPE – TNG – RPO circuit is simplex Zebra strung at 50^{o}C (292/239 MVA) while the RPO – WRK and WRK – PPI – WKM sections are strung at 80^{o}C (397/364 MVA) and 100^{o}C (448/421 MVA) respectively.

The thermal upgrade of the TKU – WKM 1 & 2 circuits from 60 to 80^{o}C and the up-rate of the RPO – WRK circuit to the ratings stated above are indicated as committed in the “SSF Review June 2006 Phase 1 – Review of committed changes to the Power System”.

The power sharing with one BPE – TKU circuit out is around 1.00 : 0.75 (BPE – TKU : BPE : TNG) hence:

Winter Capacity = (1 + 0.75) x 247 x 0.95 MW
= 410 MW

Summer Capacity = (1 + 0.75) x 202 x 0.95 MW
= 336 MW

The capacity could be further increased by thermally upgrading the BPE – TKU 1 & 2 circuits from 50^{o}C to 80^{o}C (or to 335/307 MVA). This would cost around $10.2 m (2 x 170 km x $0.03 /km - based on unit costs in Table 1) and increase the N – 1 capacity to:

Winter Capacity = (1 + 0.75) x 335 x 0.95 MW
= 557 MW

Summer Capacity = (1 + 0.75) x 307 x 0.95 MW
= 510 MW

The capacity could be further increased by duplexing the three circuits from BPE to WKM. This would cost around \$160 m ((2 x 240km + 280km) x \$0.21 /km - based on unit costs in Table 1) up-rating the BPE – TKU – WKM 1 and 2 circuits to 670/614 MVA and the BPE – TNG – RPO – WRK – PPI – WKM circuit to 765/695 MVA. The power sharing then becomes 1.00 : 0.81 (BPE – TKU : BPE : TNG) increasing the N – 1 capacity to:

Winter Capacity = (1 + 0.81) x 670 x 0.95 MW
= 1152 MW

Summer Capacity = (1 + 0.81) x 614 x 0.95 MW
= 1056 MW

The capacity could be further increased by building a new 220 kV double circuit line rated at 765/695 MVA from BPE to WKM. With a line length of 240 km this would cost around \$336 m. This would increase the N – 1 capacity to the combined rating of the remaining four circuits or 2183/ 2000 MW (assuming that the power sharing results in the new circuit carrying the same amount as the old circuits).

The loss coefficient was calculated by making the BPE bus slack and solving the power flow to give initial conditions. Adding a further 100 MW at the WKM bus and calculating the loss coefficient gives around 0.000140 MW^{-1}. Duplexing the BPE=TKU-WKM 1 and 2 and BPE-TNG-RPO-WRK-PPI-WKM circuits reduces this further to around 0.000070 MW^{-1}. The addition of a 220kV twin Zebra double circuit transmission line between BPE and WKM further reduces this to approximately 0.000036 MW^{-1}.

A2.11 SFD – BPE and SFD – (HLY+WKM+WRK)

These two transmission corridors are discussed together as they form part of a mesh and their flow is inter-dependent.

SFD – BPE

The SFD to BPE transmission consists of three circuits SFD to BRK, then two circuits BRK to BPE.

These circuits have the following ratings:

SFD – BRK 1, 2 & 3	(291/238 MVA)
BPE – BRK 1 & 2	(764/694 MVA)

The SFD – BRK circuits are simplex Zebra with the 2 & 3 circuits running at 49^{o}C (287/232 MVA) and circuit 1 running at 50^{o}C (292/239 MVA).

Assuming that the power is shared equally between the remaining two circuits the N-1 capacity can be approximated:

Winter Capacity = (1 + 1) x 287 x 0.95 MW
= 545 MW

Summer Capacity = (1 + 1) x 232 x 0.95 MW
= 441 MW

Transpower's Annual Planning Report 2006 (section 5.2.3.10) indicates the possibility of thermally upgrading these three circuits (line length of approximately 100 km) to a rating of 500/470 MVA (this is assumed to be an up-rate to 120^{o}C – similar to the HLY – SFD circuits). Based on Table 1, this would cost around $9 m (3 x 100 km x $0.03/km). This increases the N – 1 capacity of these circuits to 950/893 MW and the binding constraint for BPE – SFD inter-area transfer becomes the N – 1 limit on the two BPE – BRK circuits, or 726/659 MVA.

The capacity could be further increased by building a new 220 kV double circuit transmission line 75 km in length rated at 765/695 MVA from BPE to BRK. This would cost around $ 105 m (Table 1 – Unit Cost Estimates) and increase the N – 1 capacity to 3 x the rating of the BPE – BRK circuits, or 2177/1978 MW . This would result in an increase of the BPE – SFD inter-area transfer capacity to the BRK – SFD limits of 950/893 MW.

Duplexing the BRK – SFD circuits to twin Zebra and running at 75^{o}C would cost $63 m (3 x 100km x $0.21 m) increasing the rating to 765/695 MVA per circuit and the N – 1 transmission capacity between BRK – SFD (and hence total BPE – SFD capacity) to 1454/1321 MW.

The capacity could be further increased by continuing the new 220 kV double circuit transmission line from BRK to SFD, 100 km in length rated at 765/695 MVA. This would cost around $ 140 m (Table 1 – Unit Cost Estimates) and increase the N – 1 capacity to the BPE – BRK limit of 2177/1978 MW .

The loss coefficient was calculated by making the BPE bus slack and solving the power flow to give initial conditions. Adding a further -50 MW of generation at the SFD bus and calculating the loss coefficient gives around 0.000085 MW^{-1}. Adding a twin circuit BPE – BRK line reduces this to around 0.000063 MW^{-1}. Duplexing the BRK – SFD circuits, adding 250 MW of generation at SFD and then a further 50 MW further reduces this to approximately 0.000039 MW^{-1} before a further 220kV twin circuit line is built between BRK and SFD reducing this to 0.000027 x P_{MW}^2.

SFD – (HLY+WKM+WRK)

The SFD to (HLY+WKM+WRK) transmission consists of two circuits rated 492/469 MVA. However more power is transmitted along the lower rated circuits SFD – BRK than along SFD – (HLY + WKM + WRK). So the SFD – (HLY + WKM + WRK) transmission is limited by the sharing between these two routes, and the transmission limit on the SFD – BPE route.

Sharing between SFD – (HLY + WKM + WRK) and SFD – BPE is approx 0.18/1.0 (with all circuits in and with one SFD – BRK circuit out).

To avoid exceeding the N – 1 Capacity of 587/534 MVA on SFD – BPE, and using a ratio of 0.18/1.0, SFD – (HLY + WKM + WRK) transmission would be limited to:

Winter Capacity = 105 MW

Summer Capacity = 96 MW

This is for HVdc northwards transfer when power is flowing from Stratford to Brunswick, and from Stratford to Huntly. For HVdc southwards transfer, power still flows from Stratford to Brunswick but the power transfer is now from Huntly to Stratford. The amount of power sent from Huntly to Stratford is minimal (ratio is now -0.12/1.0).

No upgrades are planned for the Stratford to Huntly circuits, as these circuits are not loaded to their capacity. The constraints are the SFD – BRK circuits.

The loss coefficient for SFD – (HLY+WKM+WRK) was calculated from the parallel resistances of the HLY-SFD 220 kV circuits as 0.0002 MW^{-1} .

A2.12 (HLY + WKM + WRK) – OTA

The (HLY + WKM + WRK) – OTA transmission consists of six 220 kV circuits and four 110 kV circuits. Committed projects include thermally upgrading the OTA – WKM C line and bussing this line at Huntly East.

Results from the 400 kV Alternatives Studies [18] indicates the following capacities for the committed network :

N – 1 Winter Capacity	=	2588 MW	(Voltage Stability)
N – 1 Summer Capacity	=	2503 MW	(Thermal Limit)

The 400 kV Alternatives study described a number of options for increasing the capacity including building a 400 kV line, or have some intermediate investments then build a 220 kV line, or duplex the OTA – WKM A & B lines then build a 400 kV line.

1. Building a 400 kV line at \$ 710 million would increase the capacity to 2999/2818 MW. Additional transformers and reactive support at \$ 181 million would further increase the capacity to 4053/3926 MW.

2. Intermediate investments consisting of thermal upgrades, phase shifters, and reactive support at \$ 95 million would increase the capacity to 3018/2919 MW. A new 220 kV line at \$ 479 million would increase the capacity to 3285/3209 MW. Additional reactive support and phase shifters at \$ 285 million would increase the capacity to 4116/3975 MW.

3. Duplexing the OTA – WKM A and B lines and reactive support at \$ 259 million (neglecting easement costs) would increase the capacity to 3334/3281 MW. A new 400 kV line at \$ 770 million would then further increase the capacity to 4222/4078 MW.

The committed system loss coefficient was calculated by making the WKM bus slack and solving the power flow to give initial conditions. Adding a further 100 MW at the OTA bus and calculating the loss coefficient gives around 0.000025 MW^{-1} for the current system.

Addition of a 400kV line gives a loss coefficient of 0.0000117 MW^{-1}, the 220 kV line gives 0.0000145 MW^{-1} and finally, duplexing followed by a 400 kV line gives 0.0000098 MW^{-1}. Duplexing the WKM – OTA A and B circuits on there own gives a loss coefficient of 0.000019 MW^{-1}.

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[18] 'Transmission Augmentations into Auckland : Technical Analysis of Transpower's Proposal and Short Short-listed Alternatives – Part II', System Studies Group NZ Limited, Ref S001-04 Final Revision 0, 21 April 2006.

A2.13 (HLY + WKM + WRK) – TRK

The (HLY + WKM + WRK) – TRK transmission consists of three 220 kV circuits :

1.	ATI – TRK 1	(370/333 MVA)
2.	ATI – TRK 2	(370/333 MVA)
3.	OHK – KAW	(291/238 MVA)

These circuits are simplex Zebra with the ATI – TRK 1 & 2 circuits rated at 71°C and the OHK – KAW circuit at 50°C.
The power sharing for the worst case contingency of a ATI – TRK 1 220 kV circuit is about 1.0 : 0.55 (ATI – TRK1 : OHK – KAW).

The N – 1 capacity is hence:
Winter Capacity = (1 + 0.55) x 370 x 0.95 MW
= 545 MW

Summer Capacity = (1 + 0.55) x 333 x 0.95 MW
= 490 MW

At these transmission capacity limits, Tauranga and Mt Maunganui GXPs are subject to low voltage conditions. Hence, additional voltage support on the BOP 110 kV system should be considered with any further inter-area transmission upgrade.

We have assumed that the transmission capacity could initially be increased by duplexing the ATI – TRK 1 & 2 circuits to twin Zebra at 75°C (764/694 MVA) at a cost of $ 19 m (2 x 45 km x $0.21/km) and thermally up-rating the OHK – KAW – EDG circuits to 75°C (382/347 MVA) at a cost of $3.5 m (112 km x $0.03 /km).

PV analysis shows that the addition of 400 MVAr of capacitor banks (300 MVAr at TRK and 100 MVAr at MTM at a cost of $16 m and including the above augmentations) raises the N – 1 voltage stability limit to around 830 MW.

We also assume that further reactive support (600 MVAr) and on the 110 kV system (costing around $24 m) will further increase the capacity to the thermal limits of the upgraded lines. The power sharing for the worst case contingency of a ATI – TRK 1 220 kV circuit is around 1.0 : 0.42 (ATI – TRK1 : OHK – KAW).

The N – 1 capacity is hence:

Winter Capacity = (1 + 0.42) x 764 x 0.95 MW

= 1031 MW

Summer Capacity = (1 + 0.42) x 694 x 0.95 MW
= 936 MW

The loss coefficient was calculated by making the WKM bus slack and solving the power flow to give initial conditions. Adding a further 50 MW at the TRK bus and calculating the loss coefficient gives around 0.000025 MW^{-1}. Duplexing the ATI – TRK 1 & 2, and OHK – KAW – EDG, EDG – TRK 1 & 2 circuits further reduces this to around 0.000015 MW^{-1}.

A2.14 (HLY + WKM + WRK) – RDF

The (HLY + WKM + WRK) – RDF transmission consists of two 220 kV circuits:

1.	WRK – RDF	(583/477 MVA)
2.	WRK – WHI – RDF	(583/477 MVA)

These circuits are duplex Zebra running at 50°C. Ignoring generation at Whirinaki[19] means voltage stability is the binding constraint for power transmission into Hawkes Bay. Currently this is around 350 MW with the tripping of a WRK – WHI circuit.

The MW capacity for a WRK – RDF circuit is 554/453 MW[10.]

Additional reactive support in Hawkes Bay (such as a 300 MVAr SVC) will up-rate the import transmission capacity to this thermal limit.

The capacity could be further increased by thermally up-rating these lines to 75°C or 764/694 MVA. This would cost around $8.5 m (2 x 140 km x $0.03 m). To obtain these thermal limits additional reactive support would be required on the Hawkes Bay 110 kV system. We have assumed an additional SVC costing $32 m (on the RDF 110 kV bus) and additional capacitor banks at GIS (120 MVAr at a cost of around $3.5 m). This would increase the voltage stability limit past the up-graded N – 1 thermal limit of the WRK – RDF circuit, or 726/659 MVA.

This capacity could be further increased by putting in a new 220 kV double circuit transmission line rated at 765/695 MVA. With a line length of 140 km this would cost around $200 m (Table 1 – Unit Cost Estimates). This would increase the N – 1 capacity to 3 x the rating of the thermally up-rated WRK – RDF circuits or 2178/1977MW.

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[19] Whirinaki (3 x 52MW, diesel fired OCGTs) is dispatched when the spot prices are high (usually during a dry year). It can also be dispatched during grid emergencies but has a lead time of 11 minutes. This analysis ignores any generation at Whirinaki.

The loss coefficient was calculated by making the WKM bus slack and solving the power flow to give initial conditions. Whirinaki was turned off. Adding a further 100 MW at the RDF bus and calculating the loss coefficient gives around 0.000043 MW^{-1}. The addition of a 220kV twin Zebra double circuit transmission line between RDF and WKM further reduces this to approximately 0.000018 MW^{-1}.

A2.15 OTA – ALB

The OTA to ALB transmission consists of two 220 kV circuits.

1.	OTA – SWN – HEN	(984/938 MVA)
2.	OTA – HEN	(984/938 MVA)

These circuits are both duplex zebra strung at 120°C. The N – 1 inter-area transfer capacity is hence 935/891 MW.

The capacity could be further increased by putting in a new 220 kV cable rated at 621/543 MVA. With a length of 40 km this would cost around $160 m (Table 1 – Unit Cost Estimates). Note that the cable in Table 1 is rated 400 MVA continuous but it is assumed that 621/543 MVA can be achieved through cyclic loading. With the addition of series reactors to balance the loading this would increase the N – 1 capacity to the combined rating of one circuit and the new cable or 1556/1434 MW.

A further additional cable would increase the N – 1 capacity to 2177/1977 MW assuming equal load sharing.

The loss coefficient was calculated by making the OTA bus slack and solving the power flow to give initial conditions. Adding a further 100 MW at the ALB bus and calculating the loss coefficient gives around 0.000014 MW^{-1}. An additional cable from PEN to ALB lowers this to 0.0000079 $MW^{-1}$and a further cable lowers this to 0.0000067 x P_{MW}^2.

A2.16 ALB – MDN

The ALB to MDN transmission consists of two 220 kV circuits.

1.	ALB – HPI	(625/568 MVA)
	HPI – MDN	(740/666 MVA)
2.	HPI – BRB	(370/333 MVA)

The ALB – HPI section in single Chukar strung at 75°C. The HPI – MDN is double Zebra at 71°C and the HPI – BRB section is single Zebra strung at 71°C.

The N – 1 inter – area capacity is defined by the lower rated HPI – BRB circuit at 352/316 MW .

The capacity could be increased by duplexing the HPI – BRB circuit to 740/666 MVA. With a line length of 110 km this would cost around $23 m (Table 1 – Unit Cost Estimates). This would increase the N – 1 capacity to 703 / 633 MVA.

The loss coefficient was calculated by making the ALB bus slack and solving the power flow to give initial conditions. Adding a further 50 MW at the MDN bus and calculating the loss coefficient gives around 0.000070 MW^{-1}. Duplexing the HPI – BRB circuit lowers this to around 0.000058 MW^{-1}.

A2.17 NMA – OTA

There has been some discussion about a new HVdc link to transmit power from new lignite generation in Southland to Auckland.

We have assumed that this will consist of a 1400 MW +/- 350 kV bipole with :

a) 4 x 700 MW converters @ $146 m

b) 4 x 40 km 500 MW cables @ $69 m

c) 1200 km line @ $1.1 m/km

This is expected to cost about $ 2,180 m (including easement costs).

The loss coefficient was calculated by hand using the following assumptions:

1. 1200km of overhead line at 0.01869Ω/km giving 22.428 Ω per pole
2. 2 cables per pole at 0.47 Ω/cable, giving 0.24 Ω per pole
3. A total line + cable resistance of around 22.668 Ω per pole

The HVdc loss can be calculated with the following formulae:

$$\text{HVdc Loss} = R_{dc} / (2 \times V_{dc}^2) \times P_{sent}^2$$

Assuming 350 kV operating voltage this gives a loss coefficient of around 0.000093 MW^{-1}.

Appendix 3. Transmission Line Construction

This table contains inter-area transmission line construction data based on information supplied by Transpower. In some cases Transpower has advised the Commission on the viability of upgrades, in other cases Transpower has not yet investigated the viability of upgrades and we have made our own assumptions.

Circuit	Construction and rating	Assumed upgrade viability
MAN – NMA 1	Two double circuit lines. Mostly Duplex Goat at 50°C (493/404 MVA) with a short section on each line (13 km and 34 km) of Simplex Pheasant at 50°C (380/312 MVA). Overall rating 380/312 MVA.	First thermally upgrade short Simplex Pheasant sections to 75°C to give overall rating of 493/404 MVA. Then thermally upgrade Duplex Goat to 75°C and replace Simplex Pheasant with Simplex Chukar to give overall rating of 646/586 MVA.
MAN – NMA 2		
MAN – NMA 3		
MAN – INV 1		
INV – ROX 1	Simplex Zebra at 75°C (382/347 MVA)	None
INV – ROX 2	Simplex Zebra at 75°C (382/347 MVA)	None
NMA – TMH 1	Simplex Zebra at 75°C (383/348 MVA)	None
NMA – TMH 2	Simplex Zebra at 75°C (383/348 MVA)	None
CYD – CML 1	Simplex Chukar at 75°C (626/569 MVA)	None
CML – TWZ 1	Simplex Chukar at 75°C but with 8.6 km section between CML and Tarras rated at 50°C or 476/391 MVA.	Thermal upgrade of the short 8.6 km section from 50°C to 75°C or 626/569 MVA
CYD – CML 2	Simplex Chukar at 75°C (626/569 MVA)	None
CML – TWZ 2	Simplex Chukar at 75°C but with 8.6 km section	Thermal upgrade of the short 8.6 km section

	between CML and Tarras rated at 50°C or 476/391 MVA.	from 50°C to 75°C or 626/569 MVA
ROX – NSY – LIV	Simplex Goat at 50°C (247/202 MVA)	Thermal to 80°C 335/307 MVA then Duplex to 670/614 MVA
TWZ – TKB – ISL	Duplex Goat at 70°C (523/591 MVA)	None
TWZ – OPI A – ASB – BRY – ISL	Duplex Zebra at 75°C (764/694 MVA)	None
TWZ – OPIB – ASB – ISL	Duplex Zebra at 75°C (764/694 MVA)	None
LIV – ISL	Duplex Goat at 50°C (493/404 MVA)	Thermal to 70°C (620/557 MVA).
ISL – KIK 1	Simplex Zebra at 50°C (292/239 MVA)	Thermal to 75°C (382/347 MVA) then duplex to 764/694 MVA.
ISL – WPR – CUL – KIK – 1	Simplex Zebra at 75°C (383/348 MVA)	Duplex to 764/694 MVA.
ISL – WPR – CUL – KIK – 2	Simplex Zebra at 75°C (383/348 MVA)	Duplex to 764/694 MVA.
KIK – STK 1 220 kV	Simplex Zebra at 50°C (292/239 MVA)	Thermal to 75°C (382/347 MVA)
KIK – STK 2 220 kV	Simplex Zebra at 50°C (292/239 MVA)	Thermal to 75°C (382/347 MVA)
KIK – STK 110 kV	Simplex Coyote at 50°C (68/56 MVA)	Thermal to 75°C (88/81 MVA) then re-conductor
KIK – ARG – BLN 110 kV	Simplex Coyote at 50°C (68/56 MVA)	Thermal to 75°C (88/81 MVA) then re-conductor
IGH – KIK 2 110 kV	Simplex Zebra at 75°C (191/174 MVA)	Operate line at 220 kV to give (382/347 MVA)
IGH – MCH – KIK 1 110 kV	Simplex Coyote at 50°C (68/56 MVA)	Thermal to 75°C (88/81 MVA) then re-conductor
OTI – APS 66 kV	Hard drawn copper conductor (7/3.5) (2 x 32/27 MVA)	None
HAY – BPE 1	Simplex Goat at 80°C (335/307 MVA)	Duplexing to 670/614 MVA
HAY – BPE 2	Simplex Goat at 80°C (335/307 MVA)	Duplexing to 670/614 MVA
HAY – WIL – LTN – BPE	Duplex Zebra at 75°C (765/695 MVA)	None
HAY – LTN – BPE	Duplex Zebra at 75°C (765/695 MVA)	None
BPE – TKU 1	Simplex Goat at 50°C (246/202 MVA)	Thermal to 80°C 335/307 MVA then Duplex to

		670/614 MVA
TKU – WKM 1	Simplex Goat at 75°C (335/307 MVA)	Duplexing to 670/614 MVA
BPE – TKU 2	Simplex Goat at 50°C (246/202 MVA)	Thermal to 80°C 335/307 MVA then Duplex to 670/614 MVA
TKU – WKM 2	Simplex Goat at 75°C (335/307 MVA)	Duplexing to 670/614 MVA
BPE – TNG – RPO – WRK	Simplex Zebra at 50°C (292/239 MVA)	Thermal to 80°C 335/307 MVA then Duplex to 670/614 MVA
WRK – PPI – WKM	Simplex Zebra at 100°C (448/421 MVA)	Duplex to 764/694 MVA.
SFD – BRK 1, 2 & 3	Simplex Zebra at 49 °C and 50°C (287/232 MVA and 291/238 MVA)	Thermal to 75°C 382/348 MVA then duplex to 764/694 MVA.
SFD – TMN A	Simplex Zebra at 120 °C (492/469 MVA)	None
TMN – TWH A	Simplex Zebra at 120 °C (492/469 MVA)	None
TWH – HLY A	Simplex Zebra at 120 °C (492/469 MVA)	None
ATI – TRK 1	Simplex Zebra at 71°C (370/333 MVA)	Duplex Zebra to 764/694 MVA
ATI – TRK 2	Simplex Zebra at 71°C (370/333 MVA)	Duplex Zebra to 764/694 MVA
OHK – KAW	Simplex Zebra at 50°C (291/238 MVA)	Thermal to 75°C (383/348 MVA) the duplex to 764/694 MVA
WRK – RDF	Duplex Zebra at 50°C (583/477 MVA)	Thermal to 75°C (764/694 MVA)
WRK – WHI – RDF	Duplex Zebra at 50°C (583/477 MVA)	Thermal to 75°C (764/694 MVA)
OTA – SWN – HEN	Duplex Goat at 120°C (984/938 MVA)	None
OTA – HEN	Duplex Goat at 120°C (984/938 MVA)	None
ALB – HPI	Single Chukar at 75°C (617/561 MVA)	None
HPI – MDN	Duplex Zebra at 71°C (740/666 MVA)	None
HPI – BRB	Simplex Zebra at 71°C (370/333 MVA)	Duplexing at 75°C to 764/694 MVA