Attachment G

Dispatch Analysis for the Bombay – Otahuhu Transmission Investigation

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Contents

Objectives

The purpose of this study was to assess differences in dispatch costs and transmission system losses and constraints for three options for future development of the Bombay – Otahuhu 110 kV transmission system. The Electricity Demand and Generation Scenarios (EDGS) supplied by the Ministry for Business, Innovation, and Employment (MBIE) have been used, with modifications where necessary.

The Stochastic Dynamic Programming model (SDDP) developed by Power Systems Research Inc of Rio de Janeiro has been used. Simulations of a least cost optimal dispatch were carried out over the 86 year record of hydrological data published by the Electricity Authority.

MBIE EDGS Scenarios

Purpose

Five generation development scenarios have been supplied to Transpower by MBIE. The purpose of these scenarios is stated in MBIE's report "Electricity demand and generation scenarios: Scenario and results summary", July 2019, as follows:

The role of the Electricity Demand and Generation Scenarios (EDGS) is set out in the Commerce Commission's "Transpower Capital Expenditure Input Methodology Determination (Capex IM)".
Under the Capex IM, Transpower is required to use the EDGS, and reasonable variations, when preparing its proposals for major capital expenditure on the electricity transmission grid. Specifically:
"Demand and generation scenario means a description of a hypothetical future situation relating to forecast electricity demand and generation published by the Ministry of Business, Innovation and Employment (or other agency which subsequently assumes the responsibility) for the purpose of the preparation or evaluation of major capex proposals."

Data Supplied

A following section describes the "reasonable variations" referred to above. It is expected that these modified scenarios will be suitable for use in the analysis of other Transpower projects. Some further modifications were also made to additional SDDP databases to test other assumptions applicable to the WUNI voltage support analysis. These changes are described in later sections.

The EDGS and their abbreviated names use here are:

1. Reference: Current trends continue
2. Growth: Accelerated economic growth
3. Global: International economic changes
4. Environmental: Sustainable transition
5. Disruptive: Improved technologies are developed

Data supplied by MBIE for these scenarios, relevant to the SDDP dispatch studies, consisted of the following:

- Plant Name
- Installed capacity

- New or existing
- Technology (also implying fuel type)
- Transmission system bus supplied
- Forced outage factor
- Variable Operating & Maintenance costs
- Generic capacity factors
- CO_2 emissions per PJ of fuel, see Table 1
- Carbon costs by year, see Table 2
- Fuel costs by type and year, Table 2
- Decommissioning dates for plant, Table 3

All costs in the EDGS are in 2017 dollar values. A 7% discount rate is used throughout this study.

Fuel costs are the same for all scenarios. Higher carbon emission costs apply for the Environmental scenario, as in Table 2.

Table 1: CO_2 Emissions for Fuel Types

Fuel type	tonnes/PJ
Coal	91,200
Coal with CCS	9,120
Lignite	95,200
Gas	52,800
Diesel	73,000
Geothermal	8,333

Table 2: Fuel and Carbon Emissions Costs							
	Fuel Costs, $/GJ					Carbon $/t	
	Coal	Coal_CCS	Lignite	Gas	Diesel	Other Scenarios	Environmental
2018	7.05	7.05	3.00	6.19	22.52	18.5	18.5
2019	7.58	7.58	3.00	6.19	24.70	25.0	25.0
2020	7.74	7.74	3.00	6.19	26.18	25.9	25.9
2021	7.79	7.79	3.00	6.19	27.55	27.2	28.4
2022	7.79	7.79	3.00	6.19	28.78	29.2	32.5
2023	7.79	7.79	3.00	6.19	30.01	30.7	37.5
2024	7.79	7.79	3.00	6.19	31.24	32.4	42.9
2025	7.79	7.79	3.00	6.19	32.48	33.3	48.1
2026	7.79	7.79	3.00	6.19	33.71	34.8	53.1
2027	7.79	7.79	3.00	6.19	34.94	36.5	57.7
2028	7.79	7.79	3.00	6.19	36.18	38.2	62.2
2029	7.79	7.79	3.00	6.19	37.41	40.0	66.6
2030	7.79	7.79	3.00	6.19	38.64	41.7	70.9
2031	7.79	7.79	3.00	6.19	39.61	43.4	75.2
2032	7.79	7.79	3.00	6.19	40.57	45.1	79.4
2033	7.79	7.79	3.00	6.19	41.54	46.8	83.6
2034	7.79	7.79	3.00	6.19	42.51	48.5	87.8
2035	7.79	7.79	3.00	6.19	43.47	50.1	92.0
2036	7.79	7.79	3.00	6.19	44.44	51.8	96.1
2037	7.79	7.79	3.00	6.19	45.40	53.4	100.3
2038	7.79	7.79	3.00	6.19	46.37	55.1	104.4
2039	7.79	7.79	3.00	6.19	47.34	56.8	108.6
2040	7.79	7.79	3.00	6.19	48.30	58.4	112.7
2041	7.79	7.79	3.00	6.19	48.30	59.2	116.8
2042	7.79	7.79	3.00	6.19	48.30	60.0	120.9
2043	7.79	7.79	3.00	6.19	48.30	60.8	125.0
2044	7.79	7.79	3.00	6.19	48.30	61.5	129.2
2045	7.79	7.79	3.00	6.19	48.30	62.3	133.3
2046	7.79	7.79	3.00	6.19	48.30	63.1	137.4
2047	7.79	7.79	3.00	6.19	48.30	63.8	141.5
2048	7.79	7.79	3.00	6.19	48.30	64.6	145.6
2049	7.79	7.79	3.00	6.19	48.30	65.4	149.7
2050	7.79	7.79	3.00	6.19	48.30	66.1	153.8

Table 3: EDGS Plant Decommissioning Dates, as prepared by MBIE – all scenarios			
Plant	Type	Capacity	Date
Wairakei	Geo	157	2021
Taranaki_CC	CCGT	380	2023
Whirinaki	DslPkr	155	2024
Tararua_Wind_1_and_2	Wind	36.3	2026
Te_Apiti	Wind	90	2028
Te_Rere_Hau_-_all_stages	Wind	48.5	2029
Huntly_coal_unit_3	Coal	200	2030
Huntly_coal_unit_4	Coal	200	2031
White_Hill	Wind	58	2031
Tararua_3	Wind	93	2032
West_Wind	Wind	143	2032
Te_Uku	Wind	64	2034
Huntly_gas_3	OCGT	50	2034
Huntly_gas_4	OCGT	50	2034
Mahinerangi	Wind	36	2035
Huntly_unit_5_(e3p)	CCGT	400	2038
Huntly_unit_6_(P40)	OCGT	50.8	2039
Mill_Creek	Wind	60	2040
Stratford_peaker	GasPkr	200	2040
Kaimai	Wind	100	2045
Waverley	Wind	135	2045

Note: The above table refers to EDGS, as received from MBIE. Some changes have been made to the scenarios to adapt them for more detailed modelling, and further changes were made to test specific conditions for the WUNI study, as described later in this report.

Demand data for use in this study has been prepared by Transpower, using information from the EDGS. The outputs of the Transpower process, in SDDP data format, are:

- Load data by island, monthly, for 14 load blocks per month
- Load block duration for each month, in hours
- Individual bus loads, consistent with island total loads.

This demand data was used when implementing the EDGS in SDDP, and for the loss calculations for the WUNI transmission upgrade options study, with no further processing.

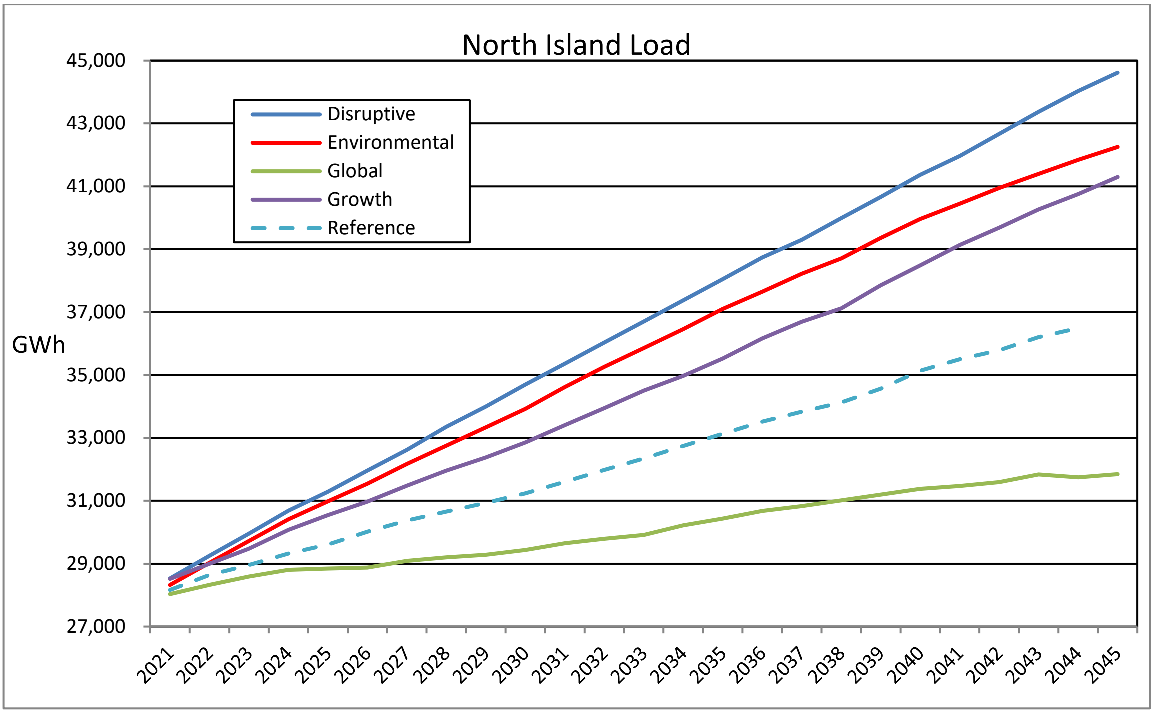

Figure 1: Total North Island load for the 5 EDGS

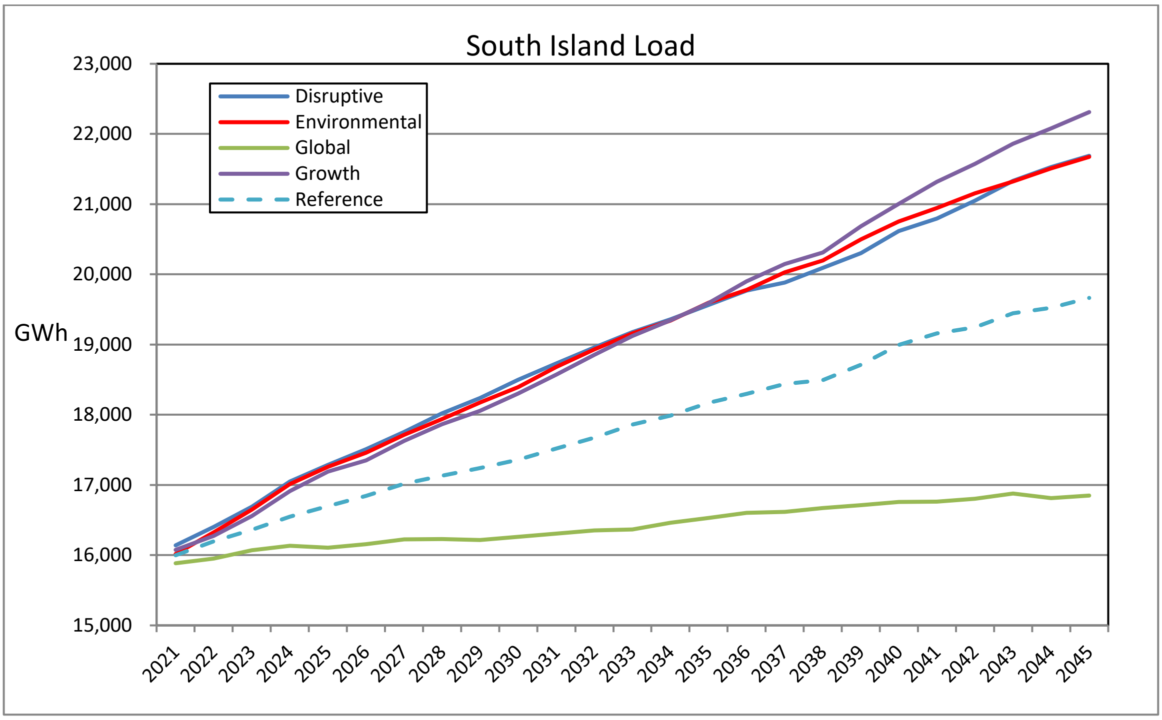

Figure 2: Total South Island load for the 5 EDGS

HVDC Link

AC transmission system constraints and upgrades were not considered in this phase of implementing the EDGS scenarios. In general, for Transpower investigations, grid upgrades are included only for the particular transmission development project under consideration, and any other upgrades that are likely to affect that particular analysis.

For optimal dispatch studies, it is essential to represent the HVDC link. No data was supplied by MBIE for the HVDC link so assumptions similar to those used in the past at Transpower have been made. A change to the more usual assumption of a maximum of 850 MW south flow has been made, increasing this to 1000 MW from 1 Jan 2025, when north flow limits are assumed to increase. This is necessary as the EDGS have very little additional generation in the South Island, which results in a large SRMC difference between the islands, if the south flow capacity is not increased (i.e. much larger and/or more frequent deficits in the South Island than in the North). To fully represent the impact of reserves requirements on HVDC link operation, very detailed unit level modelling would be required. Consequently, reserve requirements for the HVDC link are not considered for this study.

Table 4: HVDC Transfer Limits Modelled

Date	North flow (MW)	South flow (MW)
1 Jan 2021	1200	850
1 Jan 2025	1400	1000

Modifications and Assumptions for EDGS Implementation by Transpower

Different Modelling systems

The MBIE scenarios were prepared by the Ministry using the GEM model. This is a mixed integer linear program that finds a least cost development plan, subject to a range of constraints. It does not carry out a detailed generation dispatch, or represent the transmission system in any detail. Therefore some fine tuning of the results is needed to obtain a development plan better suited for Transpower's purposes. In addition some additional assumptions and plant parameters are needed for SDDP modelling due to the greater level of detail represented. These changes would seem to be permissible, given that the Capex IM permits "reasonable variations", as stated in the MBIE report regarding the EDGS (referred to earlier).

Where large deviations in SRMC from the trend occur in SDDP simulations, plant has been advanced or delayed to give a smoother result. In some cases, North Island plant has been replaced with an equivalent plant in the South Island to avoid a large difference in SRMC between the islands due to HVDC constraints.

In a number of cases, deficits seemed to be excessive, so plant commissioning has been brought forward. One of the applications of the modelling at Transpower is for the valuation of transmission losses. These losses are valued at short run marginal cost (SRMC). When deficits occur, SRMC is increased to a high value, which could result in unreasonably high values for transmission losses. These deficit effects would have tended to support the installation of unnecessarily large conductors on transmission lines.

Changes and Assumptions Applicable to All Scenarios

1. All plant commissioning and decommissioning has been assumed to be on 1 January of the year specified.
2. EDGS database specified an existing cogen plant at Hawera with 200 MW installed capacity. This is likely to refer to the Whareroa plant which has 70 MW installed capacity connected to HWA110. For the period August 2018 to July 2019, average generation was 14.6 MW, but Whareroa has run at higher average outputs in the past. It has been modelled here as having 22 MW of must run capacity. To compensate for the reduced generation resulting from this change, a geothermal plant is added to the system by assuming that the existing Wairakei plant continues in service. EDGS assumes that Wairakei will decommission in 2021.
3. EDGS assumes that Whirinaki diesel fuelled plant decommissions in 2024. It has been modelled as remaining in service to meet short peaks which would otherwise incur deficit.
4. Most "Process Gas" plants are treated as must run. These plants include Whareroa, Kapuni, Kinleith, Te Rapa, Mangahewa and the new Combined cycle gas turbine combined heat and power (CCGTCHP) plants.
5. A large amount of wind generation was allocated to Woodville (WDV) in the EDGS. Most of this has been moved to Bunnythorpe (BPE) as the BPE-WDV 110 kV line has only 70 MW capacity which is insufficient for much, if any, further expansion of generation.
6. Busses have been changed in some cases to use a point closer to the generation. This is possible due to the detailed transmission system modelling in SDDP. For example Matakitaki hydro is allocated to MCH instead of IGH.

7. All demand side response (DSR) has been replaced in SDDP by the first step of the deficit function. This applies to the first 10% of load which has been assigned the same cost as the EDGS DSR of $1889/MWh.
8. The EDGS represent the small amount of gas firing assumed to be available to the Huntly coal units as two separate OCGT units. These OCGT units decommission a little later than the Huntly coal units. The justification for this is that MBIE assume that the gas firing will continue for a short time after coal firing ceases. This separate representation of gas firing would result in an unrealistic influence on system operations, with consequences for transmission planning. The gas firing of the Huntly coal units has therefore been ignored – the units are assumed to run on coal only. This is the most appropriate assumption for transmission planning purposes as the fuel mix will not have a significant impact.
9. Some interruptible load in Auckland is modelled in the EDGS. This has been omitted from the SDDP database as no operating costs are specified by in the EDGS data (only capital costs are given).
10. CO_2 emissions for geothermal plant modelling have been revised from those used previously in Transpower modelling to be consistent with those specified in EDGS database, as in Table 1:
    - 1 PJ = 277,777.8 MWh
    - Geothermal CO_2 emission specified in EDGS data as 8,333 tonnes per PJ of generation.
    - A value of 0.03 tonnes CO_2 emitted per MWh generation is modelled in SDDP for all geothermal plant.
    - In comparison gas burn gives 52,800 tonnes CO_2 per PJ of fuel burn.
11. Upgrade work is under way at Karapiro hydro. Using information on the Mercury Energy web site, the production factor (MW/cumec) increases from 0.259 to 0.2754, installed capacity increases to MW 112.5, giving an average annual generation of 408 GWh.
12. The parameters previously used in Transpower modelling for the Waitaki North Bank Tunnel project (“NorthBT”) have been retained.
13. Deep Stream hydro is included in the EDGS. Some data for this has been obtained from the Trust Power web site. Capacity is specified there as 2 x 2.5 MW giving 23 GWh per year. Waipori inflows have been used for SDDP modelling.
14. Te Mihi is modelled in the EDGS as having an installed capacity of 114 MW. A value of 166 MW has been used for the SDDP database, as specified on the Contact Energy web site
15. Gas transport costs have not been included in the EDGS data. Previously Transpower has made assumptions for this. These costs are not modelled, to obtain consistency with EDGS and because actual data is not available. (In other circumstances a fixed rental is required for pipeline capacity, leading to a zero or very small marginal cost for gas transport.)

Reference Scenario

Advance GeoTau1 (80MW) to 2030 to compensate for Huntly gas units decommissioning earlier

Advance OCGTPkrG4, 200 MW, 2031 to 2030 to compensate for Huntly gas units decommissioning earlier

Wairau advanced from 2039 to 2035

Puketoi 2037 to 2035

GWindS7a 2031 to 2029
HaweaCG 2029 to 2028 due to SI deficits
GWindS1a 2030 to 2029
GGeoTik1 2044 to 2045
Remove GWindM2A, 200 MW, 2034, NI, replace with GWindS8a 200 MW, 2034, SI

Growth Scenario

Matakitaki 2037 to 2035
Hawea CG 2030 to 2028
Stockton 2034 to 2030
OCGTPkrG8 2033 to 2030 to compensate for Huntly gas units decommissioning earlier
GWindL1_s2 2042 to 2040
Puketoi 2037 to 2035
Add GWindS8a, 200 MW, 2028, SI
Add GWindS9a, 100 MW, SI, 2030, SI
Remove GWindS1a, 300 MW 2033, NI
Remove GWindM4b, 100 MW 2036, NI

Environment Scenario

GWindS2a, 300 MW, 2031 to 2030
OCGTPkrG5, 200 MW, 2031 to 2030 to compensate for Huntly gas units decommissioning earlier
Delete GWindS1a, 300 MW, 2030, NI, replace with GWindS8a, 200 MW, 2028 & GWindS9a, 100 MW in 2029, SI

Global Scenario

OCGTPkrG5, 200 MW, 2040 to 2039

Disruptive Scenario

OCGTPkrG4, 200 MW, 2031 to 2030 to compensate for Huntly gas units decommissioning earlier.
LowerCR 2035 to 2034

Table 5: EDGS Generation Development Scenarios, as implemented in SDDP					
	Reference	Growth	Global	Environment	Disruptive
2019			Tihiroa2 120		
2020	Ngawha 1 & 2 each 25 Waverley Wind 135	Ngawha 1 & 2 each 25 Waverley Wind 135	Ngawha 1 & 2 each 25 Waverley Wind 135	Ngawha 1 & 2 each 25 Waverley Wind 135	Ngawha 1 & 2 each 25 Waverley Wind 135
2021	OCGTPkrG1 200 Kaimai Wind 100	Tihiroa2 120 Kaimai Wind 100	North BT 140 Kaimai Wind 100	OCGTPkrG8 100 Pukaki 35 Kaimai Wind 100	Tauha2 250 Kaimai Wind 100
2022	Tauha2 250	Tauha2 250	Pukaki 35	Tauha2 250	Pukaki 35 Stockton 25 Tihiroa 120
2023	Geo1 300 TaranakiCC 0	Taharoa 54 Geo1 300 TaranakiCC 0 Tihiroa3 120	Rakaia 16 Stockton 25 TaranakiCC 0 Tauha2 250	GWindM6 100 Geo1 300 TaranakiCC 0 Tihiroa 120	GWindM6 100 GWindS2 50 Taharoa 54 Waitahora 159 GGeoRotok1 130 GGeoTau1 80 JunctionRd 100 TaranakiCC 0
2024	Karapiro 112.5 OCGTPkrG8 200	Karapiro 112.5 Pukaki 35 GWindM6 100	Karapiro 112.5 Taharoa 54 Tihiroa 120	Karapiro 112.5 Taharoa 54 Waitahora 159	Karapiro 112.5 CCGTCHP1 40 GGeoKaw2 30
2025	CCGTCHP1 40	GWindM6a 200	Rotoma 35	GWindM4a 200	Coleridge2 70 GWindM6a 200
2026	GWindM6a 200 TaraW1 0 TaraW2 0	Wairau 70 TaraW1 0 TaraW2 0 CCGTCHP1 40	TaraW1 0 TaraW2 0	GWindM6a 200 TaraW1 0 TaraW2 0 CCGTCHP1 40	TaraW1 0 TaraW2 0
2027		GWindM2a 200		GWindM2a 200	GWindM2a 200 GWindM3 300
2028	HaweacG 17 Pukaki 35 GWindM6 100 Taharoa 54 TeApiti 0	HaweacG 17 GWindS8a 200 TeApiti 0 GGeoRotok1 130	LowerCR 35 Matakitaki 40 TeApiti 0	GWindS8a 200 TeApiti 0 GGeoRotok1 130	GWindM4a 200 TeApiti 0 GGeoNgata1 100
2029	GWindS1a 200 GWindS7a 200 TeRereHau 0 TeRereHau3 0 TeRereHau4 0	TeRereHau 0 TeRereHau3 0 TeRereHau4 0 GGeoNgata1 100	HopeRiver 55 TeRereHau 0 TeRereHau3 0 TeRereHau4 0	HaweacG 17 Wairau 70 GWindS9a 100 TeRereHau 0 TeRereHau3 0 TeRereHau4 0 GGeoNgata1 100	HaweacG 17 Wairau 70 GWindM3a 200 TeRereHau 0 TeRereHau3 0 TeRereHau4 0
2030	GWindS2a 200 GGeoTau1 80 Huntlyu3 0 OCGTPkrG4 200	Stockton 25 GWindS9a 100 Huntlyu3 0 OCGTPkrG5 200 OCGTPkrG8 100	HurunNB 15 CCGTCHP1 40 Huntlyu3 0	GWindS2a 300 Huntlyu3 0 OCGTPkrG5 200 OCGTPkrG7 200	GWindS1a 200 GWindS2a 200 Huntlyu3 0 OCGTPkrG4 200 OCGTPkrG8 100 RecDieselG2 10 Tihiroa2 120
2031	WhiteHill 0 Huntlyu4 0	GWindS2a 300 WhiteHill 0 Huntlyu4 0 OCGTPkrG1 100	WhiteHill 0 Geo1 300 Huntlyu4 0	WhiteHill 0 Huntlyu4 0	GWindS7a 200 WhiteHill 0 Huntlyu4 0 Tihiroa3 120 Solar1 43
2032	TaraWd3 0 WestWind 0 GGeoNgata1 100 GGeoRotok1 130	GWindS7a 300 TaraWd3 0 WestWind 0 GGeoTau1 80	TaraWd3 0 WestWind 0	Arnold 46 GWindS7a 300 TaraWd3 0 WestWind 0 GGeoTau1 80	Arnold 46 Matakitaki 40 GWindS6a 500 TaraWd3 0 WestWind 0 Rotoma 35
2033	Solar3 6	GWindS3a 300		GWindS3a 300	Clarenc 70 HopeRiver 55

Table 5 continued					
	Reference	Growth	Global	Environment	Disruptive
2034	GWindS8a 200 TeUku 0	Arnold 46 Coleridge2 70	Mohaka 44 GWindM6a 200	Clarenc 70 Coleridge2 70	BushStream 30 HurunNB 18

		Mohaka 44 Awhitu 42 Solar1 16 Solar3 50 TeUku 0	TeUku 0	Matakitaki 40 Mohaka 44 Stockton 25 TeUku 0 Rotoma 35	LowerCR 35 Mohaka 44 TeUku 0 GGeoMan1 40 GGeoTok2 45 RecDieselG5 10 Solar3 50
2035	Wairau 70 GWindM6b 200 Mahinerangi 0 Puketoi 159 Solar3 7 CCGTCHP2 50	Matakitaki 40 GWindM3b 200 GWindM6b 200 Mahinerangi 0 Puketoi 159 CCGTCHP2 50	Mahinerangi 0 CCGTCHP2 50	GWindM2b 200 GWindM6b 200 Mahinerangi 0 CCGTCHP2 50	Mahinerangi 0 CCGTCHP2 50 Geo2 200
2036	GWindM2b 50 GWindM4b 100 Solar3 33 Waitahora 156	GWindM4 50	GWindM6b 200	HopeRiver 55 LowerCR 35 GWindM3b 200 GGeoKaw2 30	GWindM6b 300 Bromley 11.5 PropDiesel1 9.9 RecDieselG3 10 RecDieselG4 10 Solar 1 50 Solar 5 200
2037		Solar5 11	GWindM2a 200	Puketoi 200 Solar3 50 Solar5 191	ClarencCon 300
2038	Mohaka 44 GWindM2 200 Solar3 50 E3p 0 RecDieselG7 10 Tihiroa2 120 Tihiroa3 120	BushStream 30 Clarenc 70 HopeRiver 55 LowerCR 35 Solar5 46 E3p 0 GGeoKaw2 30 JunctionRd 100 OCGTPkrG3 200 OCGTPkrG7 200 Rotoma 35	GWindS1a 200 E3p 0 JunctionRd 100 Tihiroa3 120	BushStream 30 Solar1 50 Solar2a 50 Solar4 50 Solar4a 29 Solar5 200 E3p 0 GGeoMan1 40 GGeoTok2 45 OCGTPkrG1 100 OCGTPkrG3 200 Tihiroa3 120 Tikitere 45	GWindM2 300 Solar1a 100 Solar5a 200 E3p 0 OCGTPkrG1 100 OCGTPkrG5 200 OCGTPkrG7 200 Tikitere 45
2039	Taramakau 50 Waiau21 140 Whitcombe 30 GWindL1_s1 250 P40 0	Taramakau 50 Waiau21 140 Whitcombe 30 P40 0	Taramakau 50 Waiau21 140 Whitcombe 30 OCGTPkrG5 200 P40 0	Taramakau 50 Waiau21 140 Whitcombe 30 GWindL1_s1 250 GWindL1_s2 250 P40 0	Taramakau 50 Waiau21 140 Whitcombe 30 GWindL1_s1 350 P40 0
2040	GWindS2b 200 MillCreek 0 OCGTPkrG5 200 StratfordGT 0	GWindL1_s2 250 GWindS2b 200 MillCreek 0 Solar1a 39 GGeoTik1 160 StratfordGT 0 Tihiroa 120	GWindS2b 200 MillCreek 0 StratfordGT 0	MillCreek 0 Solar1a 50 GGeoTik1 160 StratfordGT 0	MillCreek 0 Geo1 200 GGeoTik1 160 StratfordGT 0
2041	GWindS1b 68	Solar1a 50		GWindS2b 200 Solar5a 193	
2042	GWindL1_s2 250	GWindS1b 68 Solar5 68 Solar5a 200		Solar5a 200	GWindS2b 200
2043		GGeoTik2 80		GGeoTik2 80	Geo3 200
2044		HurunNB 18 Solar5 193 Tikitere 45		GWindS1b 68	
2045	GWindM6c 100 Kaimai Wind 0 Waverley 0 GGeoTik1 160	GWindM6c 100 Kaimai Wind 0 Solar2a 13 Solar4 50 Solar5 200 Solar6a 200 Waverley 0 GGeoMan1 40	GWindM6c 100 Kaimai Wind 0 Waverley 0	HurunNB 18 GWindM6c 200 Kaimai Wind 0 Solar6a 200 Waverley 0	GWindM4c 300 GWindM6c 100 Kaimai wind 0 Waverley 0

Scenario SRMC Results

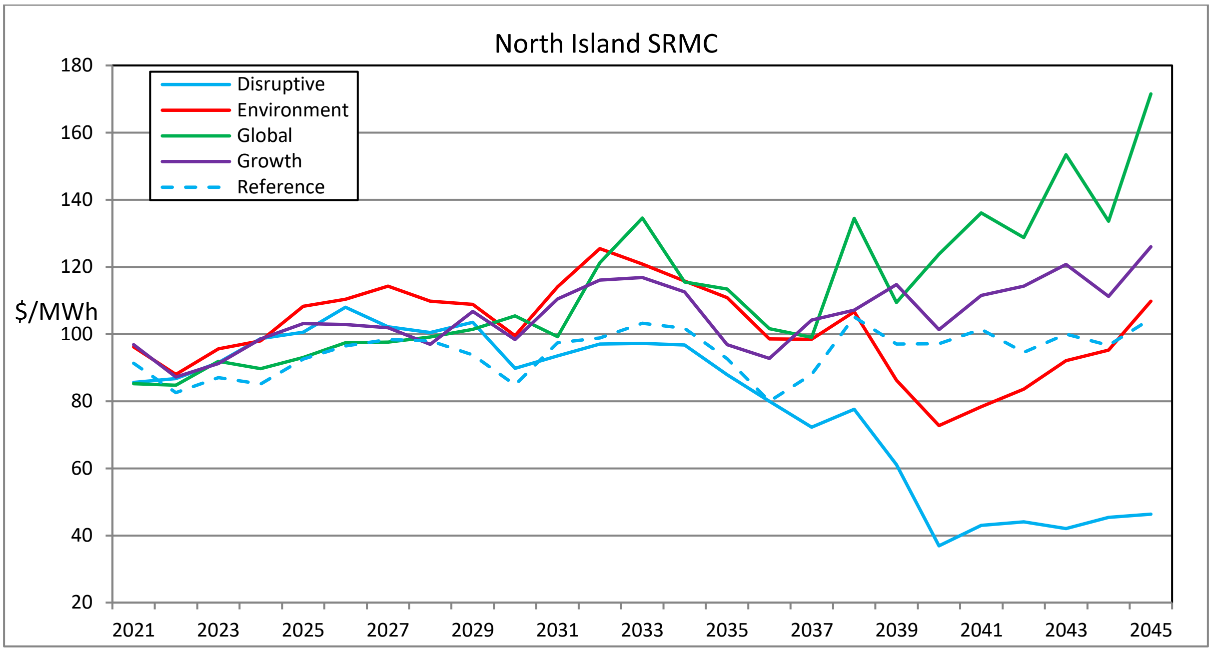

Figure 3: Annual average SRMC for the five EDGS, North Island

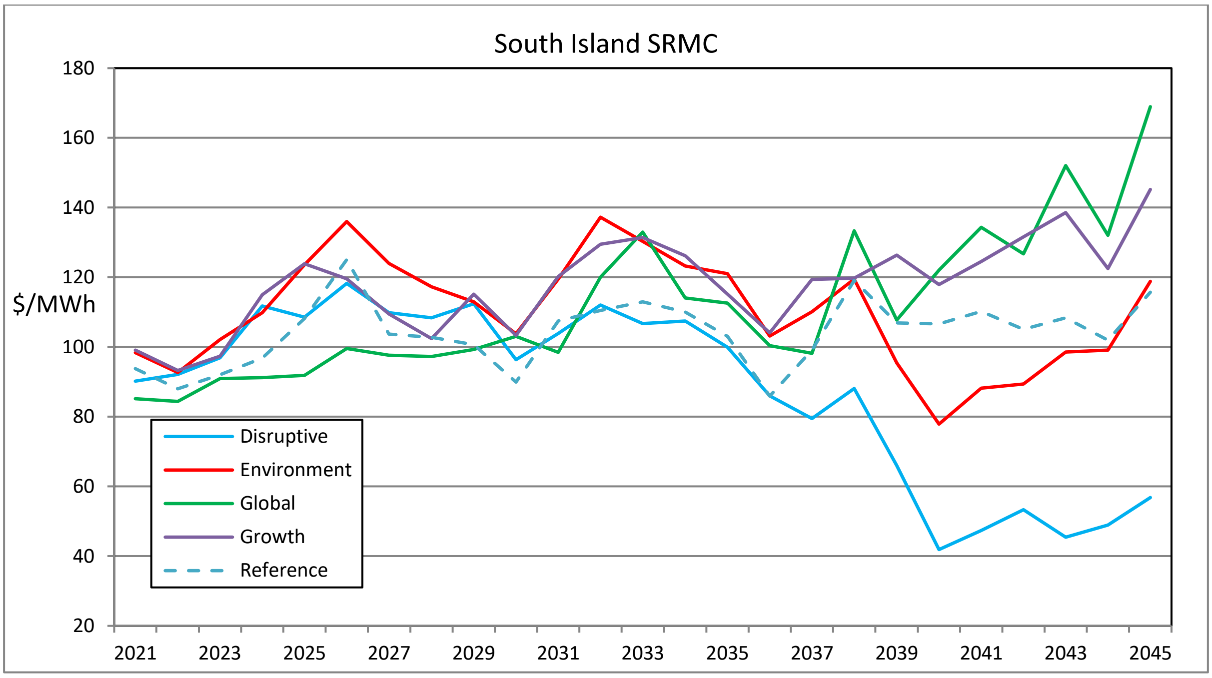

Figure 4: Annual average SRMC for the five EDGS, South Island

Transmission System Modelling

A number of transmission system upgrades are incorporated in all cases. These developments have been restricted to those in the Upper North Island which are likely to affect the current studies. Modelled developments are shown in Table 6. Tihiroa CCGT is assumed to connect to a new bus at Otorohanga on the HLY-SFD line. This plant reaches 360 MW capacity in some EDGS, so an assumption has been made that the 220 kV line from Otorohanga to Huntly is duplexed in 2038 to carry the additional load.

Table 6: Transmission developments common to all options

Date, 1 Jan	Line	R	X	MW	Explanation
2022	SFD-TF-T10	0.07	5	200	
2023	OTA-TF-T2	0.17	4.08	135	Decommission
2023	OTA-TF-T4	0.2	2.55	254	Decommission
2023	OTA-TF-T6	0.09	5.89	297	Replaces T2, T4
2023	PEN-TF-T11	0.09	5.89	297	Replaces PEN-T10
2029	Bus BHL-WKM at OHE, link OHE to OHW.				
2030	ATI-OHK-1	0.06	0.42	614	Reconductor
2030	ATI-WKM-1	0.22	1.41	614	
2030	OHK-WRK-1	0.24	1.66	614	
2033	OTA-WKM-1	2.55	15.92	371	Reconductor, replace Goat with Zebra (**)
2033	OTA-WKM-2	2.55	15.92	371	
2038	HLY-TWH-1	0.21	1.88	687	Assume duplexed due to Tihiroa CCGT developments
2038	HLY-OTO-1	0.69	6.20	687	
2038	OTO-TWH-1	0.38	3.41	687	

Three transmission development options for the BOB-OTA 110 kV lines have been studied, all modelled as being commissioned on 1 January 2023.

1. **Existing**, i.e. Like for Like Replacement – retain the existing lines, with like for like replacements in 2023.

Table 7: Line parameters for option 1 - Like for Like Replacement

Circuit	Length (km)	Conductor	Winter (MVA)	Shoulder (MVA)	Summer (MVA)	X (% p.u.)	R (% p.u.)
OTA-WRT 1	4.264	1 wolf AC 75	105	100	95	1.41	0.64
OTA-WRT 2	4.264	1 wolf AC 75	105	100	95	1.43	0.65
BOB-WRT 1	24.88	1 wolf AC 50	80	74	66	8.05	3.48
BOB-WRT 2	24.88	1 wolf AC 50	80	74	66	8.03	3.47
WIR-WRT 1	0.087	1 wolf AC 75	105	100	95	0.03	0.01
WIR-WRT 2	0.093	1 wolf AC 75	105	100	95	0.03	0.01

Note: "AC" refers to aluminium conductor

2. **Upgrade** OTA-WIR – Upgrade the OTA-WIR lines, replacing Wolf conductor with Goat.

Table 8: Line parameters for option 2 – Line Upgrades

Circuit	Length (km)	Conductor	Winter (MVA)	Shoulder (MVA)	Summer (MVA)	X (% p.u.)	R (% p.u.)
OTA-WRT 1	4.264	1 goat AC 75	168	160	152	1.32	0.29
OTA-WRT 2	4.264	1 goat AC 75	168	160	152	1.32	0.29
BOB-WRT 1	24.88	1 wolf AC 50	80	74	66	8.16	3.49
BOB-WRT 2	24.88	1 wolf AC 50	80	74	66	8.16	3.49
WIR-WRT 1	0.087	1 goat AC 75	168	160	152	0.03	0.01
WIR-WRT 2	0.093	1 goat AC 75	168	160	152	0.03	0.01

3. **Preferred** Option - Upgrade OTA-WIR line, replacing Wolf conductor with Goat, dismantle 110 kV lines between Wiri and Hamilton, supply Bombay at 220 kV from the Huntly – Otahuhu lines.

Table 9: Line parameters for option 3 – Preferred Option							
Circuit	Length (km)	Conductor	Winter (MVA)	Shoulder (MVA)	Summer (MVA)	X (% p.u.)	R (% p.u.)
OTA-WRT 1	4.264	1 goat AC 75	168	160	152	1.32	0.29
OTA-WRT 2	4.264	1 goat AC 75	168	160	152	1.32	0.29
WIR-WRT 1	0.087	1 goat AC 75	168	160	152	0.03	0.01
WIR-WRT 2	0.093	1 goat AC 75	168	160	152	0.03	0.01
BOB ICT 1			188	180	180	9.824	0.181
BOB ICT 2			188	180	180	9.824	0.181
BBT-HLY 1	44.420	2 zebra GZ 75	764	730	694	2.7132	0.3108
BBT-DRY 1	8.461	2 zebra GZ 75	764	730	694	0.5168	0.0592
BBT-HLY 2	44.420	2 zebra GZ 75	764	730	694	2.7160	0.3100
BBT-TAT 2	19.301		764	730	694	1.168	0.0950

Note: “GZ” refers to galvanized conductors

In all cases the Waikato and Upper North Island (WUNI) import constraint is applied to the sum of transmission line flows into the region, being the following:

BHL-WKM-1 BHL-WKM-2 HAM-WKM-1
HLY-OTO-1 OHE-WKM-1 OHE-WKM-2
OHW-WKM-1 ONG-RTO-1 OTA-WKM-1
OTA-WKM-2 OTO-TWH-1

Each option includes the values for the total imports constraint shown in Table 10.

Table 10: WUNI import constraint for losses calculation	
Year of change (1 Jan)	Limit (MW)
2021	2740
2027	2940
2038	3080
2043	3220

Transmission System Losses

Losses have been calculated only for lines on which flows might be affected by the transmission development options under consideration. Losses are valued at the North Island SRMC applying for the particular load block, month and inflow sequence applicable.

Table 11: Lines for Loss Calculation

ARI-BOB-1	BBT-TAT-2	HAM-WKM-1	OTA-PEN-5
ARI-HAM-1	BOB-TF-T1	HLY-OHW-1	OTA-TAT-1
ARI-HAM-2	BOB-TF-T2	HLY-OHW-2	OTA-TAT-2
ARI-HAM-3	BOB-WRT-1	HLY-TAT-2	OTA-TF-T2
ARI-HTI-1	BOB-WRT-2	HTI-TMU-1	OTA-TF-T3
ARI-RTO-1	CBG-KPO-1	KPO-TMU-1	OTA-TF-T4
BHL-OHE-1	CBG-KPO-2	OHE-OHW-1	OTA-TF-T5
BHL-OHE-2	DRY-GLN-1	OHE-OHW-2	OTA-TF-T6
BHL-PAK-1	DRY-GLN-2	OHE-WKM-1	OTA-WKM-1
BHL-PAK-2	DRY-HLY-1	OHE-WKM-2	OTA-WKM-2
BHL-WKM-1	DRY-TAT-1	OHW-OTA-1	OTA-WRT-1
BHL-WKM-2	HAM-CBG-1	OHW-OTA-2	OTA-WRT-2
BBT-DRY-1	HAM-CBG-2	OHW-WKM-1	PAK-PEN-3
BOB-HAM-1	HAM-OHW-1	OTA-PAK-3	PEN-TF-T16
BOB-HAM-2	HAM-TF-T6	OTA-PAK-4	PEN-TF-T10
BBT-HLY-1	HAM-TF-T9	OTA-PEN-2	PEN-TF-T11
BBT-HLY-2			

Results

Summary

Studies were carried out with N-1 contingency constraints represented and without these constraints. The results summarised in Table 12 are for the case without N-1 constraints. These results show no significant differences in dispatch or deficit costs between transmission development options. This is consistent with the minor differences in transmission line constraints between options. The only significant thermal line constraint identified is on the BOB-HAM lines, and largely just the period 2023 to 2026. N-1 contingency constraints had a major impact on line flows for the separate cases in which these were modelled.

Losses for the lines listed in Table 11 have been valued at the North Island short run marginal cost, for the corresponding load block, month and inflow sequence.

Table 12: NPV costs, 1 Jan 2021 - 31 Dec 2040, 7% discount rate, $m

Thermal plant costs (fuel, variable O&M, carbon emissions cost)						
	Disruptive	Environment	Global	Growth	Reference	Average
Existing	4,649	5,298	4,831	5,119	4,762	4,931
Upgrade	4,649	5,298	4,831	5,118	4,762	4,931
Preferred	4,648	5,297	4,830	5,116	4,759	4,930
Deficit Cost, total New Zealand values						
	Disruptive	Environment	Global	Growth	Reference	Average
Existing	88.8	106.4	60.8	155.6	97.6	102
Upgrade	88.8	106.3	60.8	155.0	97.8	102
Preferred	88.5	106.8	60.8	156.4	99.1	102
Loss costs, for selected lines, valued at SRMC						
	Disruptive	Environment	Global	Growth	Reference	Average
Existing	546	562	333	474	368	457
Upgrade	357	394	318	377	321	353
Preferred	335	370	299	343	294	328
Total costs (thermal plant, deficit, losses)						
	Disruptive	Environment	Global	Growth	Reference	Average
Existing	5,283	5,966	5,225	5,749	5,227	5,490
Upgrade	5,095	5,798	5,210	5,650	5,181	5,387
Preferred	5,071	5,773	5,190	5,615	5,152	5,360
Cost saving relative to Existing option						
	Disruptive	Environment	Global	Growth	Reference	Average
Upgrade	189	168	15	98	46	103
Preferred	212	193	35	133	75	130

Detailed Results - Transmission System Losses

Losses are calculated only for the selection of lines listed in Table 11. Losses due to real power flows only are calculated as a linearised or "DC" power flow model is used within SDDP. Hence there will be some additional losses due to reactive power flows.

Table 13: Annual average loss costs and quantities for selected lines, averaged over the five EDGS

	Average loss costs, ($m)			Average loss quantities ,(GWh)		
	Existing	Upgrade	Preferred	Existing	Upgrade	Preferred
2021	27.1	27.1	27.1	281.9	281.9	281.9
2022	28.3	28.3	28.3	310.1	310.1	310.1
2023	33.6	33.5	31.3	343.3	342.8	321.9
2024	35.4	35.4	33.1	351.2	350.7	329.1
2025	35.8	35.6	33.3	337.8	337.2	316.1
2026	37.3	37.2	34.7	330.8	330.2	309.2
2027	32.7	32.6	30.5	295.2	294.3	275.3
2028	33.9	33.7	31.6	310.6	309.6	290.8
2029	34.1	33.9	31.8	316.4	315.4	296.2
2030	30.9	30.8	28.8	319.3	318.2	299.1
2031	34.8	34.7	32.5	325.5	324.4	305.6
2032	36.4	36.3	34.1	318.4	317.1	299.5
2033	34.6	34.4	32.1	298.6	297.3	278.9
2034	34.8	34.6	32.6	306.5	305.0	288.8
2035	31.7	31.5	29.8	308.5	307.0	291.3
2036	27.6	27.4	26.0	304.1	302.5	287.6
2037	29.9	29.7	28.1	317.1	315.6	300.7
2038	34.7	34.5	32.7	328.5	326.9	312.2
2039	31.6	31.4	29.8	343.2	341.5	326.8
2040	28.7	28.6	27.3	372.2	370.5	356.1
NPV	**346.4**	**345.3**	**327.0**			

Note: Losses valued at North Island SRMC.

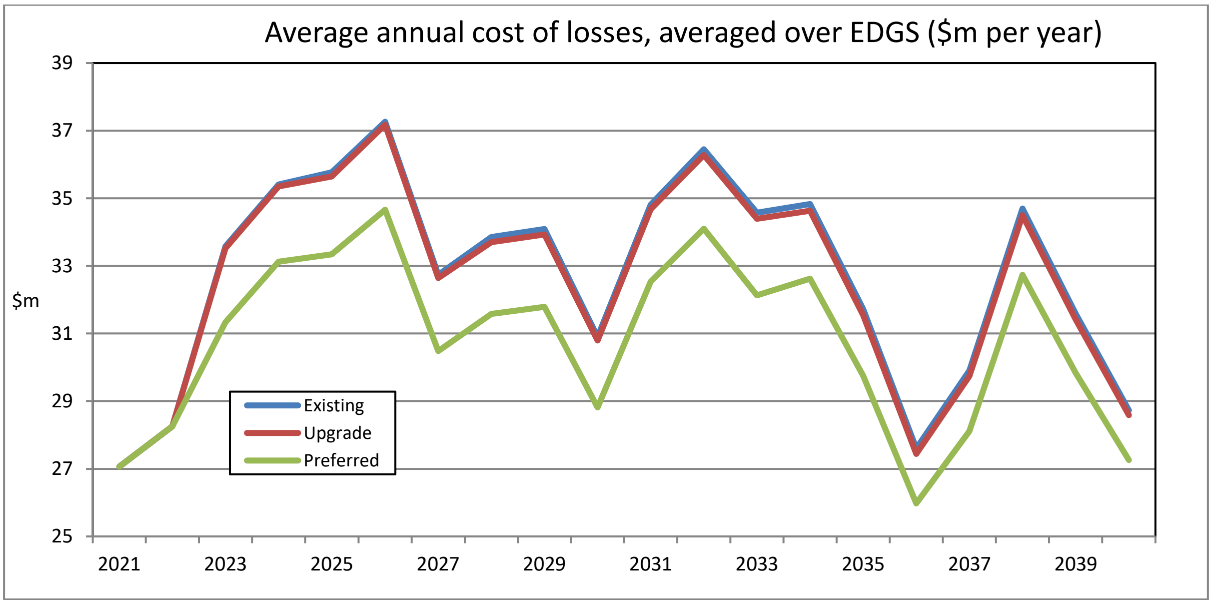

Figure 5: Annual average value of transmission losses, costed at the North Island SRMC of a case with no grid constraints, for selected lines, averaged over the five EDGS.

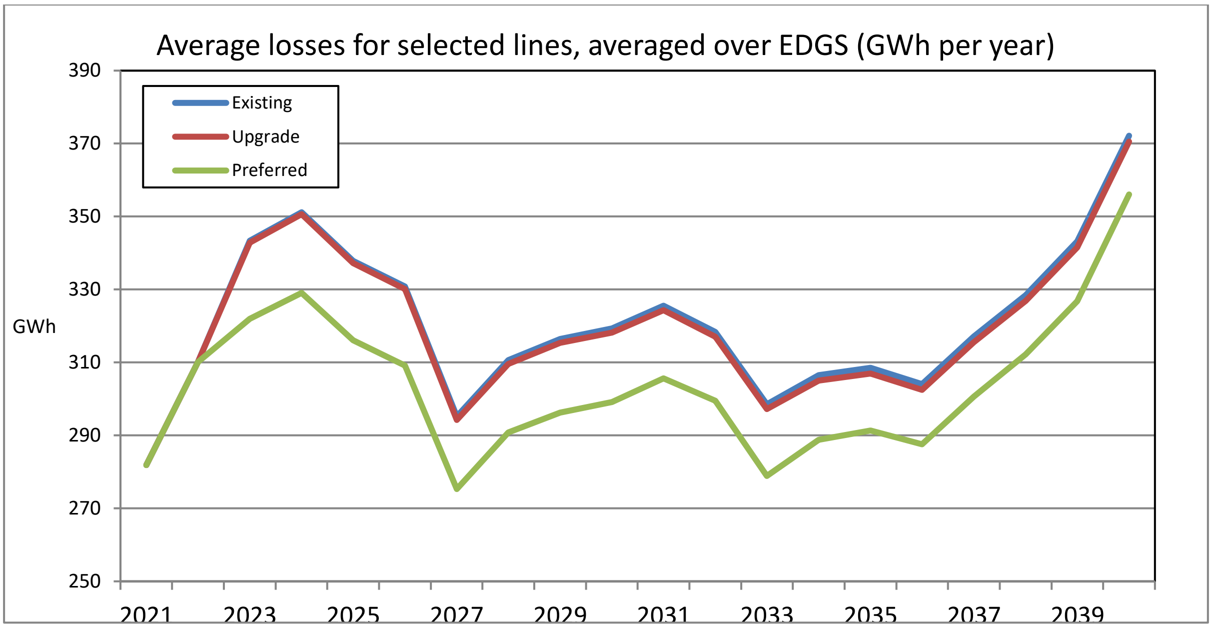

Figure 6: Annual average quantity of transmission losses, for selected lines, averaged over the five EDGS.

Transmission Constraints

A set of model runs was carried out enforcing some N-1 contingency constraints as hard constraints. These constraints led to significant deficits for the existing and upgrade options. In contrast, none of the modelled contingency constraints were active for the preferred option after the transmission upgrades are commissioned. Table 14 shows the probability of N-1 constraints being active. The columns headed "BOB-HAM-1 & BOB-HAM-2" indicate the probability of the condition where a tripping of BOB-HAM-1 would result in overloading of BOB-HAM-2.

The effect of these constraints in the modelling is to cause Karapiro generation to be reduced. Due to the minimum flow constraint at Karapiro, it is necessary to spill water to maintain that minimum flow. Consequently additional thermal generation costs are incurred. Should the existing or upgrade options be implemented, special protection schemes would be implemented, to minimise the effect of these constraints. Hence the loss calculations presented here have been carried out for cases without any N-1 constraints modelled.

Table 14: Probability of N-1 constraint being active (if enforced as hard constraints) (%)										
Existing	BOB-HAM-1 & BOB-HAM-2					OTA-WRT-1 & OTA-WRT-2				
	Disruptive	Enviro	Global	Growth	Reference	Disruptive	Enviro	Global	Growth	Reference
2021	6.7	5.7	6.4	6.7	13.3	1.1	0.9	0.1	1.1	0.9
2022	7.2	7.4	6.9	8.7	11.3	2.9	2.4	0.7	2.5	2.3
2023	24.5	17.8	19.0	29.1	28.1	6.7	6.7	4.2	6.7	6.4
2024	29.2	27.4	25.0	29.4	26.7	8.9	8.8	4.1	9.4	6.6
2025	23.3	26.2	22.6	25.6	31.8	10.3	10.5	4.2	10.9	9.5
2026	24.5	25.2	22.6	30.5	28.0	11.0	11.2	4.5	12.5	9.6
2027	10.8	11.9	10.3	15.3	13.6	23.9	21.7	4.9	16.8	10.6
2028	9.9	11.6	9.4	16.8	15.0	36.5	31.3	5.1	23.6	10.9
2029	11.6	14.0	8.0	20.7	13.4	40.1	33.5	6.6	25.4	14.6
2030	12.2	13.9	10.9	22.3	13.2	47.2	40.9	4.8	33.2	18.8
2031	10.0	12.7	11.0	26.3	13.4	58.1	49.2	4.8	33.7	21.6
2032	8.8	6.2	9.2	22.1	12.9	59.7	60.1	4.8	41.3	22.5
2033	8.0	3.1	6.7	20.6	12.7	65.1	67.6	2.1	45.9	23.8
2034	1.3	0.0	0.2	12.5	8.4	77.5	77.8	7.3	54.1	32.9
2035	1.2	0.0	0.1	11.0	7.2	80.2	85.1	6.5	56.5	37.5
2036	0.0	0.0	0.0	11.0	6.8	89.6	85.9	9.6	56.5	39.8
2037	0.0	0.0	0.0	9.8	6.4	91.3	86.9	7.1	57.2	37.5
2038	0.1	0.6	0.0	8.9	5.6	94.2	86.5	4.4	55.0	39.0
2039	0.3	1.7	0.0	9.7	7.3	96.0	86.6	8.3	58.1	39.2
2040	0.0	1.4	0.0	11.6	7.1	97.8	89.3	5.8	56.9	41.7
Upgraded	BOB-HAM-1 & BOB-HAM-2					OTA-WRT-1 & OTA-WRT-2				
	Disruptive	Enviro	Global	Growth	Reference	Disruptive	Enviro	Global	Growth	Reference
2021	6.7	5.7	6.4	6.7	13.3	1.1	0.9	0.1	1.1	0.9
2022	7.2	7.4	6.9	8.7	11.3	2.9	2.4	0.7	2.5	2.3
2023	24.4	17.6	18.7	28.8	27.9	0.0	0.0	0.0	0.0	0.0
2024	29.1	27.0	24.7	29.1	26.6	0.0	0.0	0.0	0.0	0.0
2025	22.8	26.0	22.2	25.4	31.7	0.0	0.0	0.0	0.0	0.0
2026	24.1	25.1	22.4	30.0	27.7	0.0	0.0	0.0	0.0	0.0
2027	10.1	10.9	10.1	14.8	13.2	0.0	0.0	0.0	0.0	0.0
2028	9.5	11.1	9.2	15.3	14.3	0.0	0.0	0.0	0.2	0.0
2029	10.5	12.8	7.3	19.6	12.3	0.0	0.0	0.0	0.8	0.0
2030	9.2	11.0	10.6	19.8	11.1	0.1	0.1	0.0	0.8	0.0
2031	6.5	10.6	10.7	21.6	11.3	0.3	0.5	0.0	1.2	0.0
2032	6.0	4.8	9.0	14.2	10.8	0.2	0.9	0.0	1.6	0.0
2033	4.4	3.0	6.5	12.8	10.0	0.3	0.8	0.0	2.0	0.0
2034	0.6	0.3	0.2	7.3	4.6	0.8	2.2	0.0	1.6	0.0
2035	0.9	0.0	0.1	5.8	2.5	0.7	3.8	0.0	1.2	0.0
2036	0.0	0.2	0.0	5.7	1.7	1.8	2.7	0.0	1.5	0.0
2037	0.1	0.4	0.0	6.1	1.8	2.1	2.9	0.0	1.4	0.0
2038	0.0	0.4	0.0	3.3	2.0	3.9	3.6	0.0	1.9	0.0
2039	0.0	1.7	0.0	4.8	2.2	2.8	2.1	0.0	3.2	0.0
2040	0.0	2.1	0.0	7.8	1.0	1.6	1.7	0.0	3.9	0.0
Preferred	BOB-HAM-1 & BOB-HAM-2					OTA-WRT-1 & OTA-WRT-2				
	Disruptive	Enviro	Global	Growth	Reference	Disruptive	Enviro	Global	Growth	Reference
2021	6.7	5.7	6.4	6.7	13.3	0.0	0.0	0.0	0.0	0.0
2022	7.2	7.4	6.9	8.8	11.4	0.0	0.0	0.0	0.0	0.0
2023	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2024-2040	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0