Effect of wind generation variability on asset loading

INVESTIGATION 3

WIND GENERATION INVESTIGATION PROJECT
MAY 2007

NOTICE

Version Control

Version	Date	Change
1	14/12/2006	Draft in progress.
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Executive Summary

Introduction

The Electricity Commission initiated the Wind Generation Investigation Project (WGIP) to determine what changes to the Electricity Governance Rules and Regulations (EGRs) and industry arrangements will be necessary to accommodate the connection of a large volume of wind generation. The "Implications" phase of the project is an investigation of the impacts of wind generation on the operation of the New Zealand power system and electricity market, for a specified set of wind generation development scenarios.

Nine areas where the variability of wind generation output or the technical capability of wind generation may adversely impact on the operation of the New Zealand power system and electricity market were identified. Each of these areas has been investigated to determine the likely impact under the defined scenarios and whether further analysis is required for the Options stage of the Project.

Figure 1 shows the nine areas of investigation.

Variability of wind generation output	Scheduling and dispatch	Investigation 1 Effect of unpredictability of wind generation output on pre-dispatch processes	Investigation 2 Effect of variability of wind generation output on dispatch of generation	Investigation 3 Effect of variability of wind generation output on asset loading
Wind generation technical capability	Voltage and frequency management	Investigation 4 Effect of wind generation capability on steady state voltage management	Investigation 5 Effect of wind generation capability on management of frequency excursions	Investigation 6 Effect of wind generation capability on voltage stability
	Power system stability	Investigation 7 Effect of wind generation capability on power system transient stability	Investigation 8 Effect of wind generation capability on oscillatory stability	Investigation 9 Effect of wind generation capability on dynamic voltage stability

Figure 1: WGIP investigation areas

Issues related to large scale wind generation development that are found to be significant will be advanced to the next phase of the WGIP which considers options for addressing these issues.

Transpower has been engaged by the Electricity Commission to undertake some of the nine investigations. This report documents Investigation 3 which aimed to identify the potential effects of variability of wind generation output on asset loadings for increased amounts of wind generation connected to the New Zealand power system.

Wind generation investigation project approach

The WGIP has identified nine areas for investigation. The potential impact in each area has been assessed through screening analyses.

The approach taken during the screening analyses was to determine, for a worst case credible situation in terms of potential effects upon the power system, whether the impact of wind generation would result in significant problems for operation of the power system or electricity market during the next 10 years. If the “worst case credible” situation shows no significant effects then further analysis is not required.

Management of asset loading on the New Zealand power system

The New Zealand power system consists of two island power systems (North Island and South Island) connected by an HVDC link. The combined peak demand for both islands in 2006 was 6748 MW. Most generation is located a considerable distance from load centres. The remote location of generation and the geography of New Zealand have resulted in a transmission grid which is linear in nature – comprising a “backbone” (core 220 kV grid and HVDC link) with radial supply to different regions of New Zealand.

The System Operator dispatches assets made available in a manner which avoids the cascade failure of assets resulting in the loss of demand and arising from frequency or voltage excursions or supply and demand imbalances. Generation is scheduled to ensure that power flow through assets in the power system is within asset capability and that system voltages are maintained within quality targets during and following a defined set of power system events. These are referred to as “contingent events”.

Changes in load and in the output of variable generation such as wind generation will cause shifts in power flow on the power system. Large shifts in power flow can cause the loading of assets to exceed capability and will require re-dispatch of generation to restore asset loading to being within capability.

Assumptions and approach

The methodology used to analyse the effect of wind generation output variability on asset loading was:

1. Identify current levels of load variability on transmission circuits;
2. Identify key circuits that might be affected by variability in wind generation output and demand (based on the Electricity Commission’s Wind generation Development Scenarios [1]);

3. Prototype the analysis for assessing the effects of predicted variability of wind generation output on circuit loadings for a selected key circuit;
4. Decide on the basis of the outcome of the prototype analysis whether to extend the analysis to other selected key circuits; and
5. Assess risk of the impact of wind generation output variability on circuit loadings and make recommendations.

Wind Generation Development Scenarios

The Electricity Commission developed four possible wind generation scenarios [1] which are inputs to the nine investigations. Wind generation development as in Scenario C will be modelled in the base case for these studies. Scenario C has the maximum amount of wind generation penetration and this will be the most extreme case for effects on asset loading.

Variability of wind generation output

The Bunnythorpe-Haywards circuits were chosen for preliminary investigation as the largest amounts of wind generation were located at the opposite ends of the circuits (Manawatu and Wellington) and that this is the area where new wind generation is most likely to be installed in the short term.

Garrad Hassan was requested to carry out analysis to predict the variability of wind generation output for the Bunnythorpe-Haywards circuits. The results of the analysis are contained in Appendix 2.

The additional variability in circuit loadings arising from the connection of wind generation at Bunnythorpe and Wilton was determined through the following process as follows:

- Probability distribution functions for historic circuit loadings were determined using historic data.
- Probability distribution functions for Te Apiti wind farm output were determined using historic data.
- Measured wind data and a generic wind farm power curve were used to model wind farm outputs at Bunnythorpe and Wilton. The modelled wind farm outputs were transformed into ramp rate probability distributions based on the measured ramp rate probability distribution from Te Apiti wind farm output. The wind farm power outputs were transformed into estimated (N-1) line loading by applying the appropriate north or south flow sensitivity factors. These are the wind generation-led power flows.
- Monte Carlo analysis[1] was used to determine a probability distribution function for the composite circuit loading (wind generation and historic).

[1] See Appendix 2 for details.

Findings

The Bunnythorpe-Haywards circuits were not adversely affected by wind generation output variability for the size of changes expected to occur on a weekly or monthly basis. The present analysis indicates that further analysis of the Bunnythorpe-Haywards circuits for safe operation of assets under the envisaged wind generation is not warranted. The predicted variability of loading[2] on the Bunnythorpe-Haywards corridor is quite low for large wind farms at either end (450 WW at Bunnythorpe and 300 MW at Wilton). It is expected that similar results will occur on other transmission corridors. The analysis for a single transmission corridor requires considerable effort. There is little benefit and considerable cost in repeating the same analysis for other regions. For this reason, no further analysis was carried out for this report.

The analysis has some limitations that are related to the data used to determine historic probability distribution functions. The data used was limited to a period of three months. The models used are likely to be good at predicting events which occur on an hourly or daily basis (as far as those events are represented in the data) but will not necessarily represent large but less frequent events (as those events may not have occurred during the data measurement period). The probability of large but infrequent changes in wind generation output can not be calculated with any accuracy at this time.

It is concluded that

- Wind generation output variability of the size for wind generation development Scenario C should not materially affect the loading of transmission circuits in the core transmission grid for levels of changes experienced on a daily or weekly basis.
- There are limitations in the models used for the analysis which reflect the limited operational experience of wind generation on the New Zealand power system. The probability of large but infrequent changes in wind generation output can not be calculated with any accuracy at this time.
- In the absence of changes to the EGRs or industry arrangements, there are a range of existing controls available to minimise the impact on wind generation on asset loading.

It is recommended that appropriate wind generation output data is recorded from now on and the probability of large but infrequent events is reviewed on an ongoing basis.

[2] For events with return periods of up to once a month.

1. Introduction

1.1 Background

The Electricity Commission has initiated the Wind Generation Investigation Project (WGIP) to determine the changes to the Electricity Governance Rules and Regulations (EGRs) and industry arrangements will be necessary to accommodate the connection of large scale wind generation.

The Electricity Commission has developed four possible wind generation development scenarios [1] (A, B, C and D) for the New Zealand power system.

Transpower has been engaged by the Electricity Commission to undertake an investigation into the impact of the connection of large scale wind generation as envisaged in the wind generation development scenarios upon asset loading.

1.2 Purpose

The purpose of this study is to:

- examine the effect of variability of wind generation output on the loading of transmission assets during and following contingent events;
- identify the level of wind generation at which changes to existing arrangements will be required to manage these effects; and
- make recommendations as to further investigation in this area.

1.3 Maintaining asset loading within safe limits

1.3.1 Operation of the New Zealand power system

The New Zealand power system consists of two island power systems (North Island and South Island) connected by an HVDC link. Figure 5 and Figure 6 show the North Island and South Island power systems respectively. Power system frequency is managed by a frequency keeping station in each island.

The System Operator is required to meet two objectives in scheduling generation on the New Zealand power system:

- Principal Performance Obligations (PPOs). The PPOs require the System Operator to act as a reasonable and prudent system operator. The System Operator has the objective of dispatching assets made available in a manner which avoids the cascade failure of assets resulting in the loss of demand, and arising from frequency or voltage excursions or supply and demand imbalances.
- The dispatch objective. The dispatch objective requires the System Operator to maximise for each half hour the gross economic benefits to all purchasers of electricity at the grid exit points less the costs of

supplying electricity to the grid exit points and the costs of ancillary services.

The System Operator schedules generation to ensure that assets in the power system remain within their capability and that system voltages are maintained within quality targets during and following a defined set of power system events. These are referred to as “contingent events”.

1.3.2 Asset capability

Asset owners advise asset capability limits to the System Operator. These limits include maximum asset loading and minimum and maximum voltage levels. The System Operator operates the power system to avoid assets exceeding their capability both in steady state conditions and during and following contingent events.

Asset capability limits are incorporated in scheduling and dispatch processes through security constraints. Generation is scheduled and dispatched according to offered price taking into account security constraints. Generation is dispatched so that no asset will exceed its capability following a contingent event. This means that the pre-event power flow (pre-contingent loading) on a transmission circuit is always such that after a contingent event involving the loss of another power system asset, the power flow is still within the rating of the transmission circuit.

The Grid Owner can offer short time ratings for some transmission circuits. These short time ratings are higher than steady state continuous ratings but can only be sustained for a fixed period of time (e.g. 15 minutes) reflecting the ability of the transmission line to run at a higher load for a short time. Where short time ratings are offered by the Grid Owner, pre-contingency loading on transmission circuits can be higher, but following the contingency, generation must be re-dispatched quickly to bring the loading on the transmission circuit back to its continuous rating.

As an example, the pre-contingency loading on two circuits supplying a load would normally need to be kept to 50% of the circuits’ continuous rating if the post contingency (following the loss of one of the circuits) loading on the remaining circuit is to be kept within its continuous rating. A short term rating could allow the circuits to be run with a pre-contingency loading of 60% of continuous rating. Following the loss of one of the circuits, the loading on the remaining circuit would be 120% of continuous rating. This post-contingency loading would be managed back to the continuous rating within 15 minutes by load shedding.

1.3.3 Loading on transmission circuits

The loading on a transmission circuit is dependent on generation output (injection from power stations) and demand offtake (power taken off the grid into lines companies networks). Changes in generation output or demand offtake will change the loading on a transmission circuit.

Demand offtake is constantly varying as consumers switch on and off electrical loads. The output of some generation (e.g. wind generation) is quite variable due to the nature of the fuel resource (e.g. wind). The output of other generation will vary in response to changes in system conditions (e.g. changes in power system frequency) but these changes are relatively small compared to changes in demand offtake (load).

Generation is dispatched to ensure that assets do not exceed stated capability during contingent events. Changes in demand offtake (load) and variable generation (such as wind generation) could cause:

- the pre-contingency loading on a circuit to increase to a level such that a contingent event would cause the asset to exceed its capability. This could result in the asset tripping (disconnecting from the system) if an event occurs as the post contingency loading was greater than that tolerated by the protection devices on the asset or cause the asset to operate beyond safety limits; or
- the post contingency loading on a circuit that was initially within asset capability to increase so as to exceed stated capability before generation can be re-dispatched or the lost asset can be restored.

1.4 Variability of wind generation

The Te Apiti wind farm is connected into the 110 kV network in the Manawatu region. Prior to connection, it was recognised that the output from Te Apiti could cause nearby 110 kV circuits to exceed steady state ratings at times of high HVDC transfer. A generation runback scheme was installed to reduce Te Apiti output at times when the circuit ratings could be exceeded.

Operational experience with the Te Apiti run back has seen the scheme operate regularly under certain dispatch conditions (high north or south transfer from Bunnythorpe to Haywards) .This can require considerable real time effort in dispatching and managing the power system. At these times the existing security constraints to protect these 110 kV circuits which are applied in the dispatch model need to be adjusted frequently during the day.

The Te Apiti wind farm is about a fifth of the size of the wind farm concentrations envisaged for the Manawatu region in the Electricity Commission's wind generation development scenarios. In the absence of other controls to mitigate the impact of generation variability on asset loading in situations like Te Apiti under some dispatch conditions the amount of operational effort required to manage the wind generation development envisaged in the scenarios could be considerable.

The amount of operational management required in any specific case will be related to the amount of grid capacity available, the configuration of the power system in the region and dispatch conditions. Where grid capacity is limited and grid configuration require regular tuning of constraints, real time operational management requirements for localised issues may be significant and risk distracting power system operational staff from the wider operation of the power system.

2. Approach and Assumptions

2.1 Wind generation investigation project approach

The Wind Generation Investigation Project has identified nine areas where the variability of wind generation output or the technical capability of wind generation technology could impact upon the operation of the power system and electricity market.

The approach taken to assess the impacts was to determine for a worst case credible situation[3] whether increased wind generation will have material effects on the operation of the power system or electricity market during the next 10 years assuming that no changes to power system operation or market arrangements were made. If the worst case but credible situation shows no significant effects then no further analysis is required.

In keeping with the worst case credible situation, the following assumptions were made:

- Wind generation technology is assumed to have minimal capability. For example, wind generation turbines are assumed to have no ability to support voltage or frequency. It is recognised that modern turbines do have a certain ability to support voltage and frequency.
- The wind generation development scenario where the potential effects will be the greatest is chosen as the basis of the assessment.
- The displacement by wind generation of other generation will result in the worst case outcome for the area under investigation.

The size and urgency of the impacts of wind generation determined during the preliminary analysis will allow the issues to be prioritised for attention in the next phase of the Wind Generation Investigation Project. For example, an issue that will have major impacts on the operation of the power system and electricity market for relatively low levels of wind generation will be given high priority whereas an issue that has no significant impacts can be assigned a low priority.

2.2 Investigation methodology

The methodology used to analyse the impact of wind generation output variability on asset loading was to:

1. identify current levels of load variability.
2. identify key circuits that might be affected by variability in wind generation output and demand.
3. prototype the analysis for assessing the effects of predicted variability of wind generation output on circuit loadings for a selected key circuit;

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[3] In terms of potential effects on the power system.

4. decide on the basis of the outcome of the prototype analysis whether to extend the analysis to other selected key circuits; and
5. assess risk of the impact of wind generation output variability on circuit loadings and make recommendations.

2.3 General assumptions

It is assumed that:

- Load variability will increase proportionately with load growth.
- There are no major changes to the New Zealand power system or electricity market.
- The variability of wind generation output for the assumed wind farms in the Electricity Commission's wind generation development scenarios is similar in nature to the variability of Te Apiti wind farm.
- All assets are considered to be available for service. Constraints applying during maintenance outages are not considered.

This report considers only the effect of variability of wind generation output on the core transmission grid. Local effects of variability of wind generation output of specific wind farms (e.g. the over loading of local connection assets) are assumed to be dealt with as part of the connection agreement.

2.4 Effects on circuit loading

There are two situations where changes in circuit loading will have adverse effects:

- The pre-contingency loading on a circuit increases to a level such that a contingent event would cause the asset to exceed its capability. This could result in the asset tripping if the post contingency loading was greater than protection limits or cause the asset to exceed safety limits.
- The post contingency loading on a circuit exceeds stated capability before generation can be re-dispatched or the lost asset can be restored.

The effects of exceeding circuit rating could result in damage to circuit components (e.g. current transformers) or cause conductors to sag below the minimum statutory ground clearance requirements.

The effects of exceeding protection limits on the circuit could be indiscriminate operation of the protection system causing the transmission circuit to be disconnected. This disconnection could result in cascade failure of assets.

Short term asset ratings can be offered by the Grid Owner. These ratings allow a higher loading of the asset for a defined time. For example, a short term rating higher than steady state rating could apply provided that post contingency loading is reduced to the steady state rating within an agreed time (e.g. 10 minutes). The use of short term ratings allows greater loading pre contingency and assumes that load can be managed or generation dispatched quickly following the contingent event.

2.5 Effect of variability on circuit loading

Consider the transmission circuit shown in Figure 2. The total power flow through the circuit (S) will be a function of the generation (G) and load (L) connected to each bus. If the load on bus B is varying then the power flow through the circuit will also vary.

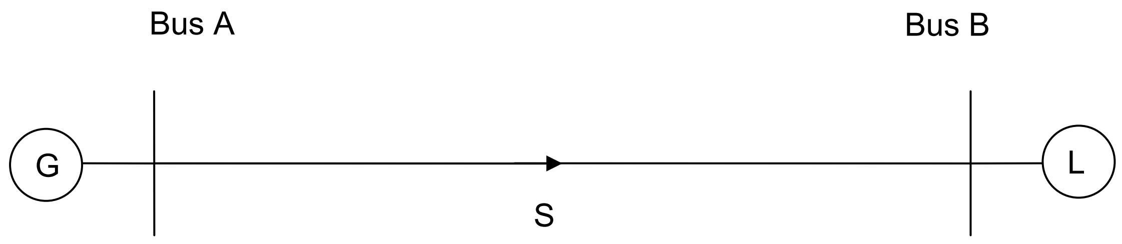

Figure 2: Transmission circuit

Where there are parallel circuits between the buses a portion of the load will be supplied by each parallel circuit. The portions will be determined by the relative impedances of the parallel circuits. If the impedances are equal then variations in load will be shared equally between the circuits.

Consider the case where wind generation (W) is connected to bus B as well as load (see Figure 3). This is done to illustrate a case where the variability of wind generation is additive with the variability of load.

The variability of the wind generation output will be reflected in the power flow through the transmission circuit. For example, if wind generation output at bus B were to rise then the amount of power flow through the transmission circuit required to meet load L would decrease. The variability of the power flow will be a function of the variability of load at Bus B and the variability of wind generation output at Bus B.

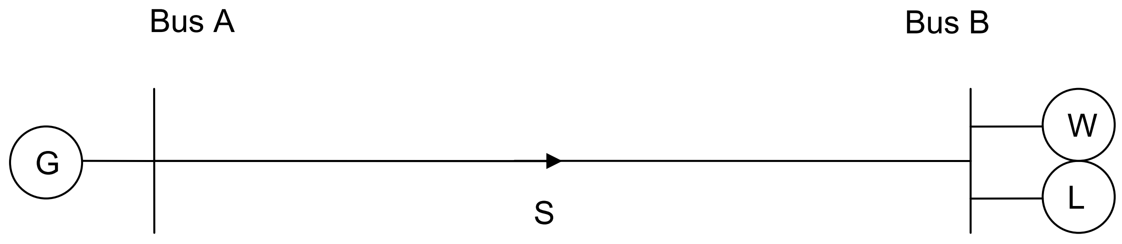

Figure 3: Transmission circuit

Figure 4 shows variation in wind generation output and load and the corresponding change in transmission circuit loading.

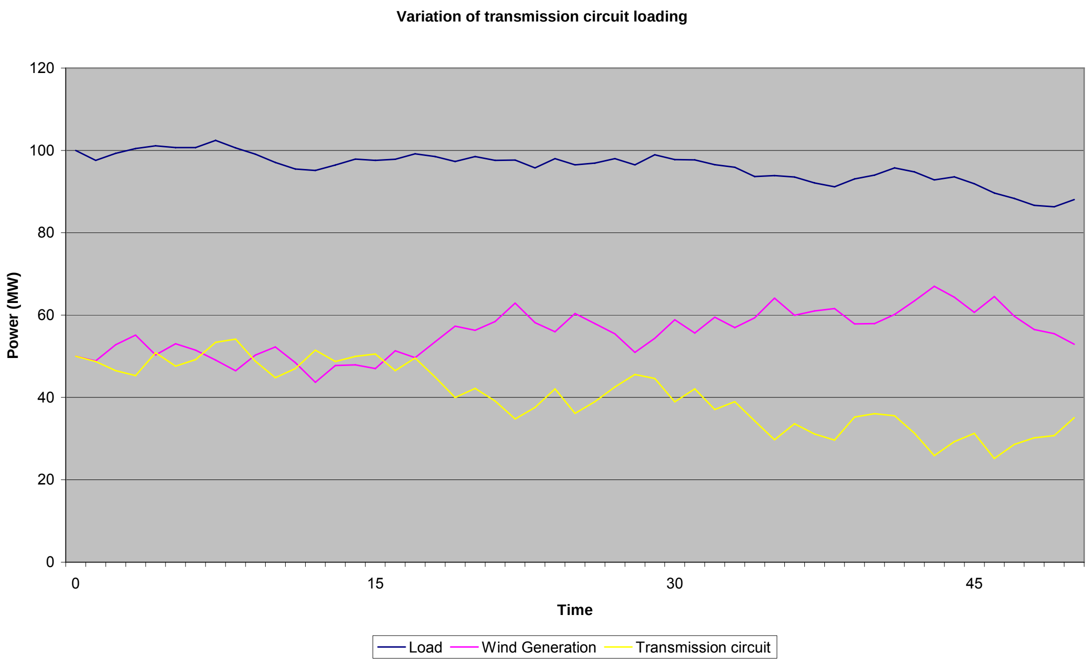

Figure 4: Variation of wind generation, load and transmission circuit loading

The combined variability of wind generation output and load at bus B would be reflected in power flow through the transmission circuit. Knowledge of the nature of the variability of wind generation output and of load will enable analysis of the combined variability.

2.6 Sensitivity factors

The effect of certain generation output on the loading of a particular transmission circuit can be expressed as a sensitivity factor. A simplistic explanation of sensitivity factors follows.

Sensitivity factors are expressed as a fraction which can be positive or negative. A positive sensitivity factor indicates that circuit loading increases for an increase in generation output. A negative sensitivity factor indicates that circuit loading decreases for an increase in generation output.

The mathematical equation relating sensitivity factors to circuit loading is:

$$P1 = P0 + sf \times \Delta G$$

Where P1 is the new loading on the circuit, P0 is the initial loading on the circuit, sf is the sensitivity factor and ΔG is the increase in generation output. The sensitivity factor for a circuit with regard to generation output of 0.5

indicates that for an increase in 1 MW of generation output, the increase in loading on the circuit is 0.5 MW. If the initial loading on the circuit (P0) is 100 MW for a given regional generation or demand then an increase of 10 MW in generation output will increase the loading (P1) on the circuit to 105 MW.

Sensitivity factors are calculated by varying the generation output for which the sensitivity factor is to be determined and letting a second generating unit's output vary to balance generation and load while holding all other generation and load constant. The choice of the second generating unit is important as an inappropriate choice will lead to the calculated sensitivity factor being inaccurate. For the purposes of this analysis, the second generating unit is located in the area of the island where frequency keeping stations are located unless this affects the accuracy of the calculation.

2.7 Wind generation development scenarios

Table 1 shows the location of new wind generation as envisaged in the Electricity Commission's wind generation development scenarios (see reference [1] for details).

Island	**Region**	**Grid Connection (for modelling purposes)**	**Scenario C (very high penetration, diversified across the country)**
North Island	Northland	Marsden 220 KV	150 MW
	Auckland	Otahuhu 220 KV	300 MW
	Waikato	Huntly 220 KV	100 MW
	Hawkes Bay	Redclyffe 220 kV	300 MW
	Wairarapa	Masterton 110 KV	0 MW
	Manawatu[4]	Bunnythorpe 220 kV	450 MW
	Wellington	Wilton 220 KV	300 MW
TOTAL NI MW			**1600 MW**
South Island	Marlborough-Nelson	Blenheim 110 KV	50 MW
	Otago/ South Canterbury	Timaru 220 kV	300 MW
	Southland	Invercargill 220 kV	300 MW
TOTAL SI MW			**650 MW**

Table 1: Location of new and existing wind generation in wind generation development Scenario C

[4] This amount includes the existing 250 MW of wind generation (Te Apiti, Tararua I, II and III) located near Bunnythorpe.

3. Areas for investigation

3.1 Overview

The transmission circuits that will be most affected by wind generation variability are those connecting regions in Table 1 where the wind generation Scenario C envisages the largest concentrations of wind generation.

The most affected circuits would include:

- Invercargill-Roxburgh 220 kV circuits;
- Roxburgh-Clyde 220 kV circuits;
- Livingstone-Waitaki circuit;
- Naseby-Roxburgh circuit ;
- Bunnythorpe-Haywards 220 kV circuits;
- Bunnythorpe-Tokaanu 220 kV circuits;
- Tokaanu-Whakamaru 220 kV circuits; and
- Wairakei-Redclyffe 220 kV circuits.

The above list of circuits is not expected to be exhaustive but does include circuits which have (or had prior to recent upgrades) a history of being constrained.

Figure 5 and Figure 6 show the locations of the wind generation envisaged in Scenario C and the transmission circuits most likely to be affected by wind generation variability. The amount and location of wind generation are indicated by the blue squares. The transmission circuits are shaded by red ovals.

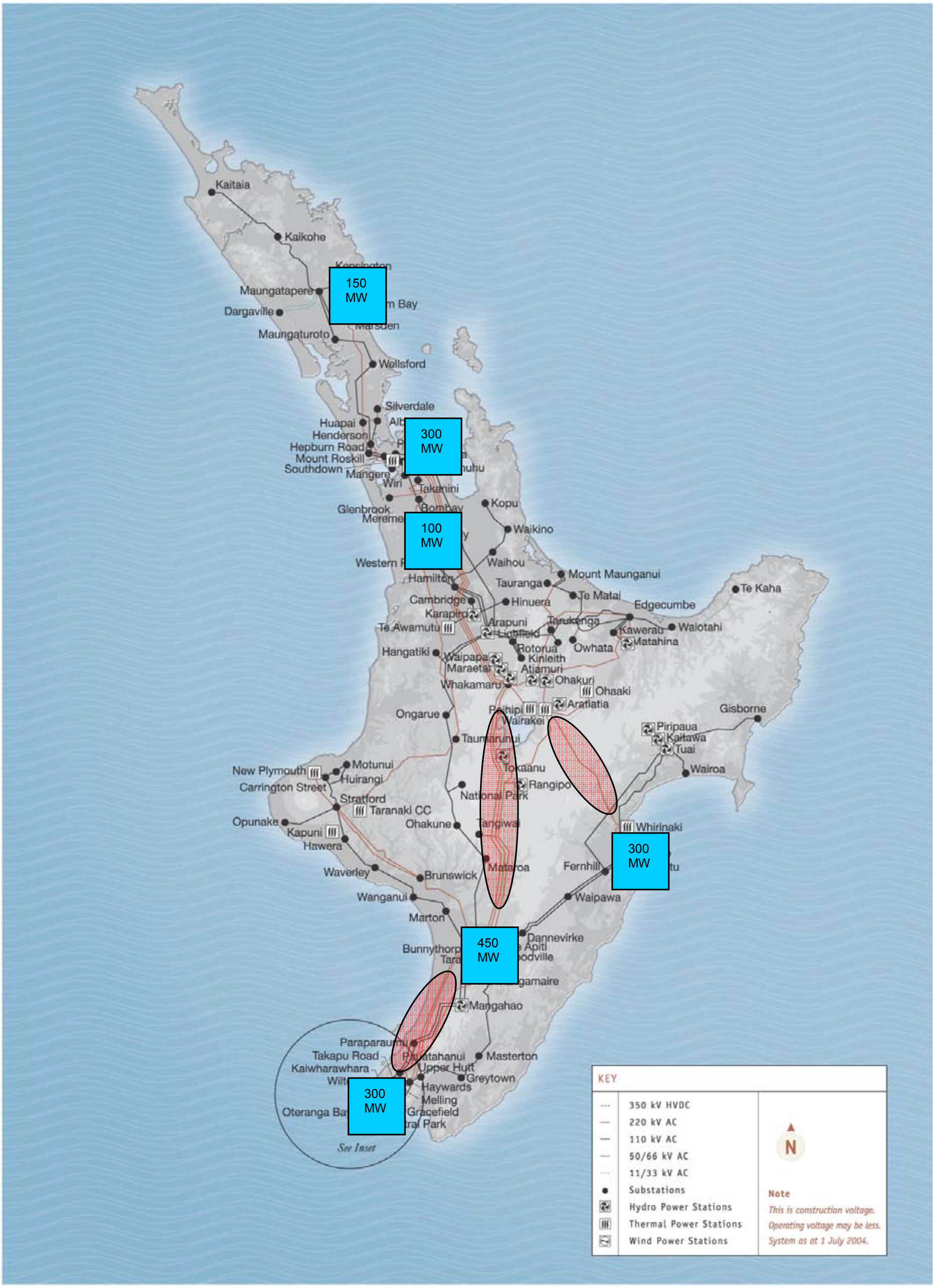

Figure 5: North Island wind generation (Scenario C) and transmission corridors studied

Figure 6: South Island wind generation (Scenario C) and transmission corridors studied

3.2 North Island

3.2.1 Lower North Island

Wind generation development Scenario C envisages 300 MW of installed wind generation capacity located in the Wellington region at Wilton and 450 MW of installed wind generation capacity located in the Manawatu region at Bunnythorpe. The 220 kV network between Wellington and Bunnythorpe has four main circuits (that may be affected by variations in wind generation output at Wilton and Bunnythorpe:

- Bunnythorpe-Haywards 1, 2 and 3; and
- Bunnythorpe-Wilton 1.

It should be noted that there are tee off connections on the Bunnythorpe-Haywards 3 circuit and the Bunnythorpe-Wilton circuit.

The 220 kV network between Bunnythorpe and the Central North Island has three main circuits (that may be affected by variations in wind generation output at Wilton and Bunnythorpe). Two of the circuits connect into Whakamaru and one circuit connects into Wairakei. It should be noted that there are tee off connections on these circuits to connect power stations at Tokaanu and Rangipo and load at Tangiwai.

Sensitivity factors for wind generation injection at Wilton and Bunnythorpe for the loadings on these circuits are shown in Table 2. Details of the calculations are contained in Appendix 1.

Circuit	Contingency	Sensitivity Factor (HVDC north/HVDC south) to generation at	
		Bunnythorpe 220 kV bus	Wilton 110 kV bus
Bunnythorpe-Haywards 1	Bunnythorpe-Haywards 3	-0.007/0.012	0.261/-0.324
Bunnythorpe-Tokaanu 1	Bunnythorpe-Tokaanu 2	0.311/-0.337	0.298/-0.353
Tokaanu-Whakamaru 1	Tokaanu-Whakamaru 1	0.354	0.348

Table 2: Lower North Island sensitivity factors

The Bunnythorpe-Haywards circuits were selected as the key circuits to be used in the prototype analysis (see Section 4.1).

3.2.2 Top of North Island

There is only a small amount of generation in the top of the North Island. The displacement of this other generation by the connection of 150 MW of installed wind generation (assumed to be connected to Marsden) as envisaged in wind generation development Scenario C will increase the amount of generation in the region and will act to reduce loadings on the circuits between Auckland and Marsden.

As the effects are not material, no further analysis of the region has been carried out.

3.2.3 Hawkes Bay

Scenario C envisages the connection of a 300 MW wind farm to Redclyffe 220 kV. The Hawkes Bay area is connected to the rest of the grid at Wairakei 220 kV (noting that the 110 kV system is operationally split at Waipawa 110 kV). The Whirinaki and Waikaremoana power stations (Tuai, Kaitawa and Piripaua) comprise the total generation in the Hawkes Bay area. Whirinaki is not normally run, which leaves the Waikaremoana scheme with a total installed capacity of 135 MW as the only generation in the region. The Hawkes Bay load ranges from about 72 MW to 300 MW.

With Hawkes Bay wind generation as envisaged in wind generation development Scenario C, the total generation output in the region can vary from zero MW to 435 MW (=300+135). Power transfer into or from Hawkes Bay can range from:

- Maximum import of around 300 MW (zero Waikaremoana generation output and zero wind generation output in combination with the highest regional demand); and
- Maximum export of 363 MW (highest Waikaremoana generation output and highest wind generation output in combination with minimum regional demand).

The maximum import conditions under wind generation development Scenario C reflect the status quo and wind generation in Hawkes Bay can only improve circuit loads because Hawkes Bay becomes a radial load fed from Wairakei under the envisaged conditions.

The maximum export conditions (wind generation output of 300 MW) have been investigated for the loss of each of the following circuits:

1. Wairakei - Whirinaki circuit; and
2. Redclyffe-Wairakei circuit.

The circuits are loaded to about 76% of continuous rating under these conditions, which reflect the highest levels of Hawkes Bay wind generation. Any wind variability (decrease) from the assumed maximum generation of 300 MW only reduces circuit loads. Hence wind variability does not cause 220 kV and 110 kV circuits in the Hawkes Bay region to operate beyond their stated capability.

3.3 *South Island*

3.3.1 Top of the South Island

The variability of the output of wind generation envisaged in wind generation development Scenario C (50 MW connected at Blenheim) and the consequential variability in transfer between Islington and the top of the South Island will be small. Most variations for a wind farm of this size will likely be within +/- 3 MW and are not likely to materially affect the variability of loading on circuits.

As the effects are not material, no further analysis of the region has been carried out.

3.3.2 Lower South Island

Wind generation development Scenario C envisages 300 MW of installed wind generation capacity located at Timaru and 300 MW of installed wind generation capacity located at Invercargill. The 220 kV network connecting Timaru and Invercargill has a number of circuits that may be affected by variations in wind generation output at Invercargill and Timaru including:

- Invercargill-Roxburgh;
- Clyde-Roxburgh;
- Livingstone-Waitaki; and
- Naseby-Roxburgh.

Sensitivity factors for wind generation injection at Timaru and Invercargill for the loadings on these circuits are shown in Table 3. Details of the calculations are contained in Appendix 1.

Circuit	Contingency	Sensitivity Factor to generation at	
		Invercargill 220 kV bus	Timaru 110 kV bus
Invercargill-Roxburgh 1	Invercargill-Roxburgh 2	-0.52	-0.001
Clyde-Roxburgh 1	Clyde-Roxburgh 2	-0.715	-0.016
Livingstone-Waitaki 1	Clyde-Twizel 1	-0.436	-0.105
Naseby-Roxburgh 1	Clyde-Twizel 1	-0.416	-0.021

Table 3: Lower South Island sensitivity factors

When power is being transferred from north to south, additional generation injected at the Invercargill 220 kV bus will reduce the amount of transfer on the circuits with the result that the circuits are less likely to be in constraint.

Transfer into the lower South Island (along with the Bunnythorpe-Haywards circuits) is a potential area for further analysis.

3.4 *Next stage*

The next part of the analysis involved determining probability distribution functions for power flows in selected transmission circuits. The analysis involved is complex and requires manipulation of large amounts of historic transmission circuit power flows recorded from SCADA data.

It was decided to carry out a preliminary analysis on a selected transmission corridor to confirm the methodology for the analysis and to determine whether assessment of other transmission corridors was necessary.

The Bunnythorpe-Haywards circuits were chosen for preliminary investigation as the largest amounts of wind generation were located at the opposite ends of the circuits (Manawatu and Wellington) and that this is the area where new wind generation is most likely to be installed in the short term.

4. Effect of wind generation output variability on Bunnythorpe-Haywards circuits

Garrad Hassan was requested to carry out analysis to predict the variability of wind generation output for the Bunnythorpe-Haywards circuits. The results of the analysis are contained in Appendix 2.

The additional variability in circuit loadings arising from the connection of wind generation at Bunnythorpe and Wilton is determined through the following process:

- Probability distribution functions for historic circuit loadings are determined using historic data.
- Probability distribution functions for Te Apiti wind farm output are determined using historic data.
- Measured wind data and a generic wind farm power curve are used to model wind farm outputs at Bunnythorpe and Wilton. The modelled wind farm outputs are transformed into ramp rate probability distributions based on the measured ramp rate probability distribution from Te Apiti wind farm output. The wind farm power outputs are transformed into estimated (N-1) line loading by applying the appropriate north or south flow sensitivity factors. These are the wind generation-led power flows.
- Monte Carlo analysis[5] is used to determine a probability distribution function for the composite circuit loading (wind generation and historic loadings)

The analysis is carried out for changes over one minute and changes over five minute periods.

The analysis makes the following assumptions:

- Wind generation output (wind conditions) and system load are independent.
- The nature of variability of output (and the probability distribution function) of the Wilton wind generation is similar to that of Te Apiti wind farm
- The impact of wind generation at Bunnythorpe 220 kV and north of Bunnythorpe is insignificant because the sensitivity of such generation on power flow on the Bunnythorpe-Haywards circuit 1 is less than 4%.

4.1 Bunnythorpe-Haywards circuit historic loadings

Garrad Hassan has analysed historic loadings on the Bunnythorpe-Haywards circuits. A cumulative probability distribution function for the loading of the

[5] See Appendix 2 for details.

Bunnythorpe-Haywards circuits is shown in Figure 7. Virtually all of the changes in loading over one minute are within +/- 10 MW. [6]

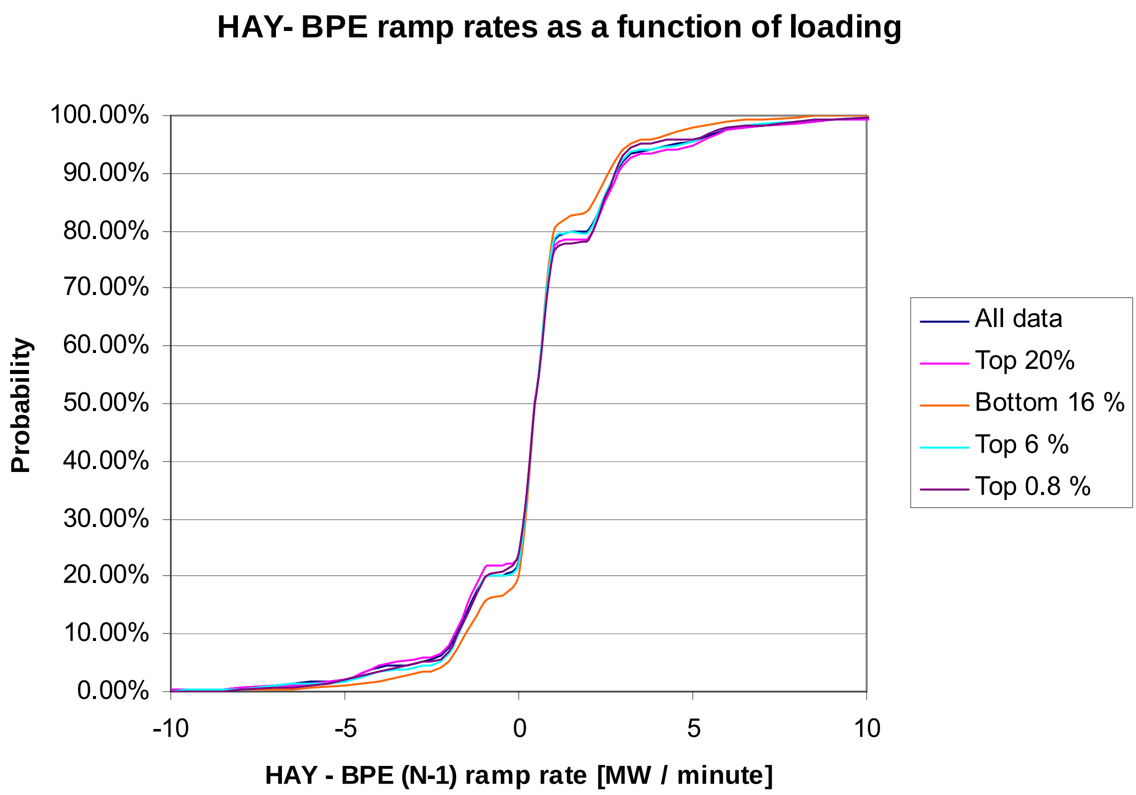

Figure 7: From Appendix 2 Figure 2: Cumulative probability distribution functions for HAY-BPE ramp rates; as function of HAY-BPE line loading.

4.2 Te Apiti Variability

Garrad Hassan analysed the historic variability of output from Te Apiti. A cumulative probability distribution function for Te Apiti is shown in Figure 8. Virtually all changes over a minute are within +/- 6 MW (around 6.6% of installed capacity).

[6] It should be noted that changes greater than 10 MW per minute will occur but infrequently.

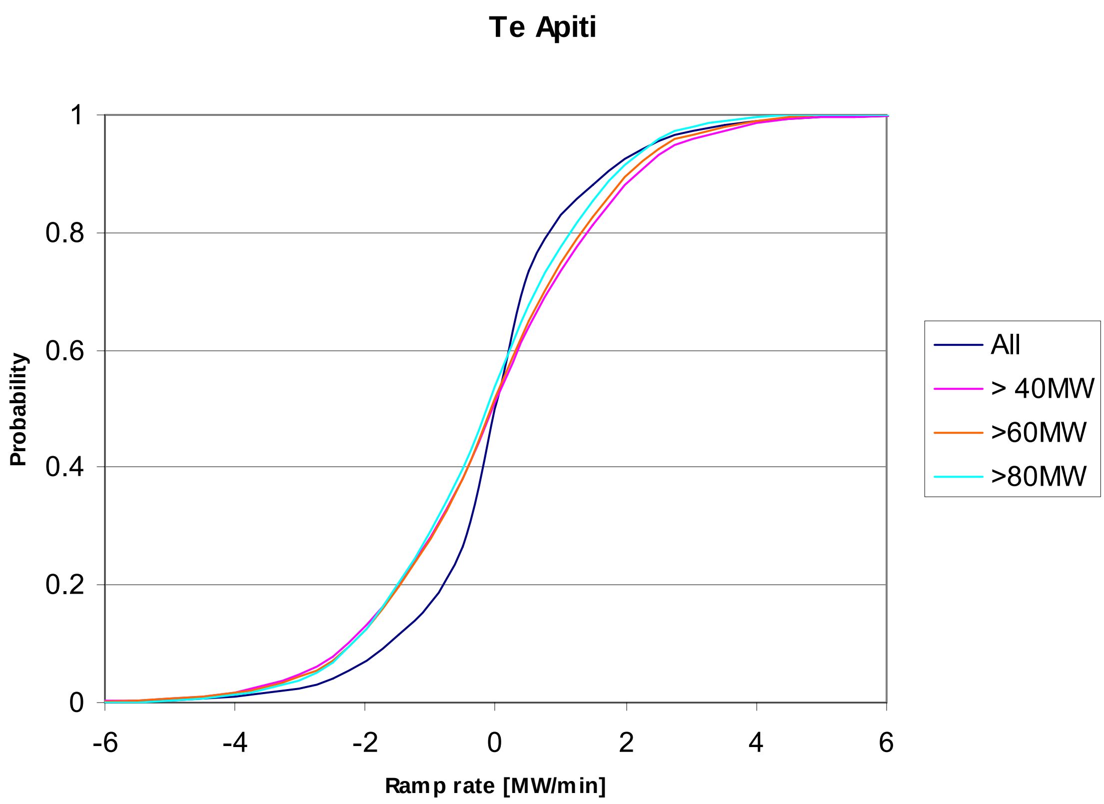

Figure 8: From Appendix 2 Figure 3: Cumulative probability distributions for Te Apiti one minute ramp rates as a function of output.

Garrad Hassan applied the calculated cumulative distribution function for Te Apiti to future wind generation as envisaged in wind generation development Scenario C to develop models to assess the effect of wind generation output variability on circuit loading.

4.3 Bunnythorpe Haywards circuit loading – wind generation development Scenario C

Garrad Hassan considered four scenarios for the development of wind generation in Wellington:

- 150 MW of installed capacity with no diversity between wind farms (“bulk”);
- 150 MW of installed capacity with diversity (“diverse”);
- 300 MW of installed capacity with no diversity; and
- 300 MW of installed capacity with diversity.

Measured wind data for the Wellington region coupled with a generic wind farm power curve is used for modelling wind farm outputs. Wind generation output changes are generated using the modelled wind farm outputs transformed

using the calculated probability distribution from Te Apiti wind farm to account for intra-wind farm diversity. Details of the modelling methodology are presented in Appendix 2.
The wind farm power outputs are transformed into estimated (N-1) line loading by applying the appropriate north or south flow sensitivity factors.

4.3.1 Sensitivity factors

Power flow in the Bunnythorpe-Haywards corridor can be in either direction depending on power system conditions. The sensitivity factors depend on the direction of power flow. For this reason, sensitivity factors have been determined for power flow in both directions.

Following the removal of Bunnythorpe-Haywards circuit 3, sensitivity factors are determined for the power flow in the remaining circuit, which is loaded close to its rating. Bunnythorpe-Haywards circuits 1 and 2 are both loaded equally and they have the same rating. So, Bunnythorpe-Haywards circuit 1 has been chosen for the analysis. The sensitivity factors are determined for a number of 220 kV bus bars. Only Bunnythorpe 220 kV, Haywards 220 kV and Wilton 220 kV and Wellington loads have sensitivity factors that are materially high enough to warrant consideration. The sensitivity factors are noted below.

HVDC north transfer

Bus/Loads	Bunnythorpe-Haywards circuit 1
Bunnythorpe 220 kV	-0.007
Haywards 220 kV	0.311
Wilton 220 kV	0.261
Wellington Load	-0.277

HVDC south transfer

Bus/Loads	Bunnythorpe-Haywards circuit 1
Bunnythorpe 220 kV	0.012
Haywards 220 kV	-0.380
Wilton 220 kV	-0.324
Wellington Load	0.346

An increase in Wellington load during high HVDC north transfer will reduce the loading on Bunnythorpe-Haywards circuits as more of the HVDC transfer is consumed in the Wellington region and does not need to be transferred north. During HVDC south transfer, an increase in Wellington load increases the amount of power that needs to be transferred on the Bunnythorpe-Haywards circuits.

Additional injection at the Bunnythorpe 220 kV bus during south transfer will marginally increase the loading on the Bunnythorpe-Haywards circuits. Additional injection at Wilton will increase the circuits' loading during north transfer.

4.3.2 Ratio of line loads

The four circuits that comprise the Bunnythorpe-Haywards corridor are generally in service except when there are forced outages or when there are planned outages for various purposes including maintenance work. For this reason, the historical circuit loading data mostly reflect conditions where all circuits have been in service. Such data can be converted to hypothetical data that reflects what the circuit loading would have been if the circuit number 3 was out of service. This conversion is made by multiplying all data by the ratio (Current in Bunnythorpe-Haywards circuit 1 with three circuits)/ (Current in Bunnythorpe-Haywards circuit 1 with all four circuits in service).[7]

These ratios have been calculated for both HVDC north and HVDC south transfer conditions and are noted below.

Ratio: I (3 circuits)/I(4 circuits) = 1.477 for HVDC north transfer
Ratio: I (3 circuits)/I(4 circuits) = 1.469 for HVDC south transfer

Note that 10 minute line load data over year 2005 and 10 second data for three months (August to October 2005) are used in the analysis.

4.3.3 Calculated Variability

Statistical techniques are used to derive one minute (N-1) Bunnythorpe-Haywards circuit 1 loading from 10-second line loading data. Wind generation-led ramp rates of Bunnythorpe-Haywards circuit 1 loading were derived from one minute ramp rate probability distributions.

The Random Walk Model[8] generated randomised ramp rates for line load changes with and without wind generation to investigate the impact of wind variability on Bunnythorpe-Haywards circuit 1. The studies covered 150 and 300 MW (both bulk and diversified) wind generation at Wilton.

[7] This assumes that the same amount of power is transferred between Bunnythorpe and Wilton but that this power is shared between three circuits rather than four. The relative impedances of the three remaining circuits will dictate how much power flows down each.
[8] The Random Walk Model is a statistical model. This is further discussed in Appendix 2.

Cumulative probability distributions are generated from the aggregate line loading by combining wind generation-led MVA variations with load-led MVA variations using Monte Carlo simulations.

Figure 9 shows five-minute line load changes with and without wind. Positive changes correspond to increases in transfer from Haywards to Bunnythorpe.

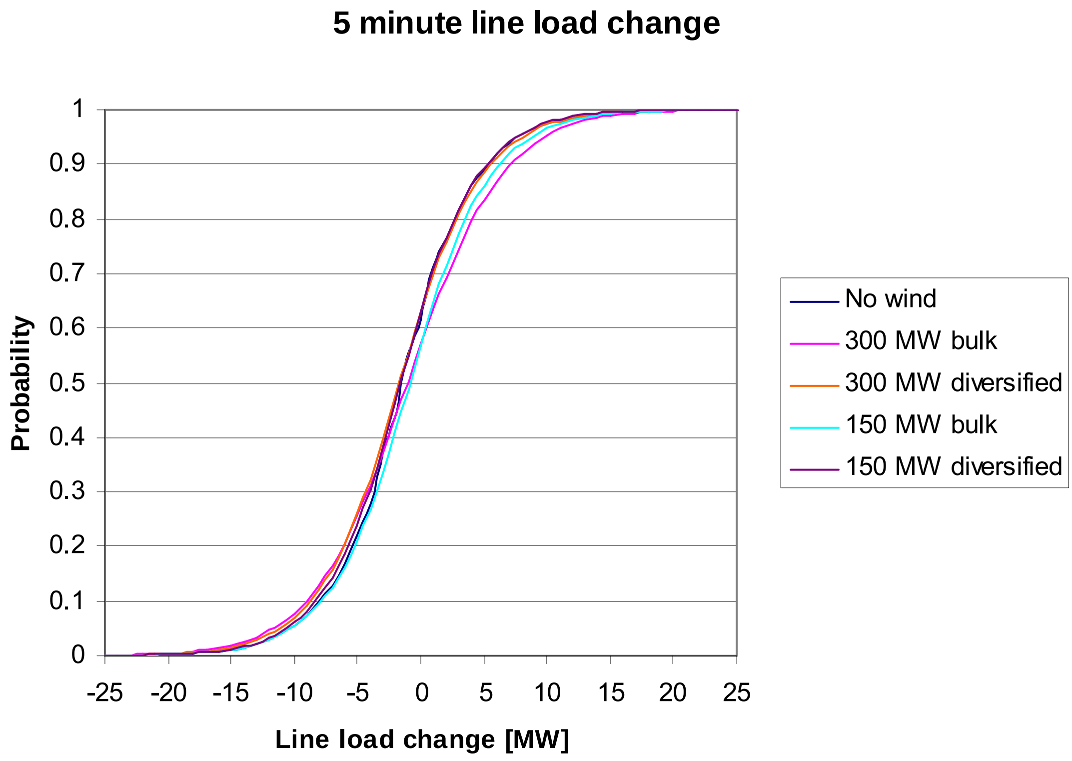

Figure 9: Cumulative Probability Functions for five-minute load change in Bunnythorpe-Haywards Circuit 1

Table 4 shows return periods for loading changes on the Bunnythorpe-Haywards circuits over five minutes.

Return Period	Probability	No wind	300 MW bulk	300 MW diversified	150 MW bulk	150 MW diversified
Once per month	0.00012	-30	-32	-30	-31	-33
Once per week	0.00050	-26	-27	-26	-26	-26
Once per day	0.00347	-18	-20	-20	-19	-19
Once per month	0.99988	26	27	25	27	25
Once per week	0.99950	21	24	22	23	21
Once per day	0.99653	16	18	16	17	16

Table 4: From Appendix 2 Table 2: HAY – BPE (N-1) loading changes over five minutes [MW]

The cumulative probability functions shown in Figure 9 show that there is no great impact on line load changes over a five minute period arising out of wind variability. Table 4 shows return periods for changes in loading over five minutes. For example, with no wind, a line loading change of 30 MW over five minutes can be expected once a month. With wind variability this increases to 33 MW over five minutes.

Table 5 shows return periods for loading changes on the Bunnythorpe-Haywards circuits over one minute.

Return Period	Probability	No wind	300 MW bulk	300 MW diversified	150 MW bulk	150 MW diversified
Once per month	0.00012	-19	-19	-19	-20	-23
Once per week	0.00050	-14	-16	-16	-15	-15
Once per day	0.00347	-11	-12	-12	-12	-12
Once per month	0.99988	16	15	16	18	14
Once per week	0.99950	12	12	12	12	11
Once per day	0.99653	8	9	9	9	8

Table 5: From Appendix Table 6: HAY – BPE (N-1) loading changes over one minute [MW]

The effect of the additional wind generation on changes on line loading over one minute periods is small. It is worth noting the loading changes for a return period of a month in Table 5. For example, the once per month loading changes for “150 MW bulk” is greater than that for “300 MW bulk”. This would seem counter-intuitive as it would be expected that 300 MW of installed wind generation capacity would produce larger variability than 150 MW of installed wind generation capacity.

The loading changes with a return period of a week and a day show a more consistent relationship. This highlights that the calculated probability distribution functions are reasonably accurate only up for return periods of less than a month. This is discussed further in Section 5.1.

Conclusions

The Bunnythorpe-Haywards corridor is not adversely affected by wind generation variability. The present analysis indicates that further analysis of the Bunnythorpe-Haywards corridor for safe operation of assets under the envisaged wind generation is not warranted.

The predicted variability of loading[9] on the Bunnythorpe-Haywards corridor is quite low for large wind farms at either end (450 MW at Bunnythorpe and 300 MW at Wilton). It is expected that similar results will occur for other

[9] For events with return periods of up to once a month.

transmission corridors such as lower South Island transfer. The analysis for a single transmission corridor requires considerable effort. There is little benefit and considerable cost for repeating the same analysis for other regions. For this reason, no further analysis will be carried out for this report.

5. Discussion

5.1 Limitations of analysis

It is important to understand the limitations of the analysis carried out in section 4. The analysis relies upon models of the variability of wind generation output. These models were derived from a limited data set which extended over three months. The models are likely to be good at predicting events with return periods of a day or a week (as far as those events are represented in the data) but will not necessarily represent less frequent events (as those events may not have occurred during the data measurement period).

The probability distribution functions should be reasonably accurate for return periods of up to a week. This is based on the rule of thumb that it is best to have at least ten times the length of data to describe the extreme of a particular return period [2].

The models also assume that the variability of future wind farm output will be similar to that presently observed at Te Apiti wind farm which is viewed to be a reasonable assumption for this study. However, the variability of wind at different locations may result in the observed variability from future wind farms being quite different. In addition the nature of wind may change with climatic conditions so that the variability of wind generation output observed at Te Apiti over a single year may be different to that observed over a longer period.

The analysis carried out in section 4 indicates that variability of wind generation output is not likely to have major effects on the loading of 220 kV circuits. This observation is based on the limited amount of information about wind generation output variability that is available. This may not hold true at some stage in the future. Furthermore, there may be asset loading issues with wind generation at specific locations especially where generation is connected to relatively low capacity transmission circuits that form parallel routes with larger capacity 220 kV routes. Such locations may require a generation runback scheme similar to that installed at Te Apiti.

It is recommended that wind generation output variability of future wind generation at different locations is monitored.

5.2 Managing the risk

The System Operator’s security checks in real time during dispatch will identify situations where changes in wind generation output could cause post contingency loadings on assets to exceed capability. These situations are logged and reviewed. A significant increase in the number of post contingency loading violations resulting from changes in wind generation output will quickly be noticed. In the absence of changes to the rules and industry arrangements, certain measures (such as those discussed below) could then be implemented to maintain asset safety.

The System Operator is currently upgrading its software applications used to manage the scheduling and dispatch of the power system (Market System Project – MSP). MSP will introduce automated design of security constraints (especially the design of constraints related to asset loading). This is likely to mitigate the impact on real-time system operation of having to fine tune constraints for dispatch scenarios as can happen with Te Apiti.

Based on the analysis carried out by Garrad Hassan, wind generation output variability seems to have no material effect on the variability of transmission circuit loading on a day to day basis. Further investigation at this stage is not warranted. However, there are a number of ways of managing the effects of wind generation output variability on asset loading should this become an issue. In the absence of changes to the EGRs and industry arrangements, the following methods are available to manage variability of loading on assets:

- *Grid reconfiguration*. The effect of wind generation variability on asset loading depends on power system configuration. For example, the removal of a circuit for maintenance will increase the sensitivity factors for the parallel circuits. Similarly, introducing operational splits in the power system will change power flows and make circuits more or less sensitive to changes in wind generation output. Selective changes in power system configuration provide one means of managing the effects of wind generation output variability on asset loading.
- *Generation runback schemes.* These schemes can be used to reduce wind generation output where a change in the output can cause circuits to exceed capability. Such a scheme is already in place at Te Apiti to manage the loading on the Bunnythorpe-Woodville circuits.
- *Asset rating*. Asset owners may choose to change the way in which steady state ratings of assets is calculated to allow for variability in asset loading. Alternatively, the System Operator could apply a margin on allowable post event asset loadings to allow for variability.
- *Automated security constraints*. The MSP will provide an automated process for managing the real time fine tuning of security constraints.

The next stage of the WGIP may consider the above methods as part of the options analysis.

The analysis carried out by Garrad Hassan for this report has emphasised the effects of small and frequent changes (e.g. the changes likely to be observed on an hourly basis). Analysis of large but infrequent changes (e.g. those that might be expected to occur once every five or 10 years) has not been carried out (although the effects can be estimated from the sensitivity factors if needed). The analysis will require much more data than is available at present.

In managing power system security, under the Policy Statement in the EGRs, the System Operator assesses the outcomes of events which may result in cascade failure against the costs and benefits of possible mitigation measures. Some events are determined to have impacts and probability of occurrence high enough that in the absence of any other controls warrant implementing policies in the scheduling and dispatch processes so as to avoid shedding demand if the event occurs. The impact and probability of occurrence of certain other events are not considered to justify the controls required to totally avoid demand shedding.

The probability of large but infrequent changes in wind generation output can not be calculated with any accuracy at this time. Therefore no assessment can be made as to whether it is economic to apply controls to mitigate the effects on asset loading for the not yet unobserved large and infrequent changes in wind generation.

It should be noted that the probability of a sudden large change in wind generation occurring at the same time as a contingent event is very low.[10] The System Operator's security checks during dispatch will identify situations where changes in wind generation output could cause post contingency loadings on assets to exceed capability.

5.3 Power system configuration

Sensitivity factors on parallel circuits are lower than those on radial circuits. For example, an increase in generation output at the end of a spur line will see a similar increase in power flow of the spur line.

The core 220 kV circuits that comprise the backbone of the power system form an interconnected network with many elements in parallel. Variations in generation injection or demand offtake alter power flow across interconnected parallel core 220 kV circuits. As a result the sensitivity of power flow on these circuits to variation in injection from wind generation is low. Low sensitivity factors contribute to low power flow variations across a number of circuits rather than a concentrated variation in a particular circuit. For instance a 1 MW change in injection many only result in a 0·33 MW change in the flow on three parallel 220 kV circuits.

The 110 kV network can in some places be operated in parallel with the 220 kV network. The lower rating of the parallel 110 kV circuits places limitations on

[10] Most transmission lines in New Zealand will experience around one or two faults a year. Protection systems will detect a fault and open circuit breakers to remove the faulted circuit and then attempt (after a second) to reconnect the circuit. The majority of attempts to automatically reconnect the circuit are successful as most faults as transient in nature. In the event that the circuit can not be restored immediately, generation will be re-dispatched with five minutes to return asset loadings to secure levels.

parallel power transfer as the 110 kV circuits will generally exceed their capability before the parallel 220 kV circuits do. This can already be observed at Te Apiti with high south power transfer from Bunnythorpe to Haywards.

Operational system splits in the 110 kV network can be put in place to allow greater transfer on the 220 kV circuits. Such operational splits may result in other parties connected to the 110 kV network receiving a lower level of connection security. Resolution of the competing factors to minimise the limitation on wind injection and maintain offtake connection security can require some form augmentation of the 110 kV network.

The effect of variability in the output of wind generation on circuit loading will be more pronounced where the wind generation is connected to a radial 110 kV network. In some cases, generation runback schemes may be required to maintain circuit loading within safe limits. Such schemes are applied in a number of locations on the New Zealand power system. A good example of such a control scheme is the existing Te Apiti runback scheme. This scheme monitors the current in each of the Bunnythorpe-Woodville circuits 1 and 2 and automatically reduces the Te Apiti wind generation if any one of these circuits overloads. It is likely that similar control schemes could be used in situations where wind farms are connected to peripheral parts of the grid.

6. Conclusions and recommendations

Wind generation output variability of the size for wind generation development Scenario C should not materially affect the loading of transmission circuits in the core transmission grid for levels of changes experienced on a daily or weekly basis.

There are limitations in the models used for the analysis which reflect the limited operational experience of wind generation on the New Zealand power system. The probability of large but infrequent changes in wind generation output can not be calculated with any accuracy at this time. It is recommended that appropriate data is recorded from now on and the situation is reviewed on an ongoing basis.

In the absence of changes to the EGRs or industry arrangements, a range of controls exist to minimise the impact on wind generation of limitations within other parts of the transmission grid.

The loading of connection assets for specific wind farms has not been considered in this report. This can be managed by agreement between the grid owner and wind farm owner.

7. References

[1] Wind Generation Scenarios – see http://www.electricitycommission.govt.nz/pdfs/opdev/comqual/windgen/wind-scenarios-Jun06.pdf.
Wind Generation Investigation Project Website – see http://www.electricitycommission.govt.nz/opdev/comqual/windgen/wgip

[2] Garrad Hassan Report "Wind Power variability and forecast accuracy in New Zealand", 2 March 2007.

Appendix 1: Sensitivity factors

Bunnythorpe-Haywards corridor

The Bunnythorpe-Haywards transmission corridor comprises four circuits.
The Bunnythorpe-Haywards circuits 1 and 2 have a lower rating than the remaining circuits. Consequently, the worst conditions occur when one of the higher rated circuits is removed from service for some reason.

The sensitivity factors for injection at selected 220 kV buses and to the Wellington load are shown for HVDC north and HVDC south transfer.

HVDC north transfer[11]

Bus/Loads	Bunnythorpe-Haywards circuit 1 or 2
Bunnythorpe 220 kV	-0.007
Haywards 220 kV	0.311
Wilton 220 kV	0.261
Wellington Load	-0.277

HVDC south transfer[12]

Bus/Loads	Bunnythorpe-Haywards circuit 1 or 2
Bunnythorpe 220 kV	0.012
Haywards 220 kV	-0.380
Wilton 220 kV	-0.324
Wellington Load	0.346

Bunnythorpe-Tokaanu Corridor

Power flow in the Bunnythorpe-Tokaanu corridor can be in either direction depending on power system conditions. The sensitivity factors depend on the direction of power flow. For this reason, sensitivity factors have been determined for power flow in both directions.

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[11] An increase in Wellington load during high HVDC north transfer will reduce the loading on Bunnythorpe-Haywards circuits as more of the HVDC transfer is consumed in the Wellington region and does not need to be transferred north. During HVDC south transfer, an increase in Wellington load increases the amount of power that needs to be transferred on the Bunnythorpe-Haywards circuits.

[12] Additional injection at the Bunnythorpe 220 kV bus during south transfer will marginally increase the loading on the Bunnythorpe-Haywards circuits. Additional injection at Wilton will increase the circuits' loading during north transfer.

Sensitivity factors are determined for the power flow in the Bunnythorpe-Tokaanu circuit 2, which is loaded close to its rating.

The sensitivity factors are noted below.

Bus/Loads	Bunnythorpe-Tokaanu circuit 2
BPE 220	0.311
HAY 220	0.297
WIL 220	0.298
TKU 220	-0.163
Wellington Load	-0.303

HVDC north transfer

The sensitivity factor for MW changes at Redclyffe is just 2%. The proposed wind generation at both Waikato and Auckland is insignificant in comparison to existing connected generation and consequently, such wind generation is not considered in the sensitivity analysis.

Bus/Loads	Bunnythorpe-Tokaanu circuit 2
BPE 220	-0.337
HAY 220	-0.354
WIL 220	-0.353
TKU 220	0.157
Wellington Load	0.355

HVDC south transfer

The sensitivity factor for MW changes at Redclyffe is about 2% for south transfer conditions as well.

Tokaanu-Whakamaru Corridor

Sensitivity factors are determined for the power flow in the Tokaanu-Whakamaru circuit 2 with circuit 1 removed from service.

The sensitivity factors are noted below.

Bus/Loads	Tokaanu-Whakamaru circuit 2
BPE 220	0.354
HAY 220	0.347
WIL 220	0.348
TKU 220	0.694
Wellington Load	-0.352

HVDC north transfer

The sensitivity factor for MW changes at Redclyffe is around 2.5%. The proposed wind generation at both Waikato and Auckland is insignificant in comparison to existing connected generation and consequently, such wind generation is not considered in the sensitivity analysis.

Invercargill-Roxburgh Corridor

The sensitivities of power flow in the Invercargill-Roxburgh circuit 1 to injection at Invercargill and Timaru wind generation are:

Bus/Loads	Invercargill-Roxburgh circuit 1
INV 220 kV	-0.520
TIM 110 kV	-0.001

Clyde-Roxburgh Corridor

The sensitivities of power flow in the Clyde-Roxburgh circuit 1 to injection at Invercargill 2 and Timaru wind generation are:

Bus/Loads	Clyde-Roxburgh circuit 1
INV 220 kV	-0.715
TIM 110 kV	-0.016

Livingstone-Waitaki Circuit

The sensitivities of power flow in the Livingstone-Waitaki circuit 1 to injection at Invercargill and Timaru wind generation are:

Bus/Loads	Livingstone-Waitaki circuit 1
INV 220 kV	-0.436
TIM 110 kV	-0.105

Naseby- Roxburgh Circuit

The sensitivities of power flow in the Naseby-Roxburgh circuit 1 to injection at Invercargill and Timaru wind generation are:

Bus/Loads	Naseby-Roxburgh circuit 1
INV 220 kV	-0.416
TIM 110 kV	-0.021

Appendix 2: Garrad Hassan Report

Our Ref: 2479/PL/01

29 November 2006

Haywards Bunnythorpe Line Loading

As part of the third stage in the Electricity Commission's Wind Generation Investigation Project (WGIP); Transpower are modeling the effects of the wind generation scenarios on critical individual transmission lines in the New Zealand electricity grid. This letter investigates the effects of developing generation in the Wellington region on the Haywards-Bunnythorpe line.

In the four generation scenarios there are two options for the development of wind generation in Wellington; either 150 MW or 300 MW. Measured wind data coupled with a generic wind farm power curve are used for modeling wind farm outputs. Ramp rates are generated using the modeled wind farm outputs transformed using the measured ramp rate probability distribution from Te Apiti wind farm to account for intra-wind farm diversity. Two methodologies for generating aggregate regional wind farm power outputs and ramp rates are used, one assuming no diversity amongst wind farms, the second assuming nominal 100 MW wind farms. Details of the modeling methodology are presented in Garrad Hassan's report to the Electricity Commission, reference 2479PR02C.

There are two operational impacts on the line that are of interest here. Firstly, the effect of increased wind generation on the line loading, that is what effect will the increase in wind generation have on the on the HAY-BPE N-1 line loading probability distribution function.

Secondly, what effect will the increase in wind generation have on the control of the transmission circuit under critical loading. Since Transpower operates a 5 minute dispatch it is possible that within a 5 minute period the line loading can change from an acceptable loading to a critical loading before re-dispatch is made to bring the line back into a controlled safe state.

HAY-BPE Line Loading

Transpower have supplied the 10 minute HAY-BPE steady state line loading, estimated N-1 line loading, and sensitivity factors for north and south flow for various buses. It is assumed that all wind generation in the Wellington region will be connected through Wilton. The sensitivity of the HAY-BPE line to generation north of the Wellington region is less than 4 % of that for the Wellington region and hence the increase in wind generation in other regions is considered to be negligible.

The electricity commission have supplied 10 minute wind data from three sites within the Wellington region all of which have good data coverage and quality. These wind data time series have been transformed to power output time series assuming a generic wind farm power curve. The cumulative 300 MW and 150 MW power outputs for diverse and non-diverse scenarios are generated from these time-series directly. Hence correlation between the sites is maintained.

The wind farm power outputs are added to the estimated N-1 line loading by applying the appropriate north or south flow sensitivity factor, and assuming the wind generation and line loading are independent. Probability distributions are generated from the aggregate line loading and presented in Figure 1, and loadings for specific probabilities presented in Table 1.

It is observed that there is a “dead band” in the line loading about 0 MVA. However this is due to the power factor in the line not being equal to 1, and the use of MVA in the modeling, with the sign denoting the direction of the real power (MW) flow.

The increase in wind power increases the northward line loading by approximately 60 MVA for the 300 MW scenario, and 30 MVA for the 150 MW scenario for the bulk of the probability distribution. There is little difference in diversified compared with non-diversified modeling approaches. The southward flow is decreased by similar amounts, respectively.

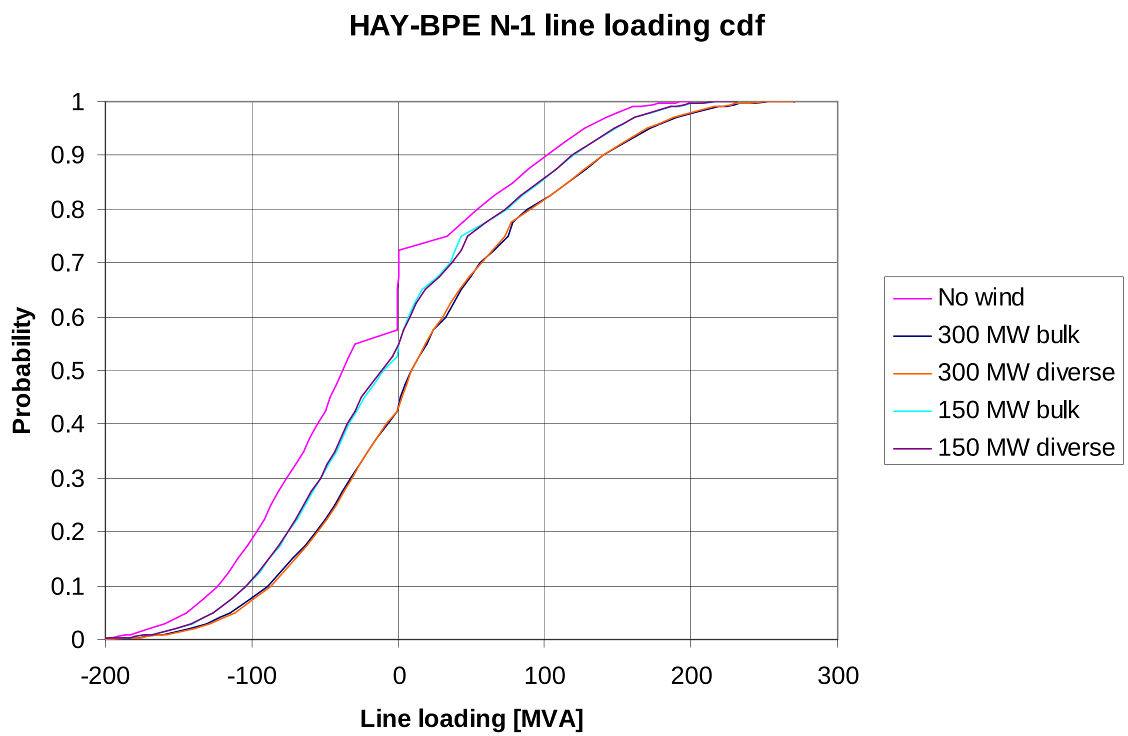

Figure 1: Probability distribution functions for the HAY-BPE line loadings for wind generation scenarios.

Return period	Probability	300 MW bulk	300 MW diverse	150 MW bulk	150 MW diverse	No wind
Once per month	0.0002	-227.9	-225.0	-229.5	-228.2	-242.3
Once per week	0.0010	-201.3	-198.3	-210.6	-212.6	-232.4
Once per day	0.0069	-167.0	-165.2	-175.5	-174.8	-187.6
Once per month	0.9998	269.3	264.9	231.2	228.8	196.9
Once per week	0.9990	253.2	250.2	217.2	216.1	192.6
Once per day	0.9931	225.4	221.7	192.7	191.0	167.8

Table 1: HAY-BPE line loadings for wind generation scenarios (MVA).

HAY-BPE Critical line loading (5 minute variability)

In the operation of the national grid Transpower uses a 5 minute dispatch. Thus while at the start of a 5 minute period Transpower may have set the loading on a transmission circuit at a sub-critical level, within the 5 minute period the loading on that transmission circuit may change sufficiently to allow the transmission circuit to progress into a critical loading range. However, it is unknown what effect the increase in wind generation will have on the probability that line loadings will become critical within a 5 minute period. To solve this problem the ramp rates as generated within the Stage 2 WGIP (2479PR02C) report for the Wellington region and ramp rates from the Transpower data are applied to a random walk model.

Transpower have supplied 10 second line loading data, from this the 1 minute N-1 line loading has been obtained. Using the line loading data a piece-wise linear probability distribution for the ramp rates is obtained, with nodes carefully selected to preserve as much information as practicable. The line loading ramp rates have an autocorrelation R-squared of 0.01, thus consecutive ramps can be considered independent. The line ramp rates as a function of line loading were also considered, to ensure that the ramp rates at a critical line loading do not have different statistical properties to the ramp rates at times of usual line loading. Figure 2 shows that the ramp rates have little dependence on the line loading and thus can be considered independent.

Using the 1 minute ramp rates probability distributions, as defined in the WGIP Report Stage 2, for Te Apiti the ramp rates on the HAY-BPE circuit can be modeled assuming the 300 MW and 150 MW scenarios and the, Transpower supplied, sensitivity factors for both bulk and diverse generation. As for the line loadings a check on autocorrelation was made, and the R-squared value is 0.02, thus the consecutive ramp rates can be considered to be independent. And, the ramp rates as a function of generation were investigated and presented in Figure 3. This shows that the ramp rates do have some dependence on the output of the wind farm, particularly if the times where generation is low are included. As a pragmatic decision the ramp rate probability distribution for times when generation is greater than 40 MW is used, as it is desirable to model the effect of active wind generation and will produce a conservative outcome.

The random walk model generates a randomized ramp rate for the line loading change, and under five scenarios (no wind, 300 MW bulk wind, 300 MW diverse wind, 150 MW bulk wind, and 150 MW diverse wind) adds a randomized wind generation ramp rate. The walk progresses through five steps where at each step the wind and load ramps are added to the previous accumulated wind and load ramps.

To illustrate how the random walk aggregates the line loads Figure 4 shows the cumulative probability distributions for line loads at each of the 1 minute steps out to 5 minutes.

The line loading changes after 5 minutes are presented in Figure 5, it can be seen that there is very little change in the line loadings except if 300 MW of undiversified wind is installed, and even then the changes are minor. Tables 2 through 6 present the line loading changes for 1, 2, 3, 4, and 5 minute steps.

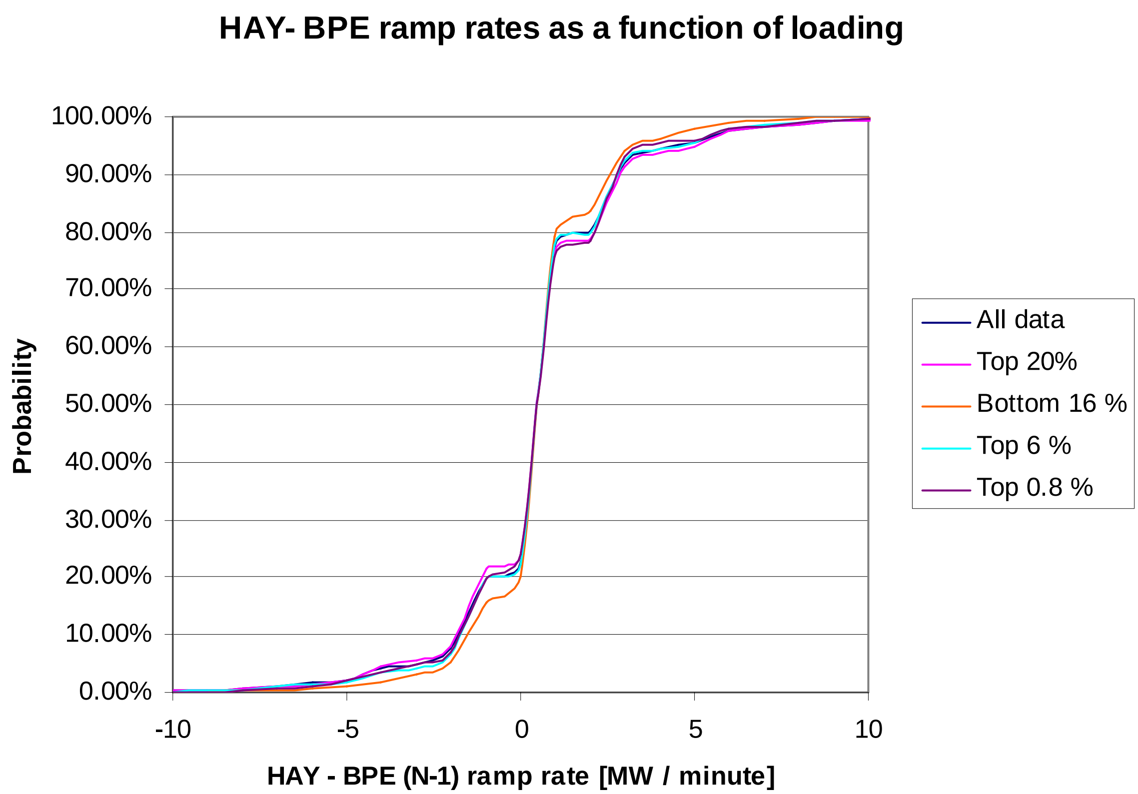

Figure 2: Probability distribution functions for HAY-BPE ramp rates; as function of HAY-BPE line loading.

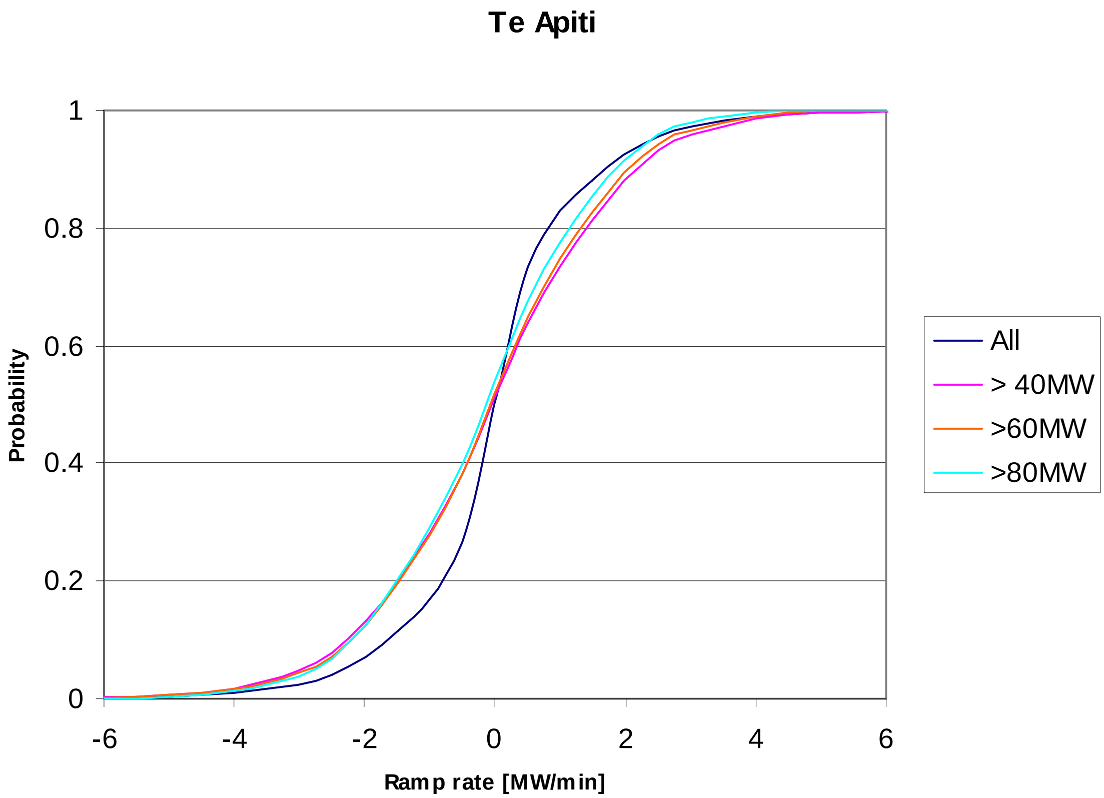

Figure 3: Cumulative probability distributions for Te Aptit 1 minute ramp rates as a function of output.

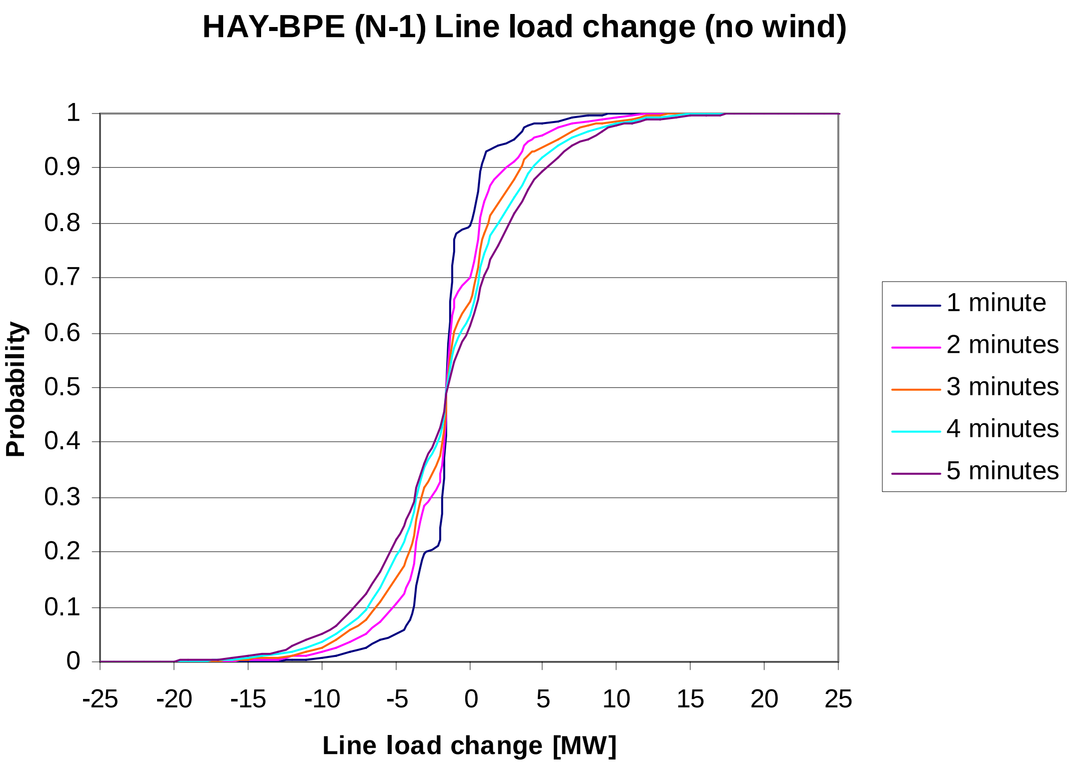

Figure 4: HAY – BPE (N-1) Modeled line load changes.

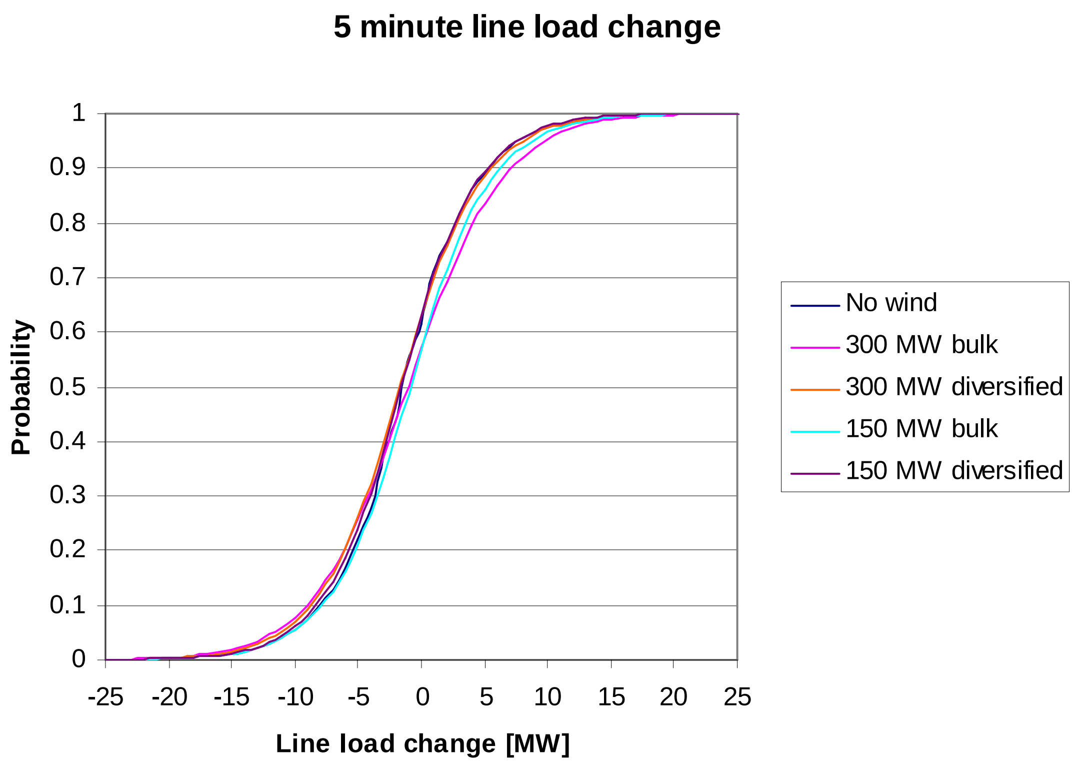

Figure 5: HAY – BPE (N-1) loading changes over 5 minutes [MW]

Return Period	Probability	No wind	300 MW bulk	300 MW diversified	150 MW bulk	150 MW diversified
Once per month	0.00012	-30	-32	-30	-31	-33
Once per day	0.00050	-26	-27	-26	-26	-26
Once per week	0.00347	-18	-20	-20	-19	-19
Once per month	0.99988	26	27	25	27	25
Once per week	0.99950	21	24	22	23	21
Once per day	0.99653	16	18	16	17	16

Table 2: HAY – BPE (N-1) loading changes over 5 minutes [MW]

Return Period	Probability	No wind	300 MW bulk	300 MW diversified	150 MW bulk	150 MW diversified
Once per month	0.00012	-31	-30	-29	-30	-34
Once per day	0.00050	-24	-25	-25	-25	-23
Once per week	0.00347	-17	-19	-18	-17	-17
Once per month	0.99988	24	25	24	26	22
Once per week	0.99950	19	22	21	21	19
Once per day	0.99653	14	17	15	16	14

Table 3: HAY – BPE (N-1) loading changes over 4 minutes [MW]

Return Period	Probability	No wind	300 MW bulk	300 MW diversified	150 MW bulk	150 MW diversified
Once per month	0.00012	-27	-28	-26	-26	-30
Once per day	0.00050	-22	-22	-22	-21	-23
Once per week	0.00347	-15	-17	-16	-15	-16
Once per month	0.99988	22	24	22	25	21
Once per week	0.99950	18	19	18	19	17
Once per day	0.99653	13	14	13	14	13

Table 4: HAY – BPE (N-1) loading changes over 3 minutes [MW]

Return Period	Probability	No wind	300 MW bulk	300 MW diversified	150 MW bulk	150 MW diversified
Once per month	0.00012	-26	-27	-25	-25	-28
Once per day	0.00050	-19	-19	-19	-19	-19
Once per week	0.00347	-14	-15	-14	-14	-14
Once per month	0.99988	21	21	20	21	18
Once per week	0.99950	15	17	16	16	14
Once per day	0.99653	11	12	11	11	11

Table 5: HAY – BPE (N-1) loading changes over 2 minutes [MW]

Return Period	Probability	No wind	300 MW bulk	300 MW diversified	150 MW bulk	150 MW diversified
Once per month	0.00012	-19	-19	-19	-20	-23
Once per day	0.00050	-14	-16	-16	-15	-15
Once per week	0.00347	-11	-12	-12	-12	-12
Once per month	0.99988	16	15	16	18	14
Once per week	0.99950	12	12	12	12	11
Once per day	0.99653	8	9	9	9	8

Table 6: HAY – BPE (N-1) loading changes over 1 minute [MW]