Wind – Regional Wind Farm Correlations

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Revision History

Issue	Issue date	Summary
A	21 Nov 05	Draft in progress
B	23 Nov 05	Draft issue
C	25 Nov 05	Draft issue with minor editing changes
D	28 Nov 05	Correction to wording in Section 2.2
E	16 Dec 05	Updated with separate North & South Island event analysis

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EXECUTIVE SUMMARY

The Electricity Commission (EC) is conducting strategic and tactical projects to assess the likely impact of wind generation development on the New Zealand power system. Garrad Hassan (GH) has been commissioned by the EC to investigate the correlation of wind speed and theoretical wind power outputs of the primary wind farm regions of New Zealand. The reason for this is to assess the degree of diversity of wind farm power output from the different regions.

Wind data from existing and potential wind farm sites has been provided to GH by the EC. Data from a total of 21 sites was analysed, covering 10 prospective wind farm regions, at 10 minute resolution. The correlation relationships (r-squared values) were explored for different averaging periods; 10 minutes, 30 minutes, 6 hours and 24 hours. A theoretical wind farm power curve was applied to the wind data to create a theoretical wind farm power output time series at each of the sites. The correlation relationships were again explored for the different averaging periods. Finally the theoretical rate of change of power output was calculated, and the correlation relationships explored at the 10 minute level.

GH has checked the plausibility of the wind data, and eliminated suspect data from the analysis. However the results of the analysis rely on the integrity of the wind data supplied to GH, and in particular the time and data stamps applied to the wind data. All times have been assumed to be NZST, except for the Wairarapa 1 data where a change to NZDT was detected in the data, which was corrected back to NZST by GH.

From the analysis of the correlation relationships the following conclusions can be drawn;

- The correlation in wind speed between the sites generally increases with increasing averaging period.
- The correlation in theoretical wind farm output between the sites is generally lower than the corresponding correlation in wind speed.
- The correlation in the theoretical rate of change in wind farm output between the sites is low, even for sites within the same region.
- At the 10 minute level r-squared values for wind farm outputs in other regions were generally below 0.5, with the exception of the Northland-Auckland-Waikato regions, where the correlation between some sites in neighbouring regions could exceed this level.

A 1100 MW wind generation scenario was developed, with each region being modelled using an assumed 100 MW wind farm capacity, an exception is made for the Manuwatu where it is assumed two 150 MW wind farms are located. The Wairarapa region was excluded from this analysis, due to the short data record at this site. A total of 225 days of data were available for the scenario. The following observations are made from the scenario;

- A generation duration curve was developed showing that for the modelled scenario, generation was more than 100 MW 95% of the time and less than 1000 MW 99% of the time.
- The theoretical rates of change of the scenario were modelled. If the rates of change at the sites are independent of each other, it could be expected that the overall scenario theoretical rate of change (i.e. MW/minute) would be approximately 2.4 times the theoretical rate of change of one 150 MW wind farm in the Manawatu. The theoretical model broadly supports this.

1. METHODOLOGY

1.1. Wind Data

Wind data were supplied to GH by the EC. The wind data were subject to checking by GH, and invalid wind data that were detected were excluded from the analysis. However the results of the analysis rely on the integrity of the wind data supplied to GH, and in particular the time and date stamps, which GH was unable to independently verify. To protect site confidentiality, sites are named according to the region that they are located.

To limit the amount of data to be processed, a "window" covering the period 1 July 2004 to 31 August 2005 was selected for analysis. This data period was chosen to remain within the data processing capabilities of Microsoft Excel, while maximising the overlapping data periods from the sites used in the analysis. The analysis period covers 427 days. The amount of data used in the analysis from each of the sites is shown in the following table.

Site	Valid days	Coverage [%]
Northland 1	426	99.77%
Northland 2	364	85.18%
Northland 3	386	90.39%
Auckland 1	422	98.77%
Waikato 1	427	99.95%
Waikato 2	354	82.79%
Waikato 3	257	60.27%
Hawkes Bay 1	324	75.95%
Hawkes Bay 2	98	22.85%
Manawatu 1	332	77.84%
Manawatu 2	361	84.47%
Manawatu 3	335	78.40%
Wairarapa 1	88	20.61%
Wellington 1	427	99.91%
Wellington 2	395	92.58%
Wellington 3	365	85.43%
Marlborough 1	423	98.96%
Central Otago 1	364	85.32%
Southland 1	348	81.47%
Southland 2	365	85.48%
Southland 3	244	57.23%

Table 1.1 – Wind data used in the analysis

When the data series were averaged, the average was considered valid if at least 50% of data making up that average were covered. For example, a 30 minute average was considered valid if at least 2, 10 minute data periods were used to calculate the average.

1.2. Wind Farm performance

A theoretical wind farm power curve was created using a Monte Carlo type calculation of wind farm performance, based on 50 Vestas V80 2 MW wind turbines. The following parameters were used for the generation of the wind farm power curve;

- Wake losses; normally distributed with a mean of 5% and a standard deviation of 2%.

- Topographic effect (wind speed at the turbine sites relative to wind speed at the measurement site); normally distributed with a mean of 100% and a standard deviation of 5%.

The resulting wind farm power curve is shown in the figure below;

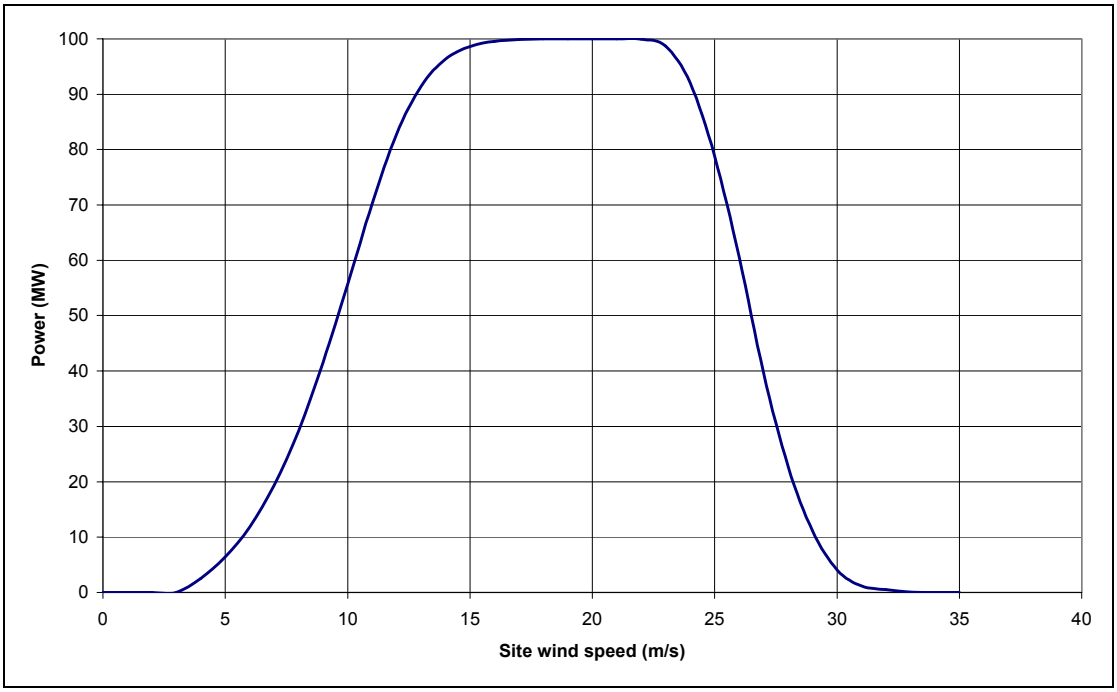


Figure 1.1 – Wind farm power curve used in the analysis

The wind farm power curve was applied to the 10 minute wind speed data to create theoretical wind farm power output time series at each of the sites with 10 minute resolution. Calculation of longer averaging periods was based on averaging of this 10 minute wind farm power output time series.

1.3. Wind Farm output variation

The rate of change of output (ramp rate) for each wind farm was calculated from the difference of successive theoretical 10 minute wind farm power output at each site. It should be noted that this may differ significantly from rates of change of outputs at real wind farms due to the fact that the output is modelled from the 10 minute average of wind measurements carried out at a single point. This has two notable effects;

- The outputs of real wind farms will vary in real time. Fast variations may tend to get "smoothed" through the use of 10 minute averages.
- Modelling from a single point makes the implicit assumption that the wind speeds experienced by the wind turbines are coherent. In a real wind farm this is not the case due to random fluctuations in the wind (turbulence) and the fact that it takes time for wind speed changes to propagate through a wind farm.

The above effects counterbalance each other to a certain extent. However, even if the analysis is not accurate in an absolute sense, it should be indicative as to how variations in one region are related to variations in others.

1.4. Wind energy scenario

A scenario was developed in consultation with the EC. For all the regions except the Manawatu and Wairarapa, a 100 MW wind farm was assumed to be located at the site with the most complete data record. In the Manawatu, 150 MW wind farms were assumed at each of the two sites with the longest data records in the region. The Wairarapa region was excluded from the scenario as there is only a short data period available for this region. The scenario has a total theoretical capacity of 1100 MW. The following sites were used in the analysis;

Site	Wind Farm Size (MW)
Northland 1	100
Auckland 1	100
Waikato 1	100
Hawkes Bay 1	100
Manawatu 2	150
Manawatu 3	150
Wellington 1	100
Wellington 2	100
Marlborough 1	100
Central Otago 1	100
Southland 2	100

Table 1.2 – The wind energy scenario modelled

With the wind data available there was an equivalent of 225 days of data where data from all the sites in the scenario are available concurrently. The wind data was used to generate a theoretical wind generation output time series for the scenario, and from this a theoretical rate of change of output of the scenario was also inferred. The events leading to the 10 largest rates of change were investigated further, and a generation duration curve was developed using the power output data.

2. RESULTS OF THE ANALYSIS

2.1. Correlation of wind speed between sites

Using concurrent data the R-squared correlation coefficients have been calculated between each of the sets of sites. Averaging periods of 10 minutes, 30 minutes, 6 hours, and 24 hours have been used. The results are presented in the following tables.

GH is suspicious of the integrity Manawatu 1 data as all three Manawatu sites are known to be in the Manawatu Gorge area, and the correlation of Manawatu 1 is significantly lower than the other Manawatu sites. The Manawatu 1 data supplied also had a significant number of gaps.

The Southland 3 site has a suspiciously low correlation to any other site in the data set.

	N. 1	N. 2	N. 3	A. 1	Wko. 1	Wko. 2	Wko. 3	H. B. 1	H. B. 2	M. 1	M. 2	M.3	Wpa. 1	Wel. 1	Wel. 2	Wel. 3	Mlb. 1	O. 1	S. 1	S. 2	S. 3
Northland 1																					
Northland 2	0.45																				
Northland 3	0.82	0.39																			
Auckland 1	0.69	0.32	0.66																		
Waikato 1	0.37	0.14	0.36	0.50																	
Waikato 2	0.50	0.26	0.50	0.63	0.52																
Waikato 3	0.38	0.22	0.35	0.51	0.58	0.63															
Hawkes Bay 1	0.06	0.00	0.08	0.11	0.18	0.16	0.09														
Hawkes Bay 2	0.02	0.04	0.03	0.01	0.05	0.06	0.07	0.16													
Manawatu 1	0.02	0.02	0.02	0.03	0.10	0.02	0.01	0.28	0.10												
Manawatu 2	0.00	0.02	0.00	0.01	0.04	0.03	0.01	0.47	0.18	0.38											
Manawatu 3	0.02	0.01	0.03	0.04	0.12	0.06	0.03	0.51	0.15	0.59	0.79										
Wairarapa 1	0.00	0.01	0.00	0.00	0.00	0.00	*	0.02	*	0.02	0.09	0.10									
Wellington 1	0.01	0.00	0.01	0.01	0.02	0.01	0.00	0.12	0.26	0.10	0.23	0.21	0.16								
Wellington 2	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.14	0.31	0.11	0.25	0.26	0.28	0.52							
Wellington 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.27	0.06	0.13	0.13	0.16	0.76	0.47						
Marlborough 1	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.06	0.10	0.08	0.08	0.10	0.09	0.34	0.25	0.37					
Central Otago 1	0.05	0.01	0.05	0.08	0.10	0.10	0.06	0.17	0.04	0.06	0.13	0.14	0.02	0.07	0.07	0.04	0.06				
Southland 1	0.02	0.00	0.02	0.03	0.05	0.03	0.02	0.10	0.02	0.02	0.08	0.09	0.01	0.02	0.05	0.01	0.01	0.27			
Southland 2	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.01	0.05	0.05	0.14	0.02	0.05	0.02	0.02	0.22	0.17		
Southland 3	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	*	0.00	0.01	0.02	0.02	0.00	0.01	0.00	0.00	0.04	0.02	0.11	

Note * - No concurrent data for these sites

Table 2.1 – Correlation [r^2] for 10 minute average wind speed data

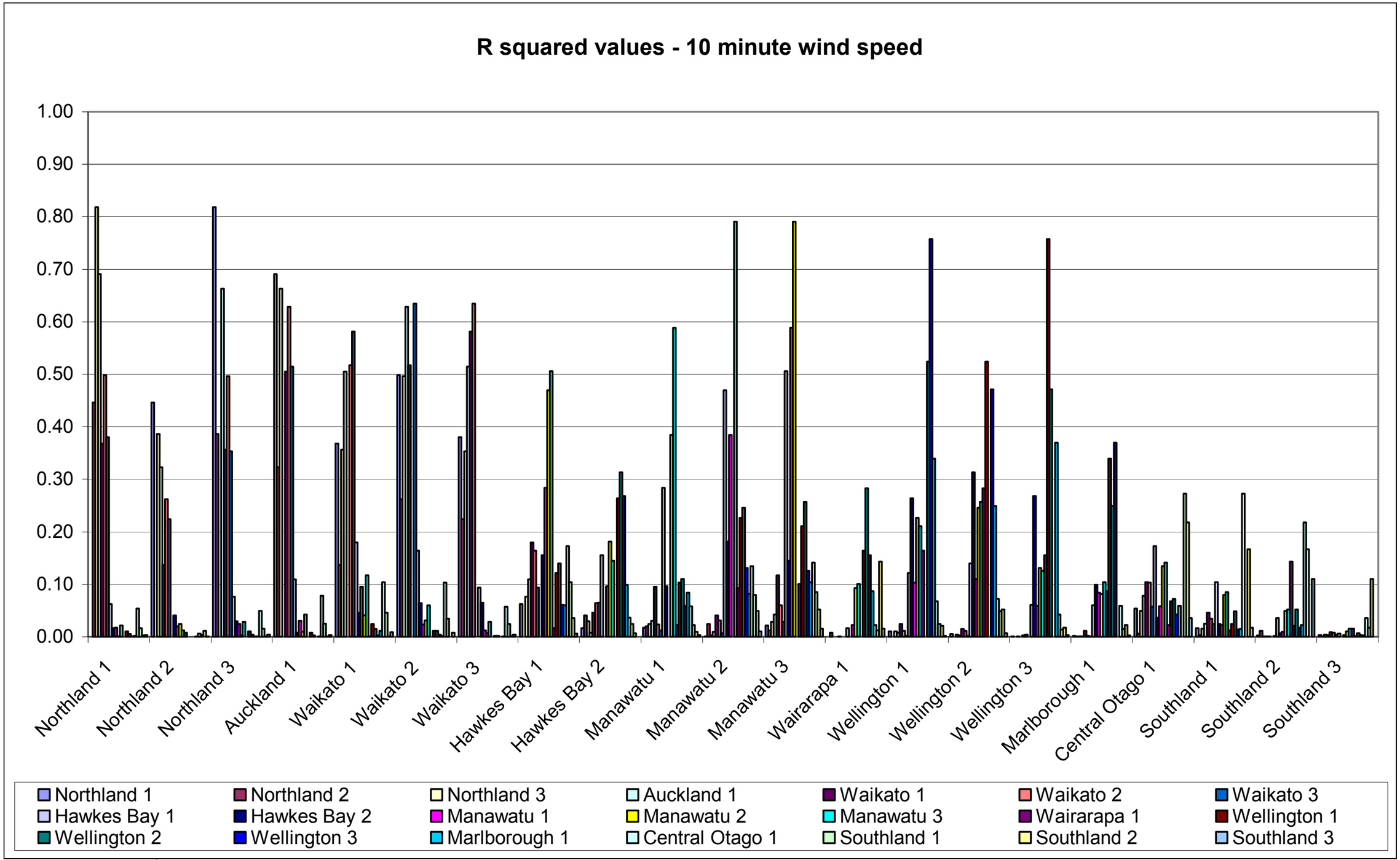


Figure 2.1 – Correlation [r^2] for 10 minute average wind speed data

	N. 1	N. 2	N. 3	A. 1	Wko. 1	Wko. 2	Wko. 3	H. B. 1	H. B. 2	M. 1	M. 2	M.3	Wpa. 1	Wel. 1	Wel. 2	Wel. 3	Mlb. 1	O. 1	S. 1	S. 2	S. 3
Northland 1																					
Northland 2	0.46																				
Northland 3	0.85	0.40																			
Auckland 1	0.72	0.34	0.69																		
Waikato 1	0.38	0.14	0.37	0.53																	
Waikato 2	0.52	0.27	0.51	0.65	0.54																
Waikato 3	0.40	0.23	0.37	0.54	0.61	0.66															
Hawkes Bay 1	0.06	0.00	0.08	0.11	0.19	0.17	0.10														
Hawkes Bay 2	0.02	0.04	0.03	0.01	0.05	0.07	0.07	0.16													
Manawatu 1	0.02	0.02	0.03	0.03	0.10	0.02	0.01	0.29	0.10												
Manawatu 2	0.00	0.03	0.00	0.01	0.04	0.03	0.01	0.49	0.19	0.40											
Manawatu 3	0.02	0.01	0.03	0.04	0.12	0.06	0.03	0.52	0.15	0.60	0.81										
Wairarapa 1	0.00	0.01	0.00	0.00	0.00	0.00	*	0.02	*	0.02	0.10	0.10									
Wellington 1	0.01	0.00	0.01	0.01	0.03	0.01	0.00	0.13	0.27	0.11	0.23	0.22	0.17								
Wellington 2	0.01	0.00	0.00	0.00	0.02	0.01	0.00	0.14	0.33	0.11	0.25	0.26	0.29	0.54							
Wellington 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.28	0.06	0.14	0.13	0.16	0.78	0.49						
Marlborough 1	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.06	0.10	0.09	0.09	0.11	0.09	0.35	0.26	0.38					
Central Otago 1	0.06	0.01	0.05	0.08	0.11	0.11	0.06	0.18	0.04	0.06	0.14	0.14	0.02	0.07	0.07	0.04	0.06				
Southland 1	0.02	0.00	0.02	0.03	0.05	0.04	0.03	0.11	0.03	0.02	0.08	0.09	0.01	0.03	0.05	0.01	0.02	0.28			
Southland 2	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.01	0.05	0.05	0.15	0.02	0.05	0.02	0.02	0.22	0.17		
Southland 3	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	*	0.00	0.01	0.02	0.02	0.00	0.01	0.00	0.00	0.04	0.02	0.11	

Note * - No concurrent data for these sites

Table 2.2 – Correlation [r^2] for 30 minute average wind speed data

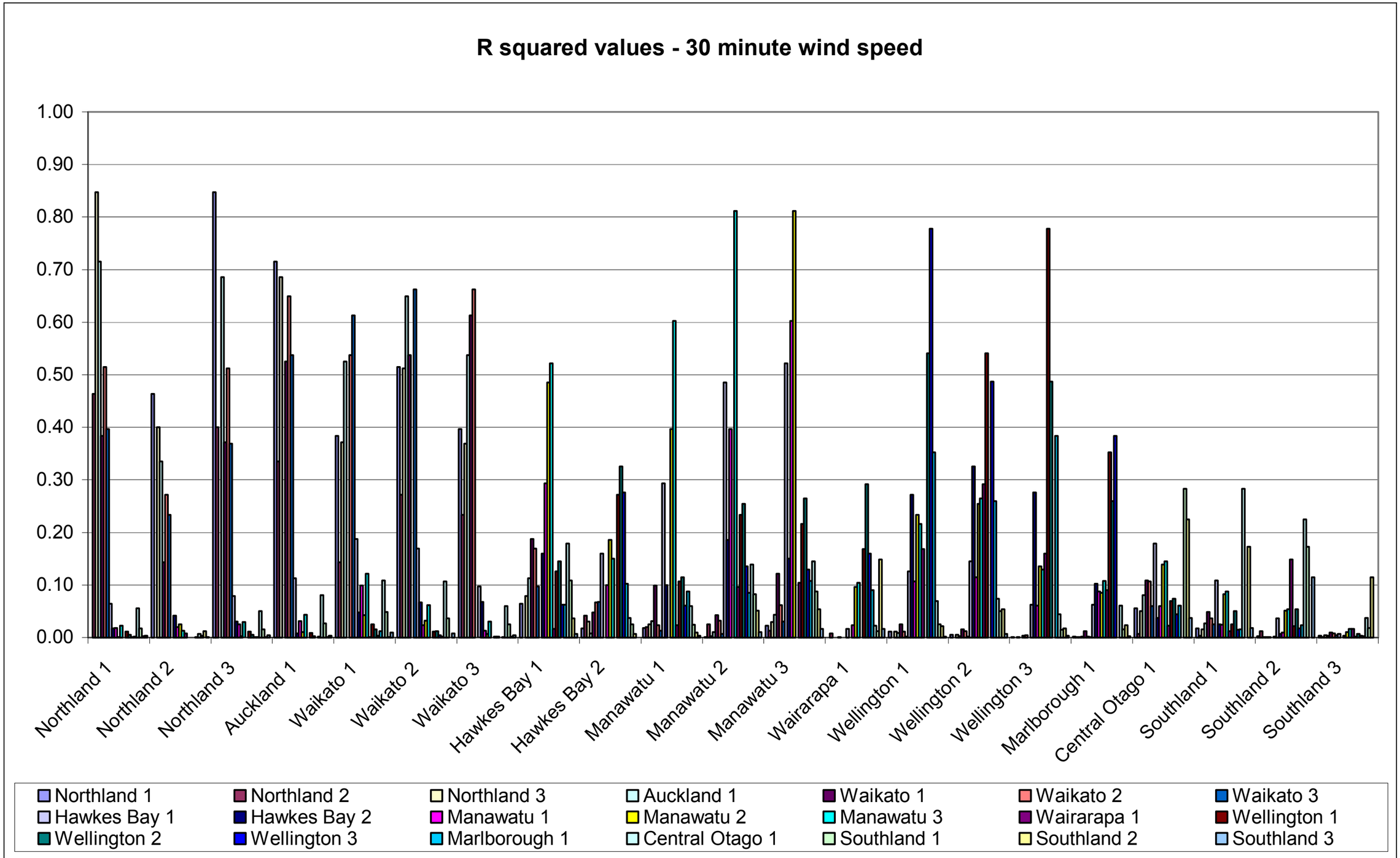


Figure 2.2 – Correlation [r^2] for 30 minute average wind speed data

	N. 1	N. 2	N. 3	A. 1	Wko. 1	Wko. 2	Wko. 3	H. B. 1	H. B. 2	M. 1	M. 2	M.3	Wpa. 1	Wel. 1	Wel. 2	Wel. 3	Mlb. 1	O. 1	S. 1	S. 2	S. 3
Northland 1																					
Northland 2	0.54																				
Northland 3	0.93	0.47																			
Auckland 1	0.82	0.40	0.78																		
Waikato 1	0.48	0.19	0.46	0.64																	
Waikato 2	0.61	0.33	0.60	0.75	0.66																
Waikato 3	0.49	0.30	0.45	0.64	0.75	0.78															
Hawkes Bay 1	0.08	0.00	0.10	0.14	0.24	0.21	0.13														
Hawkes Bay 2	0.02	0.05	0.04	0.01	0.06	0.08	0.08	0.19													
Manawatu 1	0.02	0.02	0.03	0.04	0.12	0.03	0.02	0.38	0.13												
Manawatu 2	0.00	0.03	0.00	0.01	0.06	0.04	0.01	0.59	0.22	0.47											
Manawatu 3	0.03	0.02	0.04	0.05	0.15	0.08	0.04	0.63	0.18	0.65	0.89										
Wairarapa 1	0.00	0.01	0.00	0.00	0.00	0.00	*	0.03	*	0.03	0.13	0.13									
Wellington 1	0.01	0.00	0.01	0.01	0.03	0.01	0.00	0.16	0.33	0.13	0.29	0.26	0.22								
Wellington 2	0.01	0.00	0.01	0.00	0.02	0.02	0.00	0.18	0.41	0.15	0.31	0.32	0.37	0.63							
Wellington 3	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.08	0.34	0.08	0.17	0.16	0.20	0.85	0.57						
Marlborough 1	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.08	0.14	0.12	0.12	0.14	0.14	0.46	0.34	0.50					
Central Otago 1	0.07	0.01	0.06	0.10	0.14	0.13	0.08	0.22	0.05	0.07	0.18	0.18	0.03	0.09	0.09	0.05	0.08				
Southland 1	0.02	0.00	0.02	0.03	0.06	0.05	0.03	0.14	0.03	0.03	0.10	0.11	0.02	0.03	0.06	0.02	0.02	0.36			
Southland 2	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.05	0.01	0.01	0.07	0.07	0.20	0.03	0.07	0.02	0.03	0.28	0.22		
Southland 3	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.01	*	0.01	0.02	0.02	0.02	0.00	0.01	0.01	0.00	0.05	0.02	0.16	

Note * - No concurrent data for these sites

Table 2.3 – Correlation [r^2] for 6 hour average wind speed data

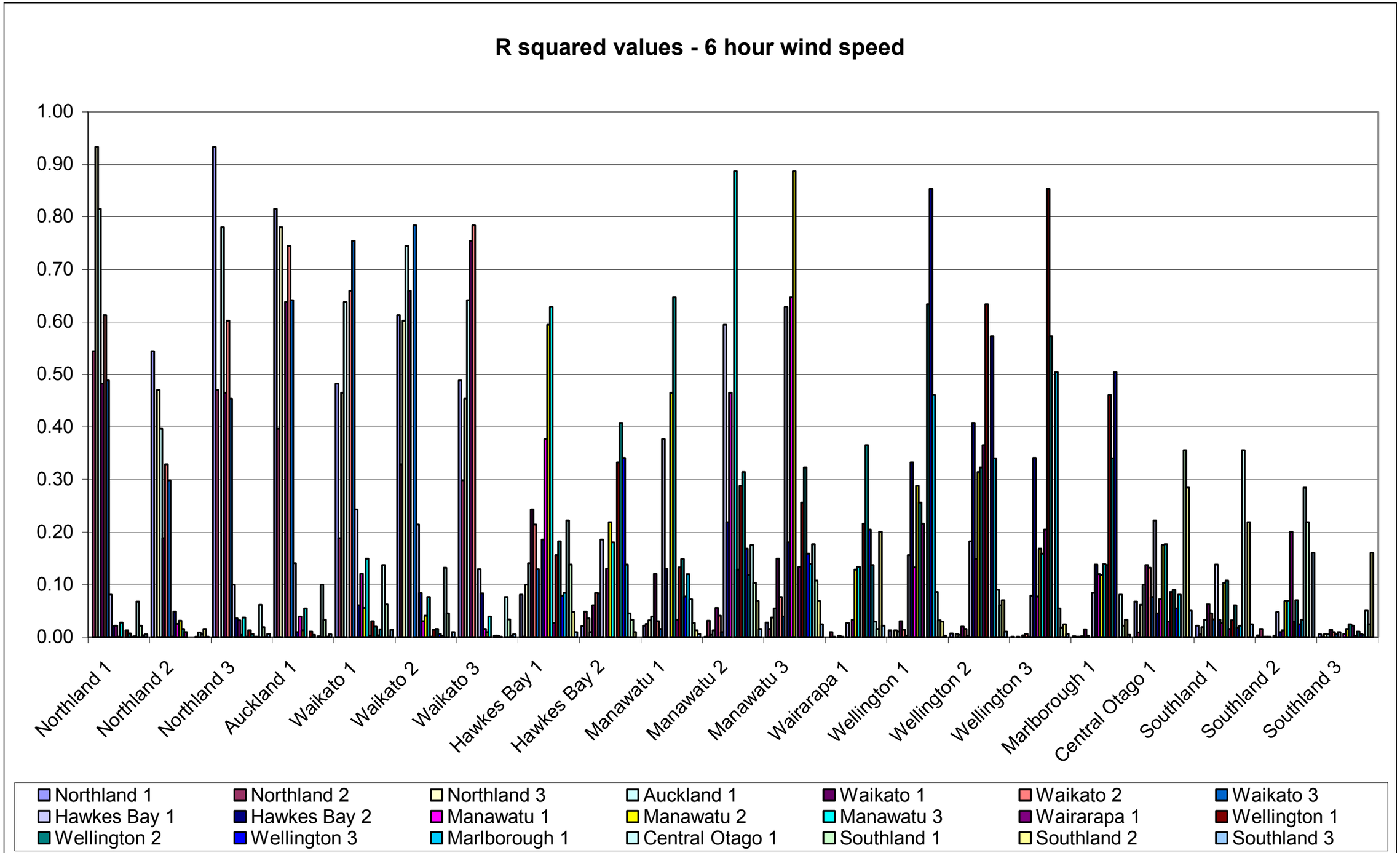


Figure 2.3 – Correlation [r^2] for 6 hour average wind speed data

	N. 1	N. 2	N. 3	A. 1	Wko. 1	Wko. 2	Wko. 3	H. B. 1	H. B. 2	M. 1	M. 2	M.3	Wpa. 1	Wel. 1	Wel. 2	Wel. 3	Mlb. 1	O. 1	S. 1	S. 2	S. 3
Northland 1																					
Northland 2	0.63																				
Northland 3	0.96	0.56																			
Auckland 1	0.88	0.49	0.85																		
Waikato 1	0.65	0.28	0.63	0.79																	
Waikato 2	0.73	0.42	0.72	0.83	0.80																
Waikato 3	0.64	0.42	0.61	0.78	0.85	0.89															
Hawkes Bay 1	0.12	0.01	0.15	0.20	0.35	0.30	0.18														
Hawkes Bay 2	0.02	0.06	0.03	0.01	0.08	0.10	0.09	0.20													
Manawatu 1	0.03	0.03	0.05	0.06	0.13	0.04	0.00	0.45	0.15												
Manawatu 2	0.01	0.03	0.01	0.03	0.11	0.07	0.02	0.71	0.23	0.57											
Manawatu 3	0.05	0.01	0.07	0.09	0.23	0.12	0.06	0.72	0.17	0.69	0.94										
Wairarapa 1	0.02	0.00	0.02	0.02	0.02	0.02	*	0.06	*	0.11	0.22	0.26									
Wellington 1	0.01	0.00	0.01	0.01	0.04	0.02	0.00	0.23	0.46	0.15	0.36	0.31	0.46								
Wellington 2	0.01	0.00	0.01	0.01	0.03	0.02	0.00	0.26	0.54	0.20	0.41	0.40	0.59	0.69							
Wellington 3	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.11	0.49	0.07	0.20	0.17	0.40	0.88	0.60						
Marlborough 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.22	0.13	0.19	0.18	0.36	0.59	0.45	0.65					
Central Otago 1	0.09	0.02	0.08	0.14	0.20	0.19	0.11	0.34	0.06	0.09	0.26	0.24	0.07	0.10	0.11	0.06	0.09				
Southland 1	0.04	0.01	0.03	0.05	0.09	0.07	0.05	0.21	0.04	0.03	0.15	0.15	0.03	0.04	0.08	0.02	0.03	0.46			
Southland 2	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.08	0.01	0.03	0.12	0.13	0.28	0.06	0.11	0.04	0.07	0.35	0.27		
Southland 3	0.01	0.00	0.01	0.01	0.03	0.02	0.00	0.03	*	0.02	0.05	0.06	0.06	0.01	0.02	0.02	0.02	0.14	0.06	0.36	

Note * - No concurrent data for these sites

Table 2.4 – Correlation [r^2] for 24 hour average wind speed data

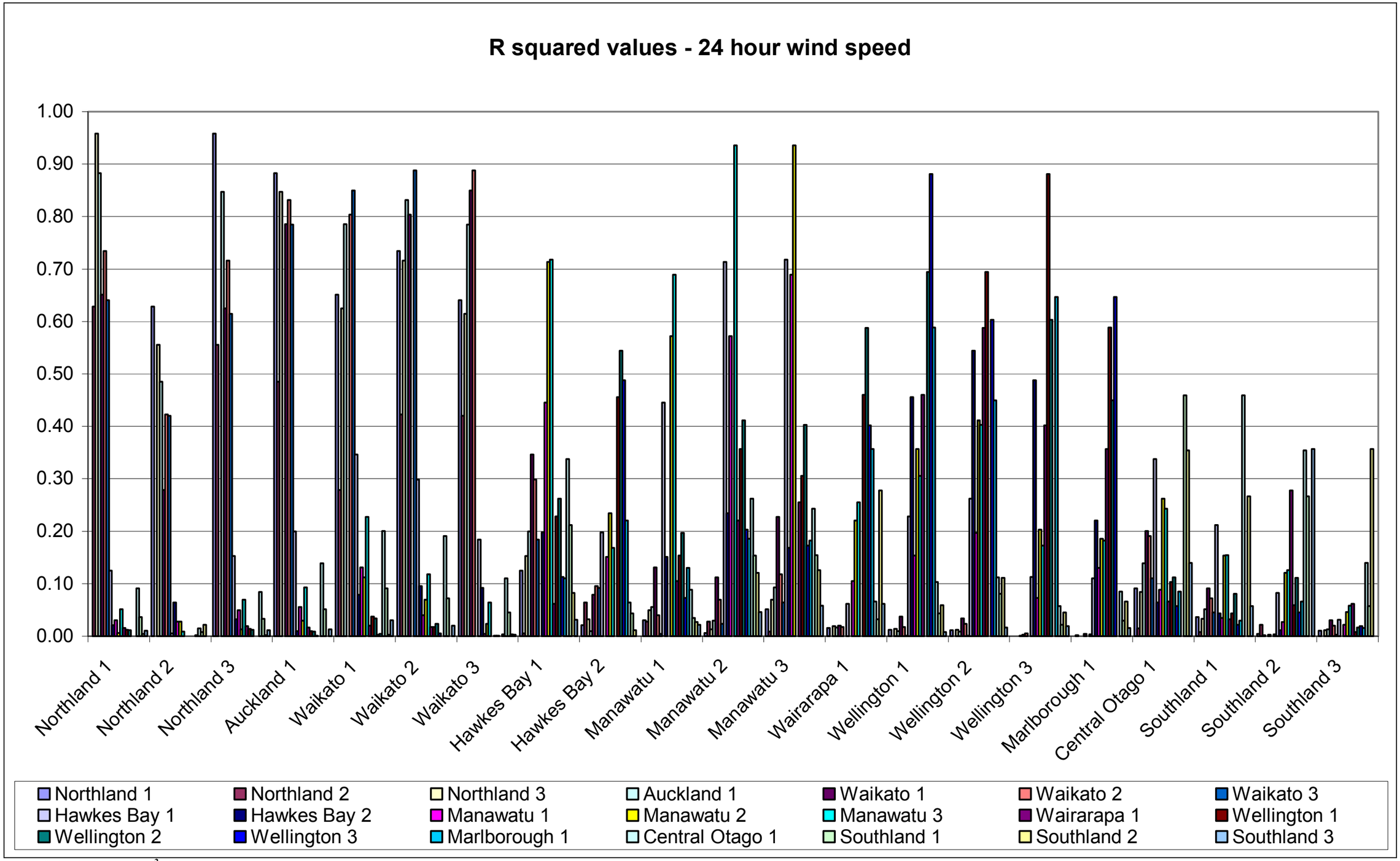


Figure 2.4 – Correlation [r^2] for 24 hour average wind speed data

2.2. Correlation of wind farm outputs

Using the wind farm power curve as stated in Section 1.2, the R-squared correlation coefficients of concurrent wind farm outputs were calculated. Averaging periods of 10 minutes, 30 minutes, 6 hours, and 24 hours have been used. The results are presented in the following tables.

	N. 1	N. 2	N. 3	A. 1	Wko. 1	Wko. 2	Wko. 3	H. B. 1	H. B. 2	M. 1	M. 2	M.3	Wpa. 1	Wel. 1	Wel. 2	Wel. 3	Mlb. 1	O. 1	S. 1	S. 2	S. 3
Northland 1																					
Northland 2	0.41																				
Northland 3	0.69	0.33																			
Auckland 1	0.58	0.25	0.61																		
Waikato 1	0.25	0.09	0.27	0.39																	
Waikato 2	0.36	0.20	0.40	0.52	0.39																
Waikato 3	0.26	0.16	0.26	0.41	0.45	0.52															
Hawkes Bay 1	0.05	0.00	0.05	0.07	0.09	0.11	0.06														
Hawkes Bay 2	0.00	0.03	0.01	0.00	0.03	0.06	0.05	0.11													
Manawatu 1	0.01	0.02	0.01	0.02	0.05	0.01	0.01	0.16	0.08												
Manawatu 2	0.00	0.02	0.00	0.01	0.03	0.03	0.00	0.44	0.16	0.27											
Manawatu 3	0.02	0.01	0.03	0.04	0.10	0.05	0.02	0.45	0.12	0.42	0.77										
Wairarapa 1	0.00	0.01	0.00	0.00	0.00	0.00	*	0.01	*	0.00	0.05	0.06									
Wellington 1	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.12	0.26	0.08	0.24	0.21	0.13								
Wellington 2	0.01	0.00	0.00	0.00	0.01	0.02	0.00	0.15	0.30	0.08	0.26	0.27	0.22	0.50							
Wellington 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.25	0.05	0.13	0.12	0.12	0.71	0.42						
Marlborough 1	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.05	0.09	0.07	0.08	0.09	0.06	0.31	0.22	0.33					
Central Otago 1	0.05	0.00	0.03	0.05	0.05	0.07	0.03	0.15	0.02	0.03	0.13	0.12	0.02	0.07	0.07	0.04	0.06				
Southland 1	0.02	0.00	0.01	0.02	0.03	0.02	0.01	0.10	0.01	0.01	0.07	0.08	0.01	0.02	0.04	0.01	0.01	0.25			
Southland 2	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.04	0.04	0.12	0.01	0.03	0.01	0.01	0.15	0.15		
Southland 3	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.01	*	0.00	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.03	0.02	0.11	

Note * - No concurrent data for these sites

Table 2.5 – Correlation [r^2] for 10 minute average power output

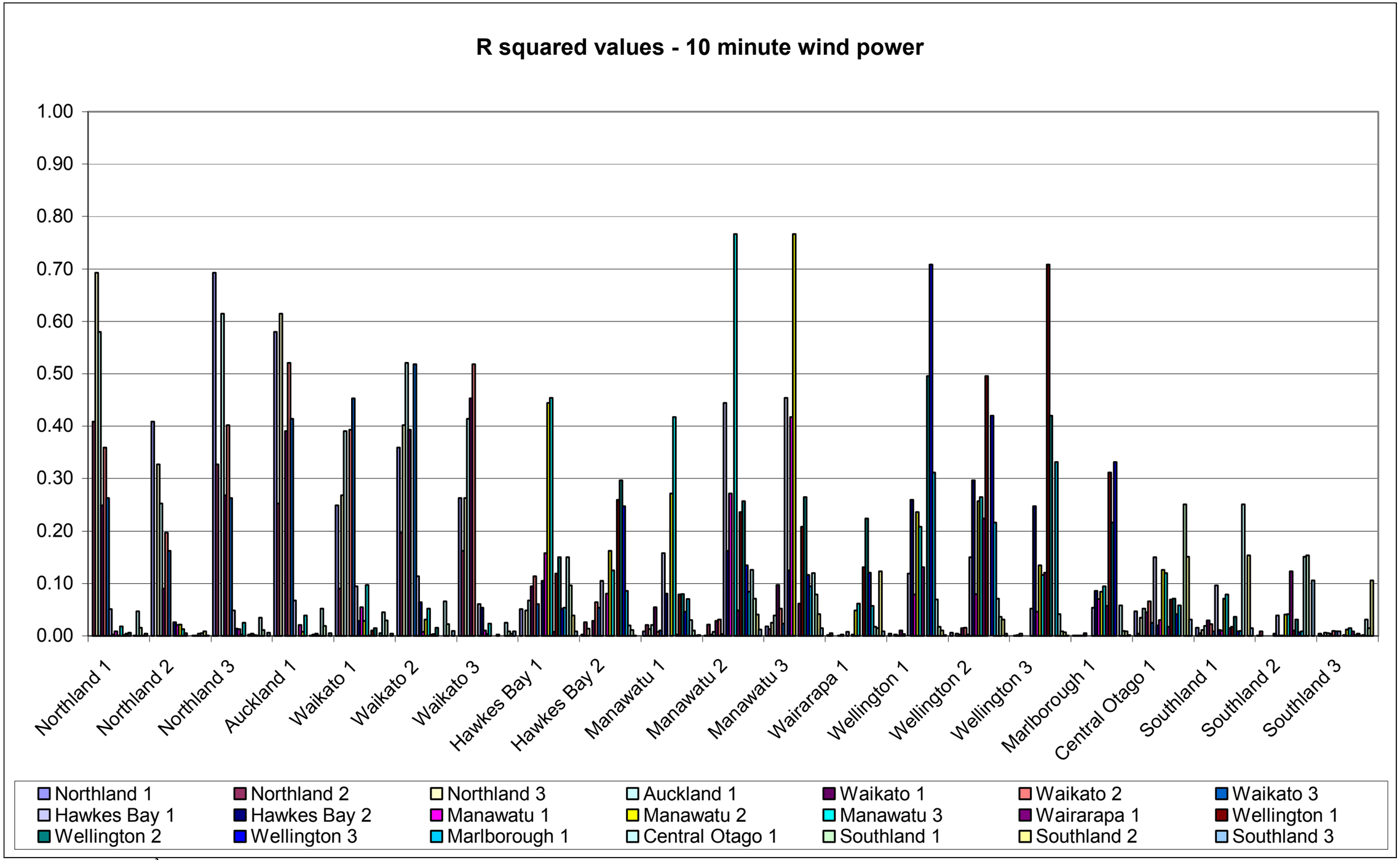


Figure 2.5 – Correlation [r^2] for 10 minute average wind speed data

	N. 1	N. 2	N. 3	A. 1	Wko. 1	Wko. 2	Wko. 3	H. B. 1	H. B. 2	M. 1	M. 2	M.3	Wpa. 1	Wel. 1	Wel. 2	Wel. 3	Mlb. 1	O. 1	S. 1	S. 2	S. 3
Northland 1																					
Northland 2	0.43																				
Northland 3	0.72	0.34																			
Auckland 1	0.60	0.26	0.64																		
Waikato 1	0.26	0.10	0.28	0.41																	
Waikato 2	0.37	0.21	0.42	0.54	0.41																
Waikato 3	0.28	0.17	0.28	0.44	0.49	0.55															
Hawkes Bay 1	0.05	0.00	0.05	0.07	0.10	0.12	0.06														
Hawkes Bay 2	0.00	0.03	0.01	0.00	0.03	0.07	0.06	0.11													
Manawatu 1	0.01	0.02	0.01	0.02	0.06	0.01	0.01	0.17	0.08												
Manawatu 2	0.00	0.02	0.00	0.01	0.03	0.03	0.00	0.46	0.17	0.28											
Manawatu 3	0.02	0.01	0.03	0.04	0.10	0.05	0.02	0.47	0.13	0.43	0.79										
Wairarapa 1	0.00	0.01	0.00	0.00	0.00	0.00	*	0.01	*	0.00	0.05	0.06									
Wellington 1	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.12	0.27	0.08	0.24	0.21	0.14								
Wellington 2	0.01	0.00	0.00	0.00	0.02	0.02	0.00	0.16	0.31	0.08	0.27	0.28	0.23	0.51							
Wellington 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.26	0.05	0.14	0.12	0.12	0.73	0.44						
Marlborough 1	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.06	0.09	0.07	0.09	0.10	0.06	0.33	0.23	0.35					
Central Otago 1	0.05	0.00	0.04	0.05	0.05	0.07	0.03	0.16	0.02	0.03	0.13	0.12	0.02	0.07	0.07	0.04	0.06				
Southland 1	0.02	0.01	0.01	0.02	0.03	0.02	0.01	0.10	0.01	0.01	0.07	0.08	0.02	0.02	0.04	0.01	0.01	0.26			
Southland 2	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.04	0.04	0.13	0.01	0.03	0.01	0.01	0.16	0.16		
Southland 3	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.01	*	0.00	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.03	0.02	0.11	

Note * - No concurrent data for these sites

Table 2.6 – Correlation [r^2] for 30 minute average power output

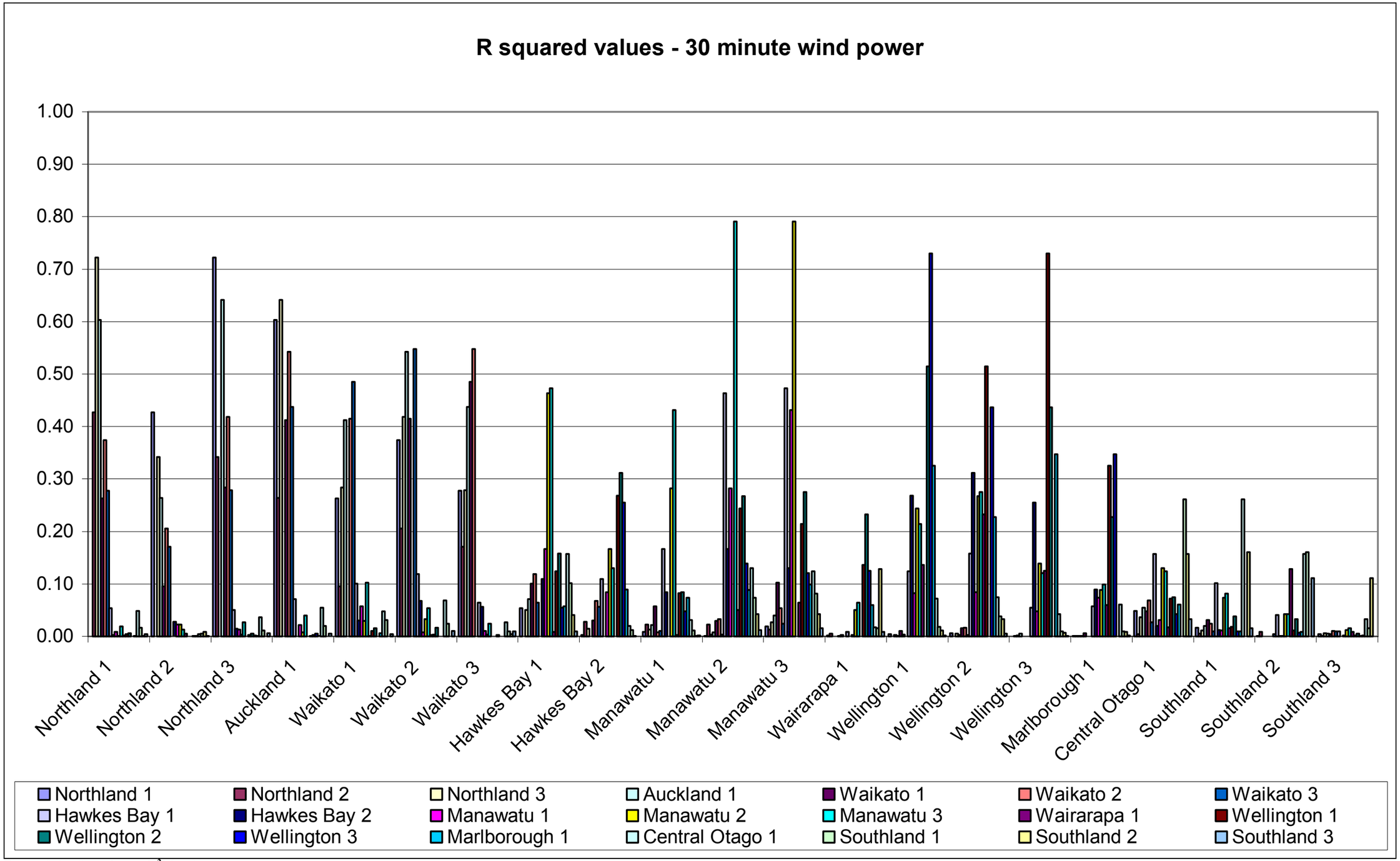


Figure 2.6 – Correlation [r^2] for 30 minute average power output

	N. 1	N. 2	N. 3	A. 1	Wko. 1	Wko. 2	Wko. 3	H. B. 1	H. B. 2	M. 1	M. 2	M.3	Wpa. 1	Wel. 1	Wel. 2	Wel. 3	Mlb. 1	O. 1	S. 1	S. 2	S. 3
Northland 1																					
Northland 2	0.51																				
Northland 3	0.82	0.42																			
Auckland 1	0.70	0.32	0.75																		
Waikato 1	0.35	0.13	0.38	0.54																	
Waikato 2	0.46	0.26	0.51	0.65	0.55																
Waikato 3	0.35	0.22	0.36	0.55	0.64	0.69															
Hawkes Bay 1	0.07	0.00	0.07	0.10	0.15	0.16	0.09														
Hawkes Bay 2	0.00	0.03	0.02	0.00	0.04	0.09	0.07	0.13													
Manawatu 1	0.01	0.03	0.02	0.03	0.08	0.01	0.01	0.23	0.11												
Manawatu 2	0.00	0.03	0.00	0.01	0.04	0.04	0.01	0.58	0.20	0.35											
Manawatu 3	0.02	0.02	0.03	0.05	0.14	0.07	0.03	0.59	0.16	0.48	0.88										
Wairarapa 1	0.00	0.01	0.00	0.00	0.00	0.00	*	0.01	*	0.01	0.07	0.09									
Wellington 1	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.16	0.33	0.11	0.30	0.26	0.18								
Wellington 2	0.01	0.00	0.01	0.00	0.02	0.02	0.00	0.21	0.39	0.11	0.33	0.34	0.31	0.61							
Wellington 3	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.07	0.32	0.06	0.17	0.15	0.18	0.81	0.52						
Marlborough 1	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.08	0.13	0.11	0.12	0.13	0.10	0.43	0.31	0.47					
Central Otago 1	0.06	0.01	0.05	0.07	0.06	0.09	0.03	0.21	0.02	0.04	0.17	0.15	0.02	0.09	0.09	0.05	0.08				
Southland 1	0.02	0.01	0.01	0.03	0.04	0.03	0.01	0.14	0.02	0.01	0.09	0.10	0.02	0.02	0.05	0.01	0.01	0.33			
Southland 2	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.06	0.00	0.00	0.06	0.06	0.17	0.02	0.04	0.01	0.01	0.21	0.21		
Southland 3	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	*	0.00	0.02	0.02	0.01	0.00	0.01	0.00	0.00	0.05	0.02	0.16	

Note * - No concurrent data for these sites

Table 2.7 – Correlation [r^2] for 6 hour average power output

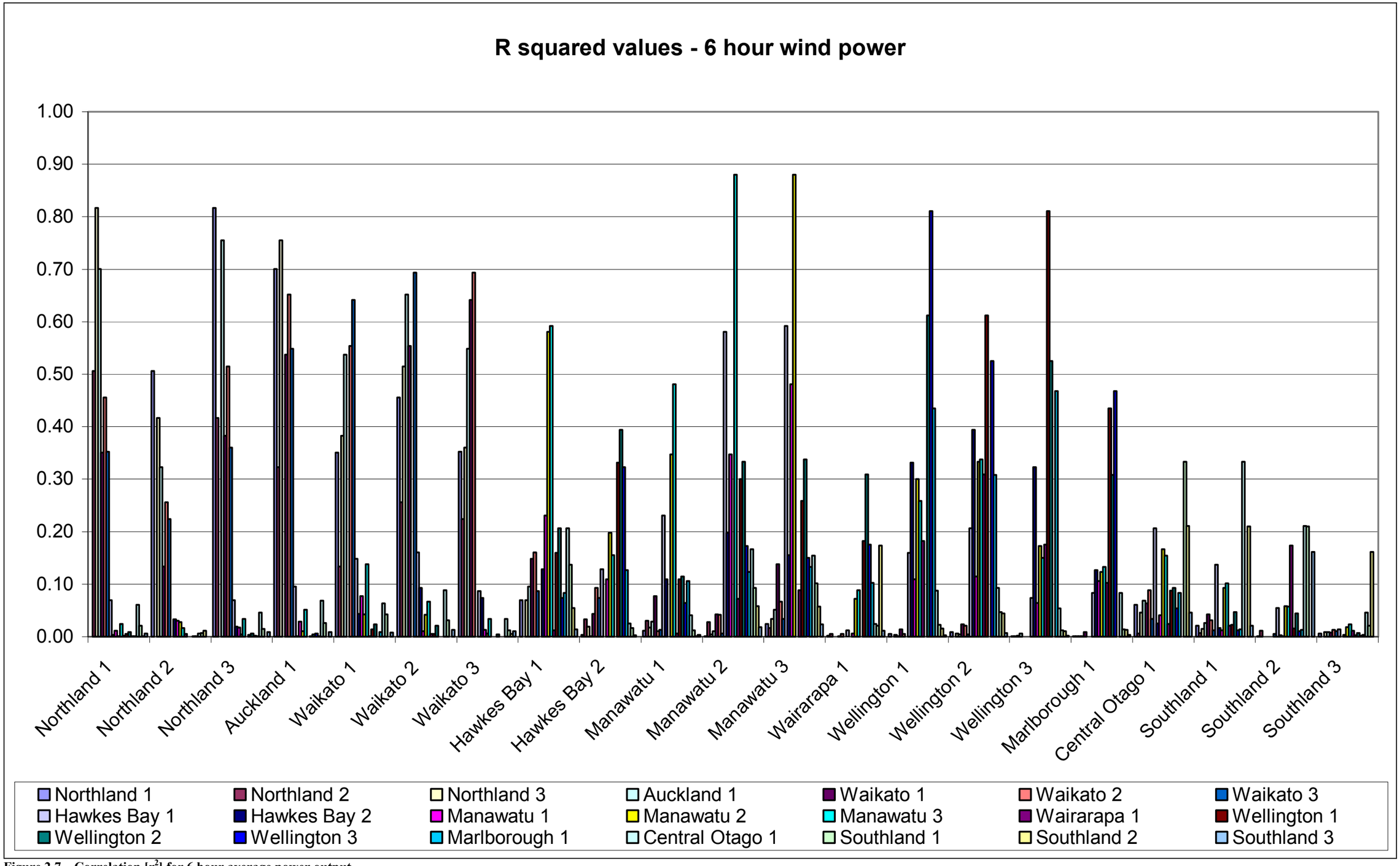


Figure 2.7 – Correlation [r^2] for 6 hour average power output

	N. 1	N. 2	N. 3	A. 1	Wko. 1	Wko. 2	Wko. 3	H. B. 1	H. B. 2	M. 1	M. 2	M.3	Wpa. 1	Wel. 1	Wel. 2	Wel. 3	Mlb. 1	O. 1	S. 1	S. 2	S. 3
Northland 1																					
Northland 2	0.58																				
Northland 3	0.86	0.51																			
Auckland 1	0.78	0.41	0.83																		
Waikato 1	0.49	0.22	0.54	0.69																	
Waikato 2	0.58	0.35	0.64	0.76	0.74																
Waikato 3	0.49	0.33	0.53	0.70	0.76	0.82															
Hawkes Bay 1	0.11	0.00	0.10	0.13	0.24	0.23	0.13														
Hawkes Bay 2	0.00	0.04	0.02	0.00	0.06	0.11	0.08	0.14													
Manawatu 1	0.02	0.04	0.03	0.04	0.10	0.02	0.01	0.28	0.12												
Manawatu 2	0.01	0.03	0.01	0.02	0.10	0.07	0.02	0.70	0.23	0.43											
Manawatu 3	0.05	0.01	0.06	0.09	0.24	0.11	0.06	0.70	0.16	0.51	0.93										
Wairarapa 1	0.00	0.00	0.01	0.01	0.01	0.01	*	0.02	*	0.01	0.14	0.16									
Wellington 1	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.23	0.45	0.11	0.38	0.32	0.42								
Wellington 2	0.02	0.00	0.01	0.01	0.05	0.03	0.00	0.29	0.51	0.13	0.44	0.41	0.50	0.69							
Wellington 3	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.11	0.45	0.06	0.22	0.18	0.35	0.85	0.57						
Marlborough 1	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.11	0.21	0.12	0.20	0.19	0.30	0.58	0.44	0.64					
Central Otago 1	0.09	0.01	0.07	0.11	0.10	0.13	0.04	0.34	0.04	0.06	0.26	0.23	0.05	0.11	0.12	0.06	0.10				
Southland 1	0.03	0.01	0.03	0.04	0.06	0.05	0.01	0.22	0.02	0.01	0.14	0.15	0.03	0.03	0.06	0.01	0.02	0.43			
Southland 2	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.10	0.01	0.01	0.11	0.12	0.23	0.04	0.09	0.03	0.04	0.30	0.27		
Southland 3	0.01	0.00	0.02	0.02	0.02	0.03	0.01	0.04	*	0.01	0.05	0.06	0.03	0.01	0.01	0.01	0.01	0.13	0.06	0.35	

Note * - No concurrent data for these sites

Table 2.8 – Correlation [r^2] for 24 hour average power output

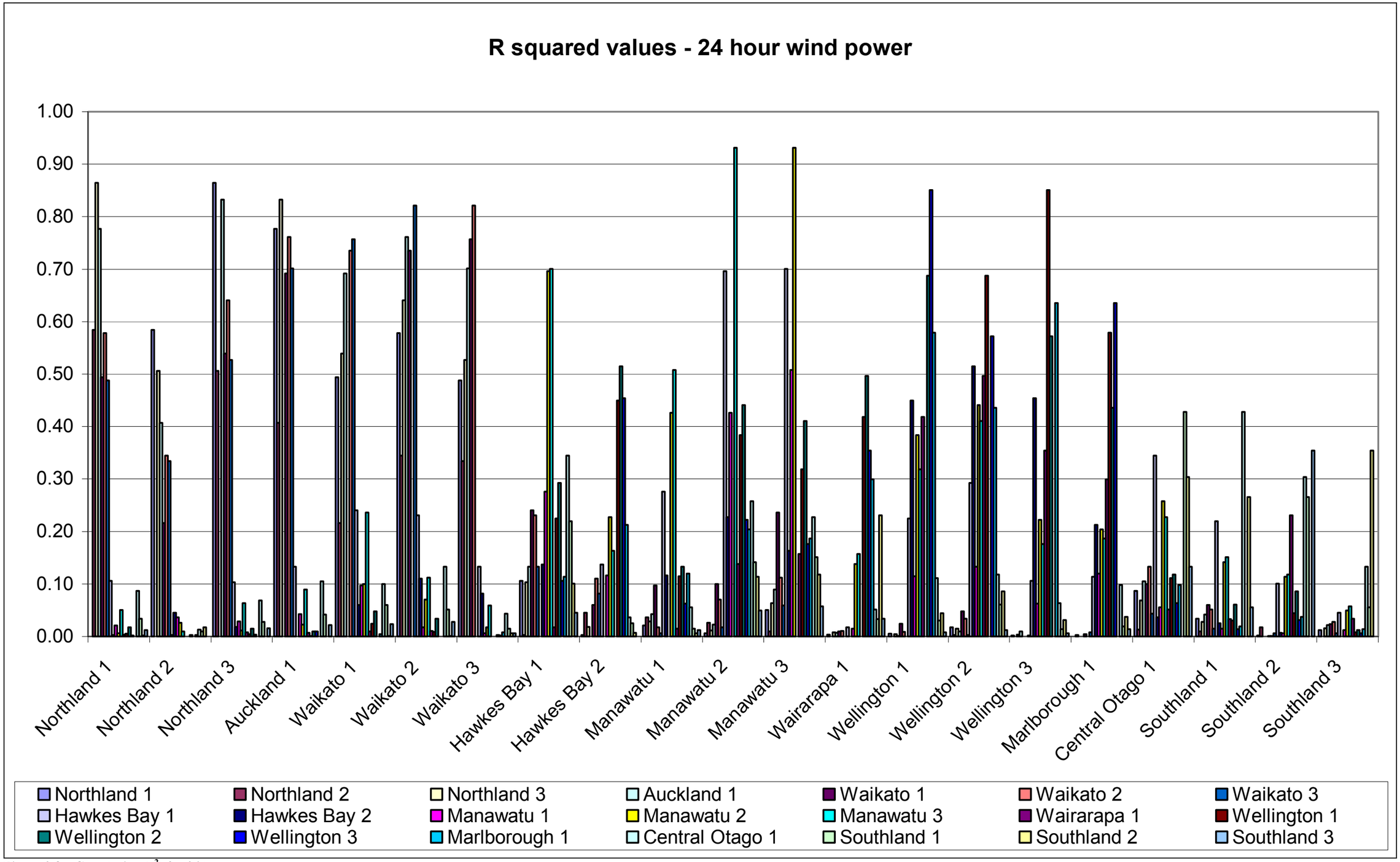


Figure 2.8 – Correlation [r^2] for 24 hour average power output

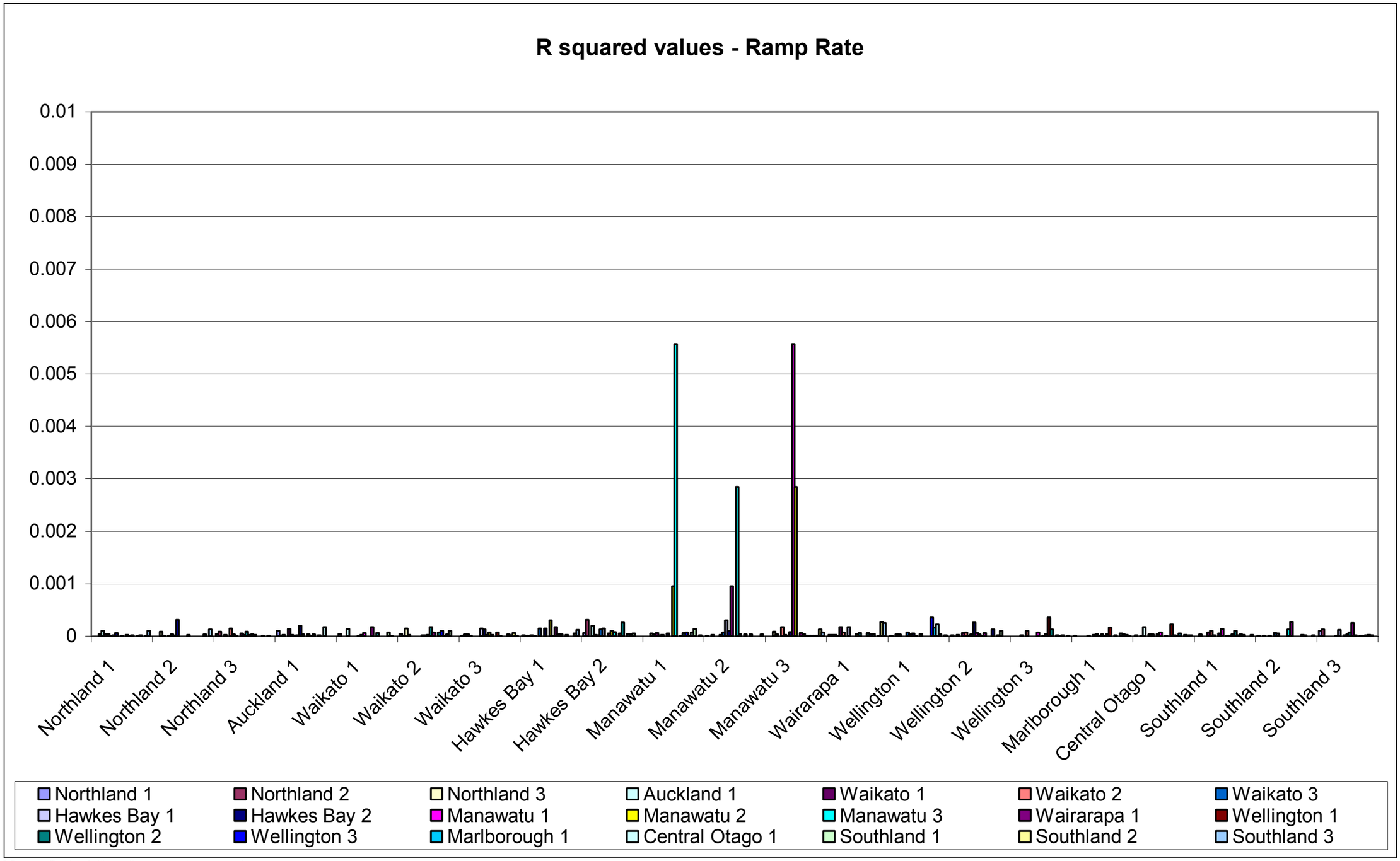
2.3. Correlation of wind farm output variation

From the 10 minute predicted wind farm output time series, the rates of change of theoretical wind farm output were calculated.

	N. 1	N. 2	N. 3	A. 1	Wko. 1	Wko. 2	Wko. 3	H. B. 1	H. B. 2	M. 1	M. 2	M.3	Wpa. 1	Wel. 1	Wel. 2	Wel. 3	Mlb. 1	O. 1	S. 1	S. 2	S. 3
Northland 1																					
Northland 2	0.000																				
Northland 3	0.000	0.000																			
Auckland 1	0.000	0.000	0.000																		
Waikato 1	0.000	0.000	0.000	0.000																	
Waikato 2	0.000	0.000	0.000	0.000	0.000																
Waikato 3	0.000	0.000	0.000	0.000	0.000	0.000															
Hawkes Bay 1	0.000	0.000	0.000	0.000	0.000	0.000	0.000														
Hawkes Bay 2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000													
Manawatu 1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000												
Manawatu 2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001											
Manawatu 3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.003										
Wairarapa 1	0.000	0.000	0.000	0.000	0.000	0.000	*	0.000	*	0.000	0.000	0.000									
Wellington 1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000								
Wellington 2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000							
Wellington 3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000						
Marlborough 1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000					
Central Otago 1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000				
Southland 1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000			
Southland 2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
Southland 3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

Note * - No concurrent data for these sites

Table 2.9 – Correlation [r^2] for 10 minute average rate of change of power output



Note – Scale differs from previous graphs

Figure 2.9 – Correlation [r^2] for 10 minute average rate of change of power output

2.4. Wind energy scenario

2.4.1. Wind generation duration curve

The following wind generation duration curve has been developed from the scenario.

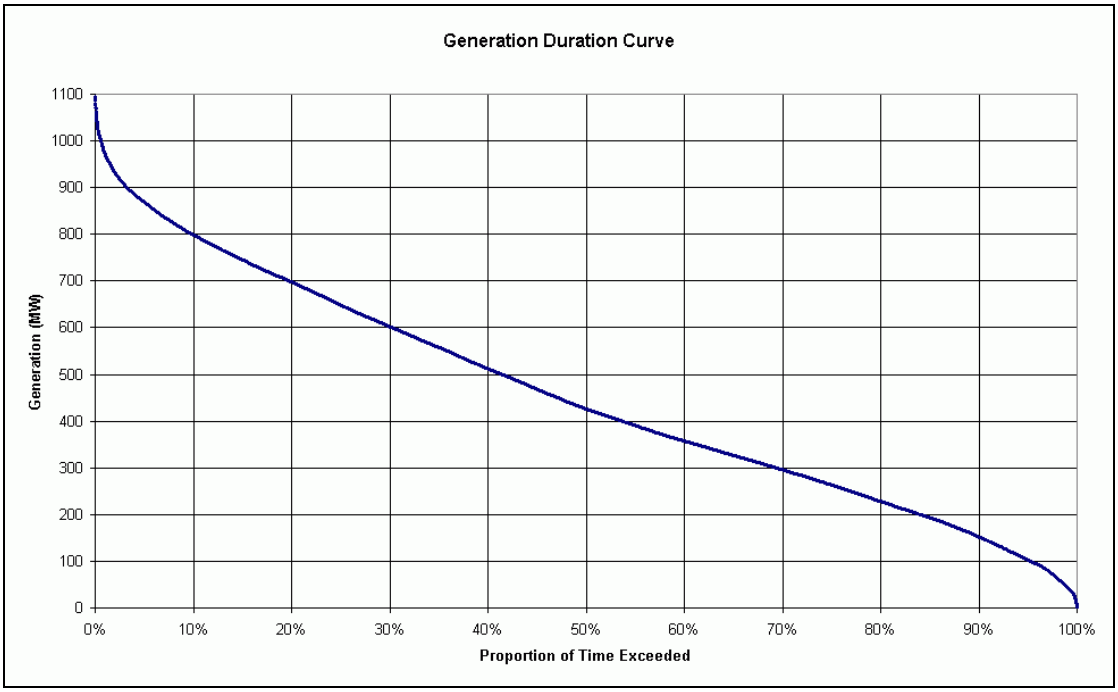


Figure 2.10 – Generation duration curve for the modelled wind energy scenario

2.4.2. Rate of change of output

The following figure shows the frequency of occurrence of rates of change in output.

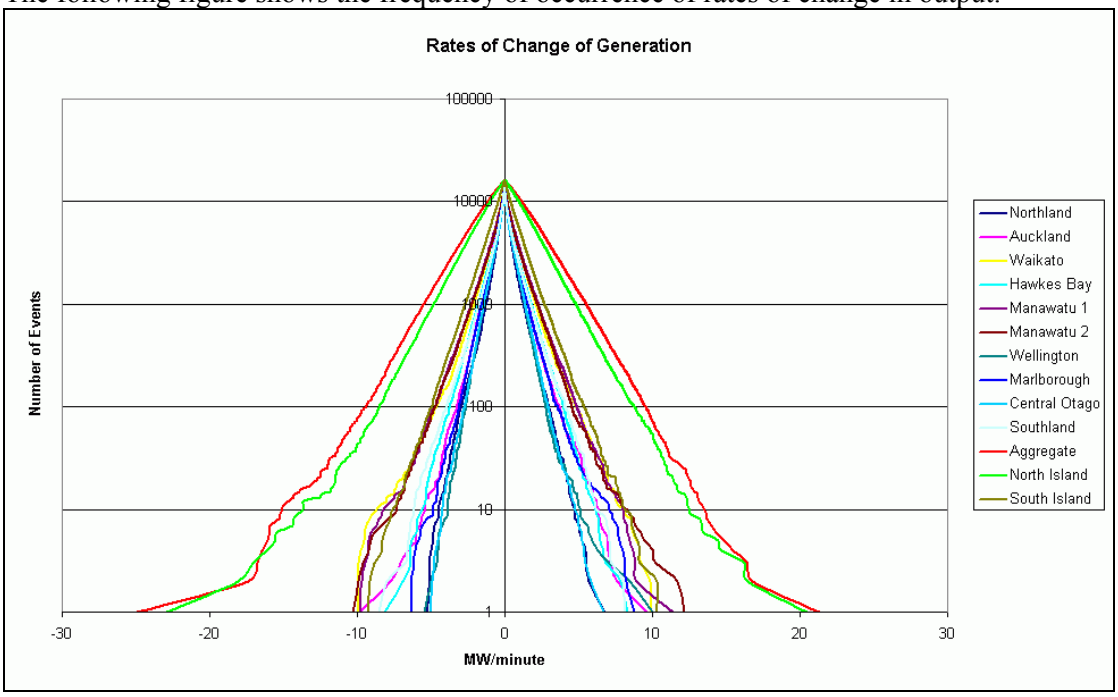


Figure 2.11 – Frequency of rate of change in output for the modelled wind energy scenario

2.4.3. Ten largest rates of change in theoretical output for the scenario modelled

The scenario was examined to identify the ten largest rates of change recorded in the 225 days of data. These are shown in the following table, and each event is examined in more detail in the following pages.

Rank	Date and Time (NZST)	MW change over 10 minutes
1	10 December 2004, 17:20	-250 MW
2	25 March 2005, 11:10	213 MW
3	26 November 2004, 10:50	-174 MW
4	3 September 2004, 16:10	167 MW
5	28 September 2004, 11:40	167 MW
6	30 June 2005, 05:50	-165 MW
7	21 April 2005, 11:20	165 MW
8	30 June 2005, 05:40	-161 MW
9	29 November 2004, 16:20	-160 MW
10	23 April 2005, 04:40	-159 MW

Table 2.10 – Ten largest changes in theoretical output for the scenario modelled

10 December 2004 17:10 to 17:20

Over this time period the theoretical scenario output falls from 894 MW at 17:10 to 644 MW at 17:20, or approximately 250 MW over 10 minutes. This is caused by rapid decreases in theoretical outputs at both the Waikato 1 and Manawatu 3 wind farms, coupled with more moderate decreases in theoretical output at the Auckland 1, Hawkes Bay 1, Wellington 1 and Hawkes Bay 1 wind farms. The outputs of the other wind farms were largely unchanged. These changes are shown in the figure below, the outputs of individual wind farms are referenced to the left hand scale, the aggregate (in red) to the right hand scale.

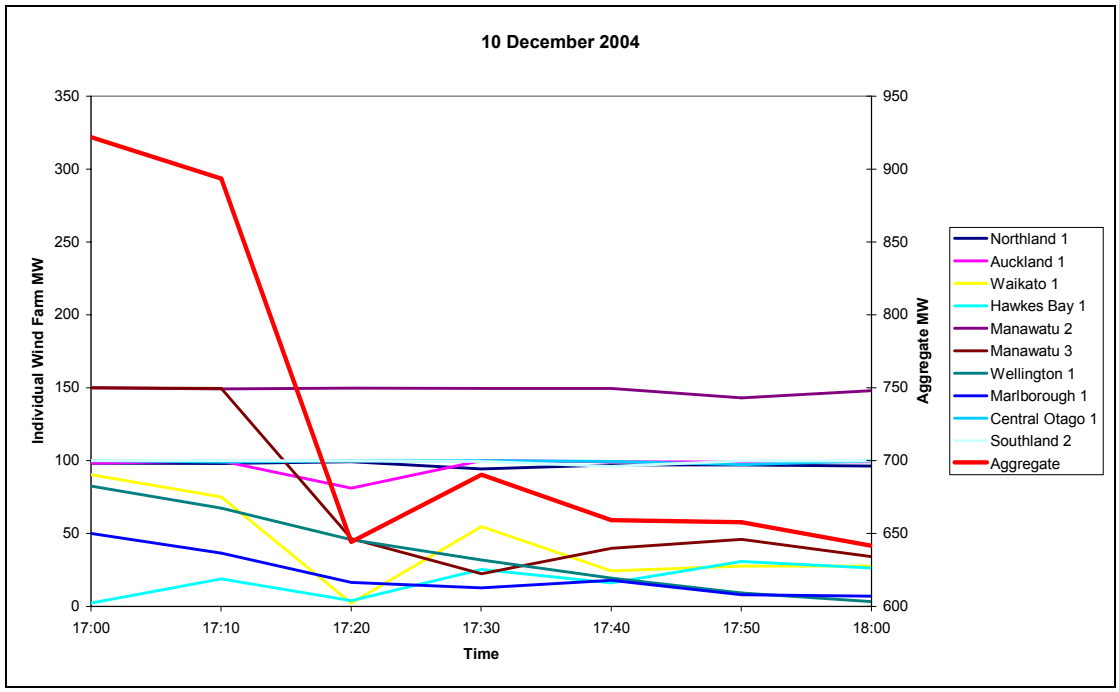


Figure 2.12 – Theoretical wind farm power outputs on 10 December 2004

Looking at an equivalent plot of wind speeds it can be seen that the large decreases in the theoretical power outputs of the Waikato 1 and Manawatu 3 wind farms are an increase in wind speed above 25 m/s and a decrease in wind speed below 15 m/s respectively.

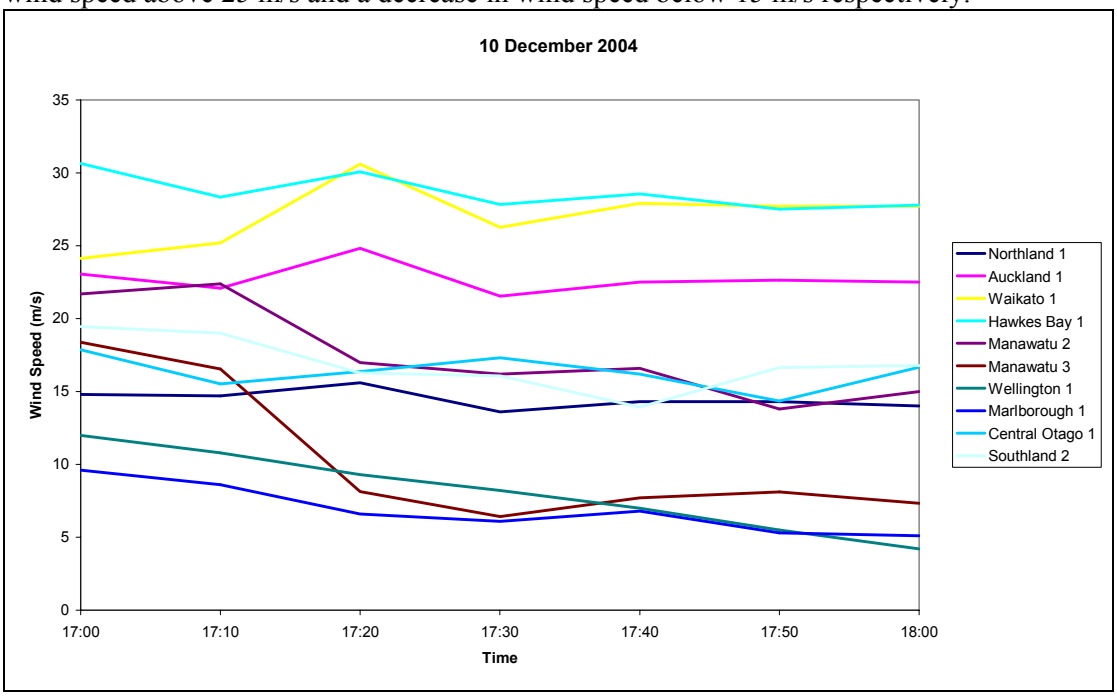


Figure 2.13 – Wind speeds recorded on 10 December 2004.

25 March 2004 11:00 to 11:10

Over this time period the theoretical scenario output increases from 530 MW at 11:00 to 743 MW at 11:10, or approximately 213 MW over 10 minutes. This change is shown in the figure below. This is driven by a large increase in the theoretical power output at Manawatu 2, combined with smaller increases at Manawatu 3, Waikato 1 and Central Otago 1.

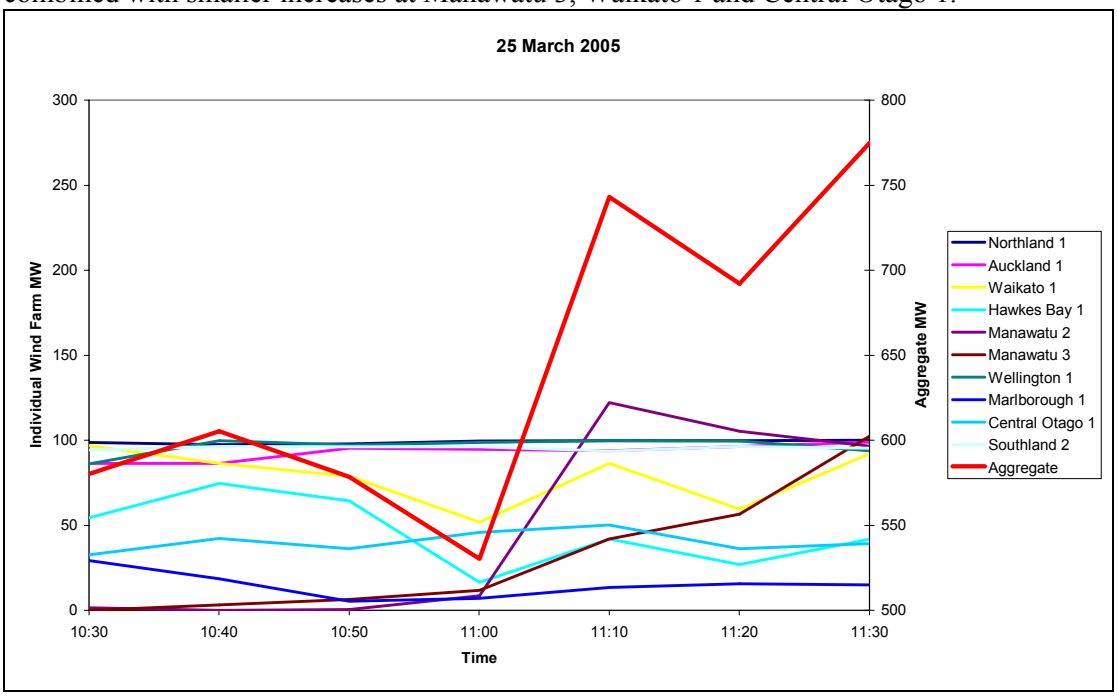


Figure 2.14 – Theoretical wind farm power outputs on 25 March 2005

Looking at the corresponding wind speed plots it can be seen that the changes in theoretical power output are being driven by increases in wind speeds ant the Manawatu 2 and Waikato 1 sites, and to a lesser extent at the Manawatu 3 and Central Otago 1 sites.

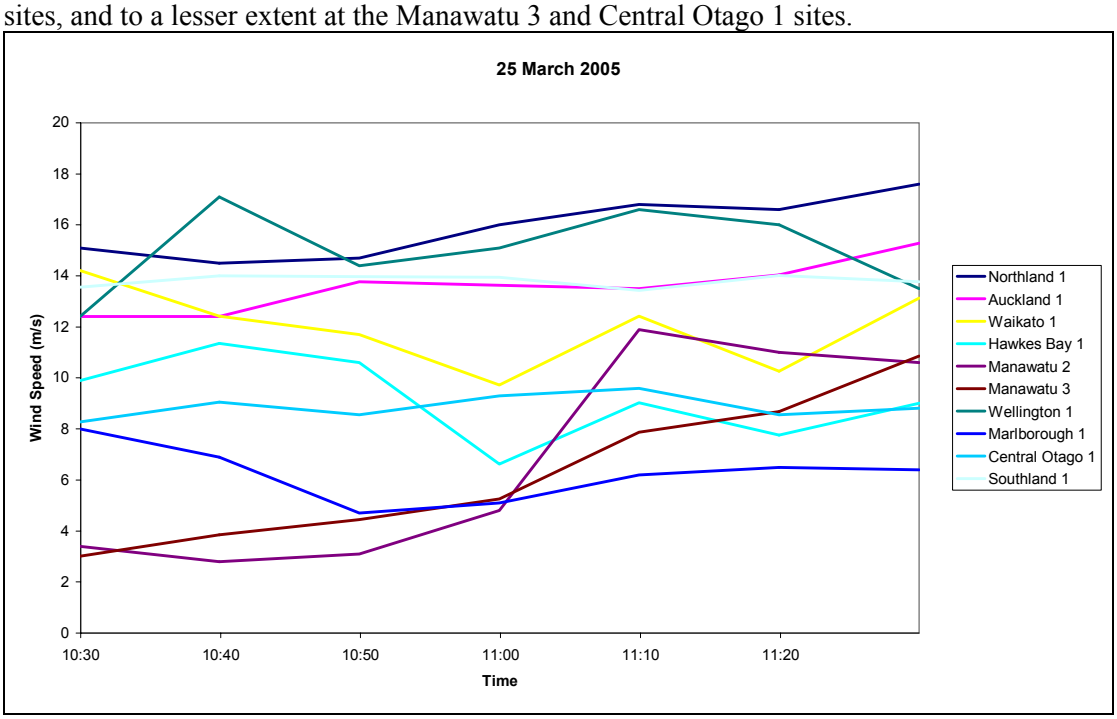


Figure 2.15 – Wind speeds recorded on 25 March 2005.

26 November 2004 10:50 to 11:00

Over this time period the theoretical scenario output decreases from 1043 MW at 10:50 to 869 MW at 11:00, or approximately 174 MW over 10 minutes. This change is shown in the figure below. This is driven by a large decrease in the theoretical power output at Waikato 1 and to a lesser extent Manawatu 3 and Southland 2. Manawatu 2 counterbalanced this to a certain extent with a small rise in theoretical output.

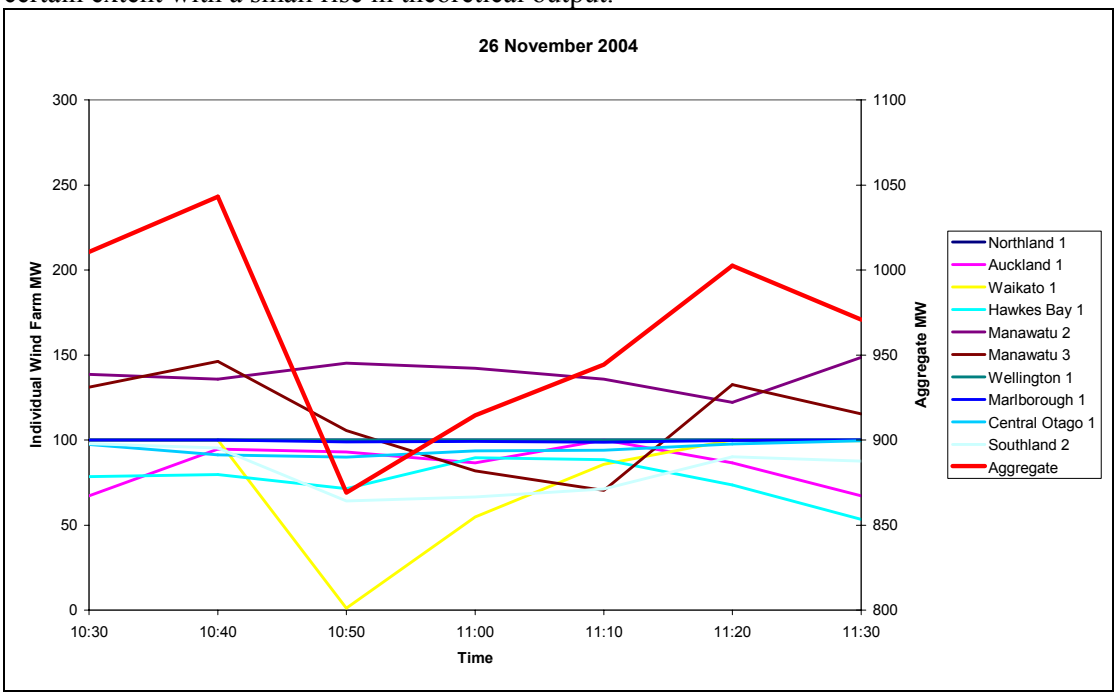


Figure 2.16 – Theoretical wind farm power outputs on 26 November 2004

As can be seen from the plot below, the decrease in theoretical Waikato 1 generation is driven by an increase in wind speed above 25 m/s, while the decrease in theoretical Manawatu 3 generation is driven by a decrease in wind speed below 15 m/s at that site.

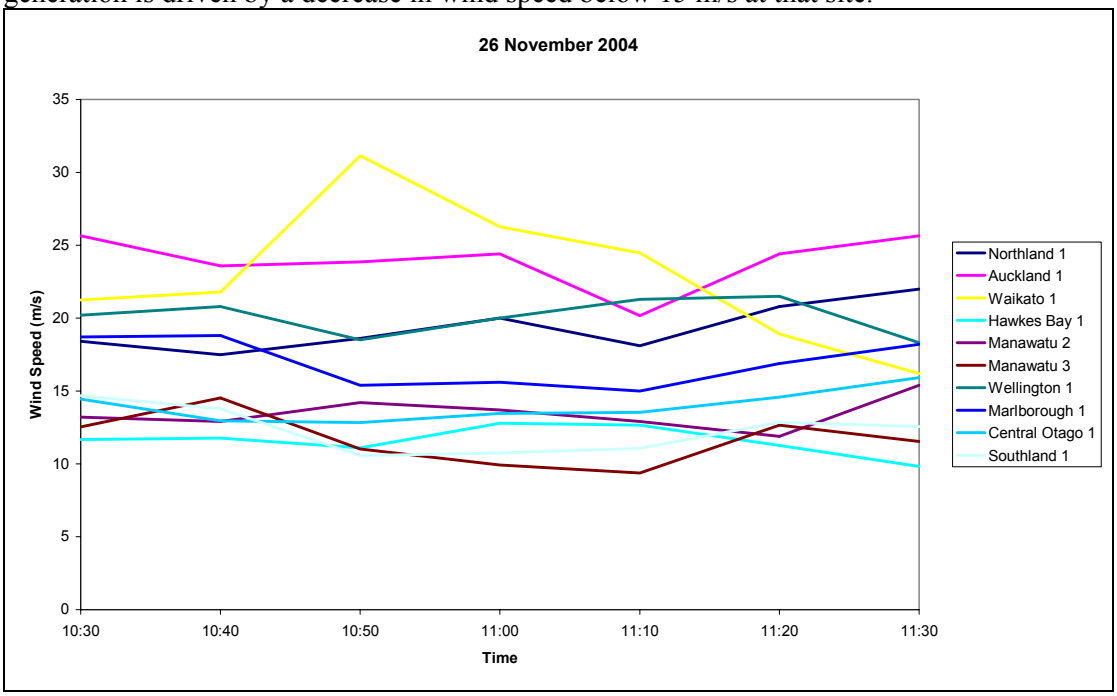


Figure 2.17 – Wind speeds recorded on 26 November 2004

3 September 2004 16:00 to 16:10

Over this time period the theoretical scenario output increases from 459 MW at 16:00 to 627 MW at 16:10, or approximately 168 MW over 10 minutes. This change is shown in the figure below. This is driven by increases in the theoretical power output at Manawatu 2, Manawatu 3 and Auckland 1.

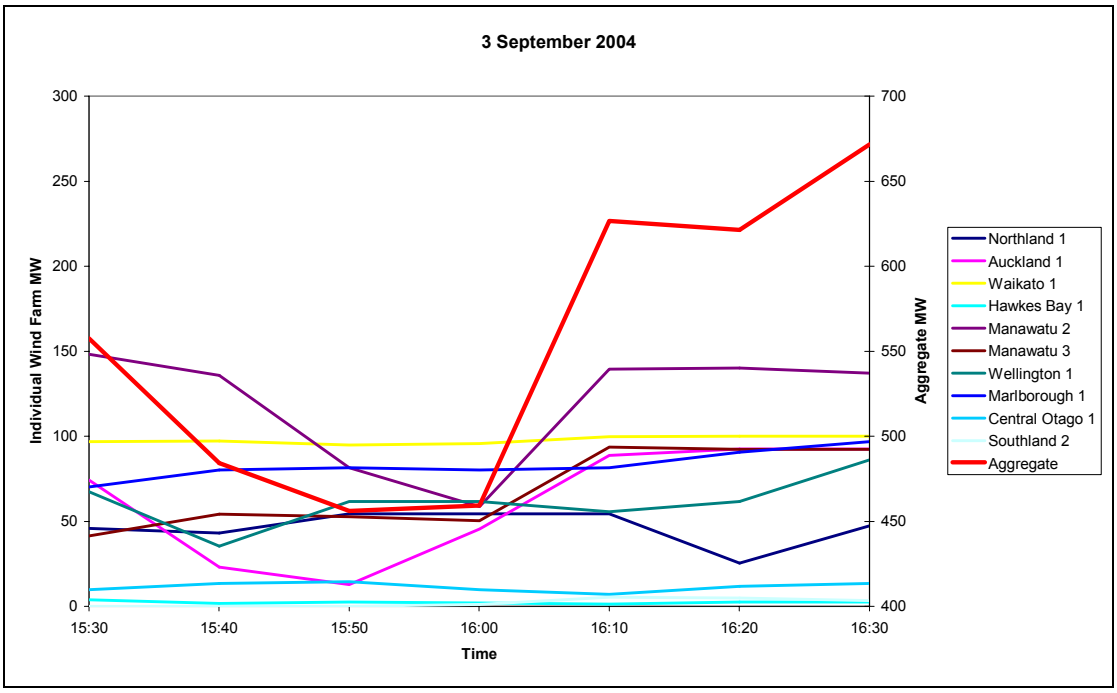


Figure 2.18 – Theoretical wind farm power outputs on 3 September 2004

From the plot below, it can be seen that the increases in theoretical power output at these sites are all driven by increases in wind speeds (below 15 m/s) occurring at the sites.

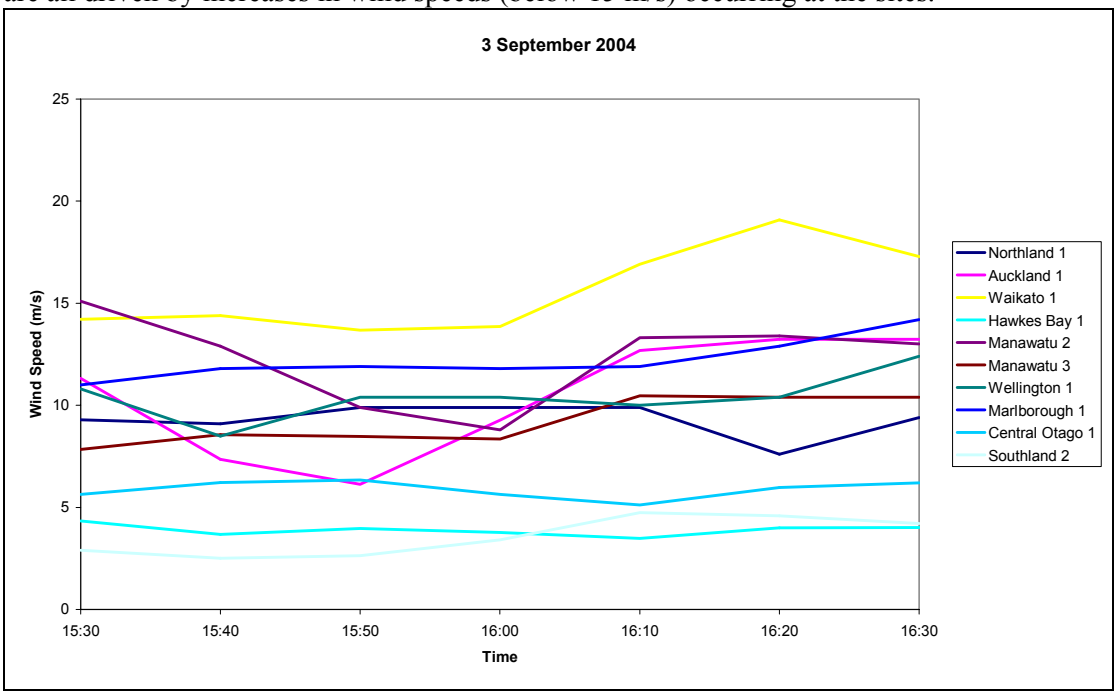


Figure 2.19 – Wind speeds recorded on 3 September 2004

28 September 2004 11:30 to 11:40

Over this time period the theoretical scenario output decreases from 816 MW at 11:30 to 649 MW at 11:40, or approximately 167 MW over 10 minutes. This change is shown in the figure below. This is driven by decreases in the theoretical power output at Manawatu 2 and Manawatu 3.

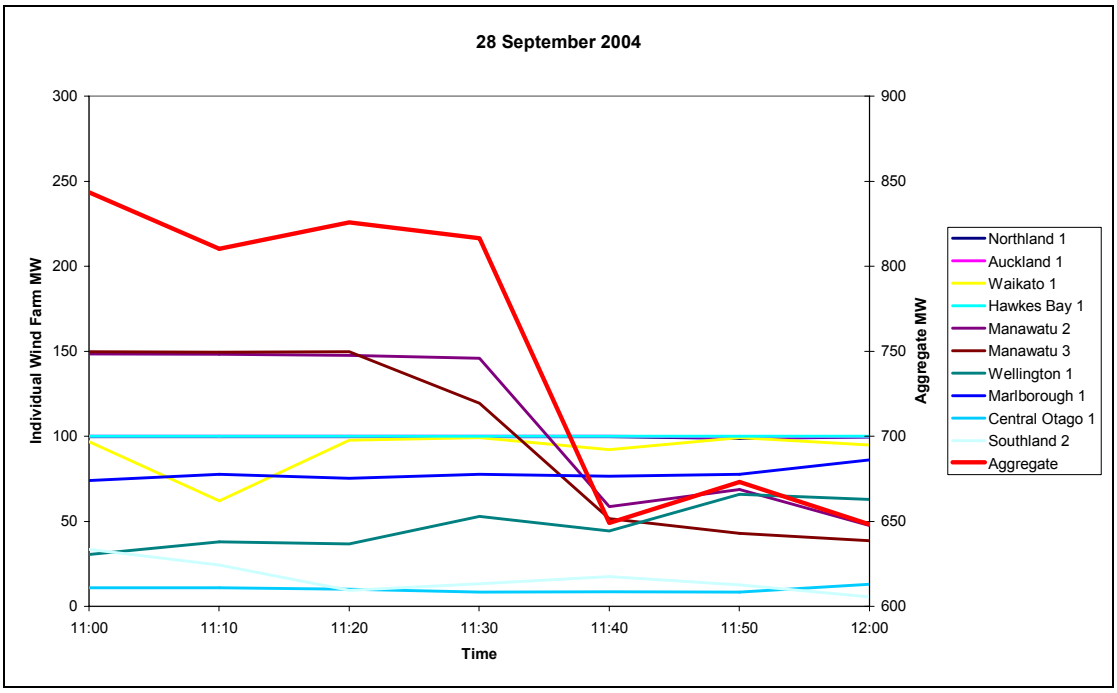


Figure 2.20 – Theoretical wind farm power outputs on 28 September 2004

From the plot of wind speeds, below, it can be seen that the wind speed at both Manawatu 2 and Manawatu 3 decrease below 15 m/s.

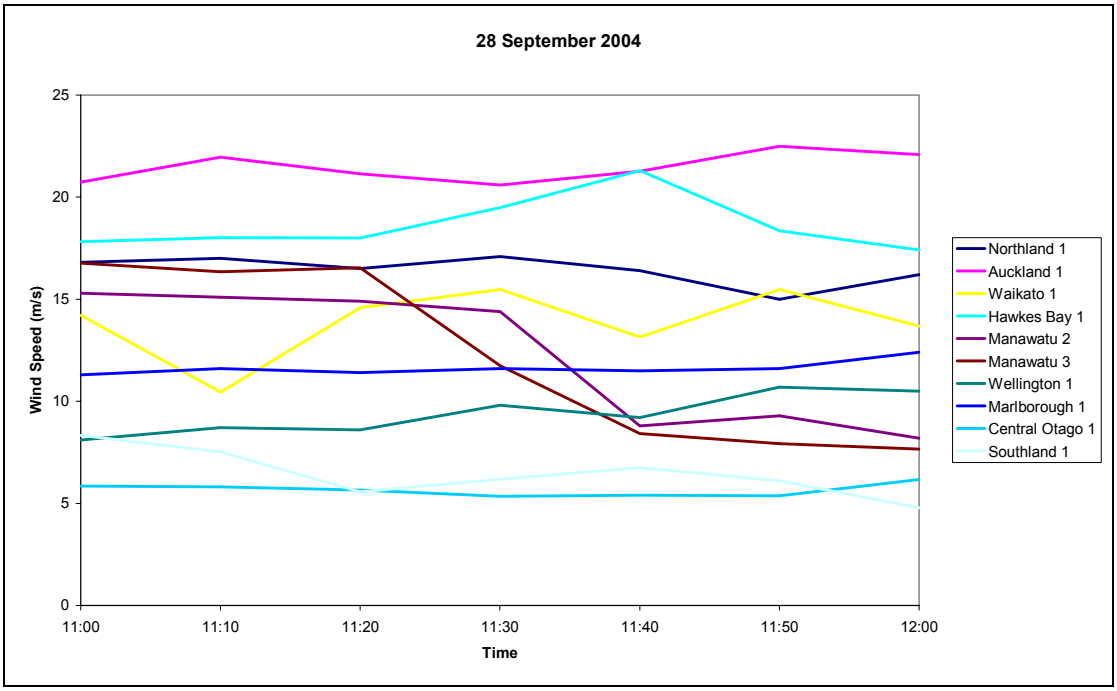


Figure 2.21 – Wind speeds recorded on 28 September 2004

30 June 2005 5:30 to 5:50

Over this time period the theoretical scenario output decreases from 838 MW at 5:30 to 677 MW at 5:40, or approximately 161 MW over 10 minutes. This is followed by a further fall to 512 MW at 5:50, or 165 MW over 10 minutes. This change is shown in the figure below. This is driven by decreases in the theoretical power output at Manawatu 2, Manawatu 3, Waikato 1 and Central Otago 1.

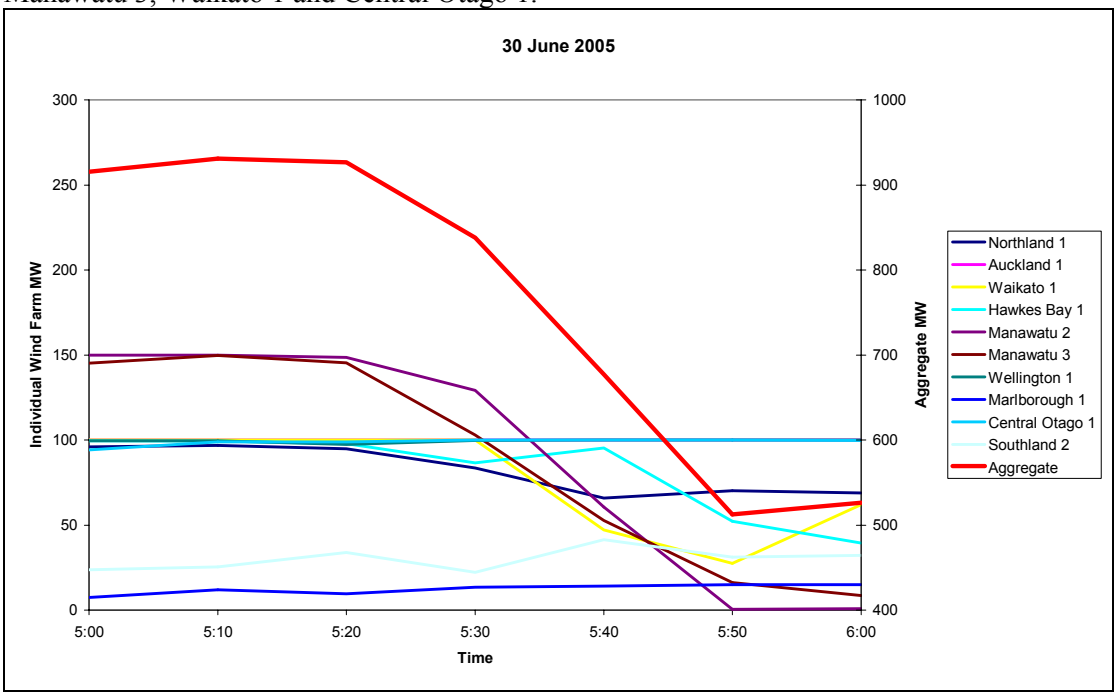


Figure 2.22 – Theoretical wind farm power outputs on 30 June 2005

From the figure below, it can be seen that decreases in theoretical power outputs are caused by decreases in wind speed below 15 m/s at Manawatu 2, Manawatu 3 and Central Otago 1. While the decrease at Waikato 1 is caused by an increase in wind speed above 25 m/s.

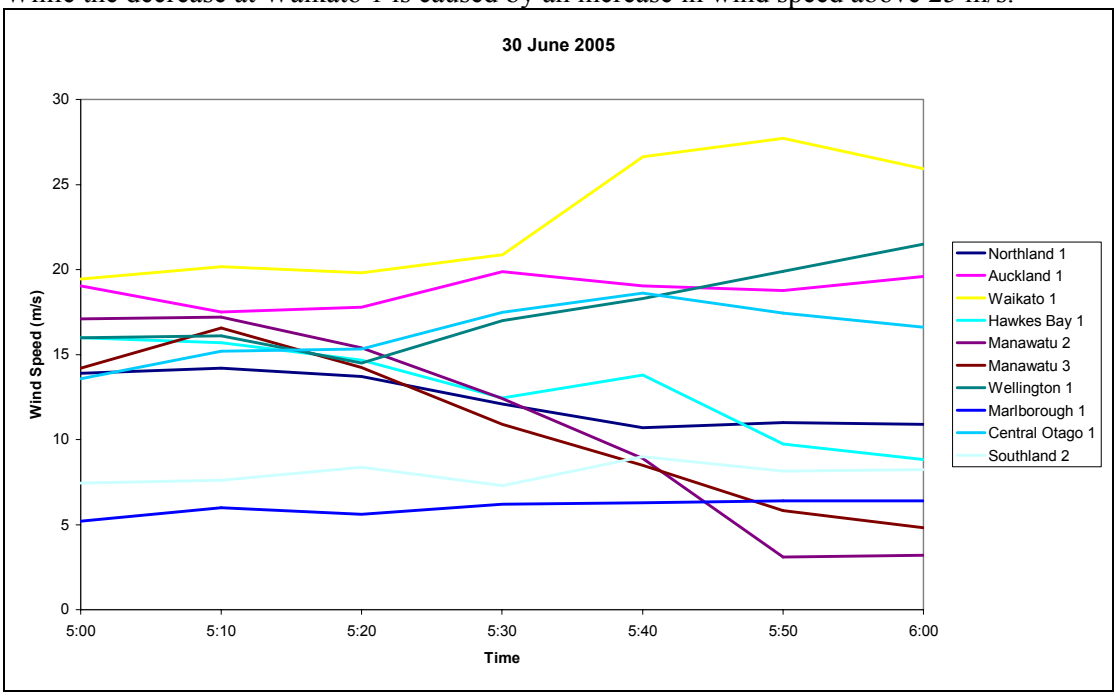


Figure 2.23 – Wind speeds recorded on 30 June 2005

21 April 2005 11:10 to 11:20

Over this time period the theoretical scenario output increases from 476 MW at 11:10 to 640 MW at 11:20, or approximately 164 MW over 10 minutes. This is caused by increases in the theoretical power outputs at Manawatu 2 and Manawatu 3

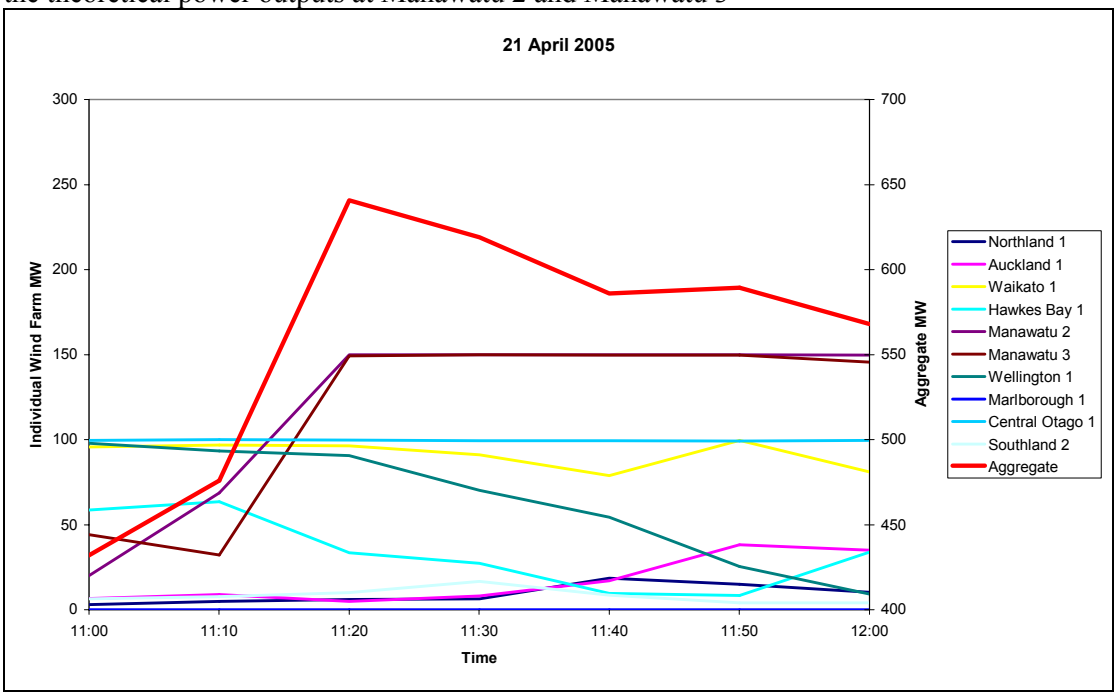


Figure 2.24 – Theoretical wind farm power outputs on 21 April 2005

As can be seen from the figure below, the increases in theoretical power output at the Manawatu 2 and Manawatu 3 sites are driven by increases in wind speed at the sites from below 15 m/s.

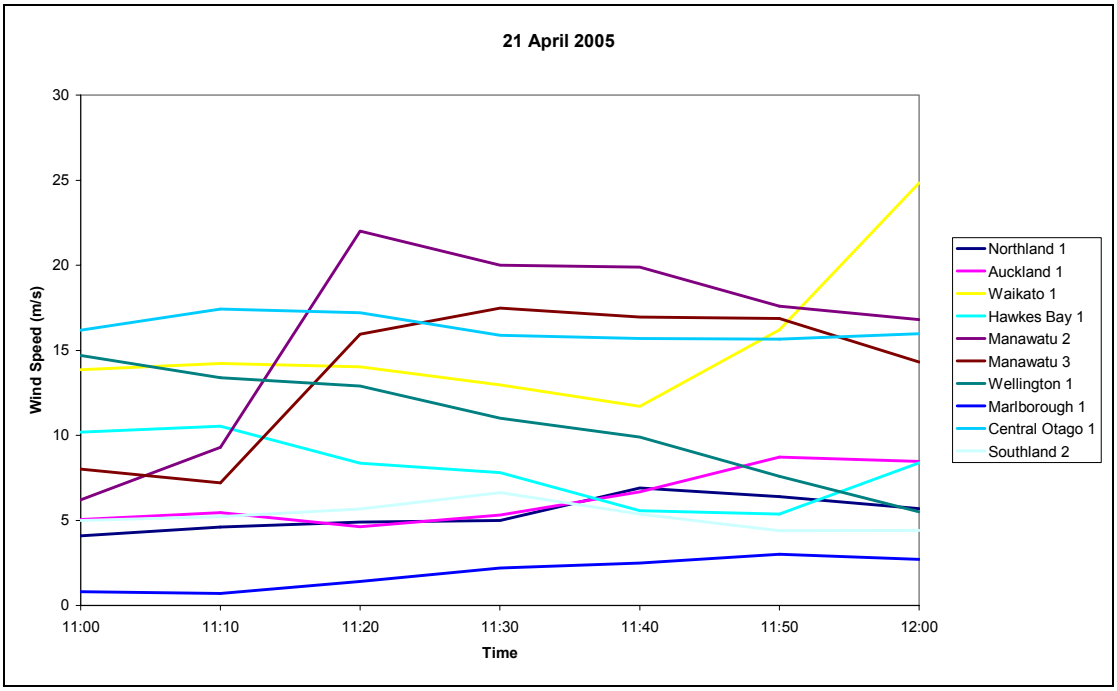


Figure 2.25 – Wind speeds recorded on 21 April 2005

29 November 2004 16:10 to 16:20

Over this time period the theoretical scenario output decreases from 720 MW at 16:10 to 560 MW at 16:20, or approximately 160 MW over 10 minutes. This is caused by combined decreases in the theoretical outputs at Hawkes Bay 1, Manawatu 2, Manawatu 3, Marlborough 1, Central Otago 1, and Southland 2.

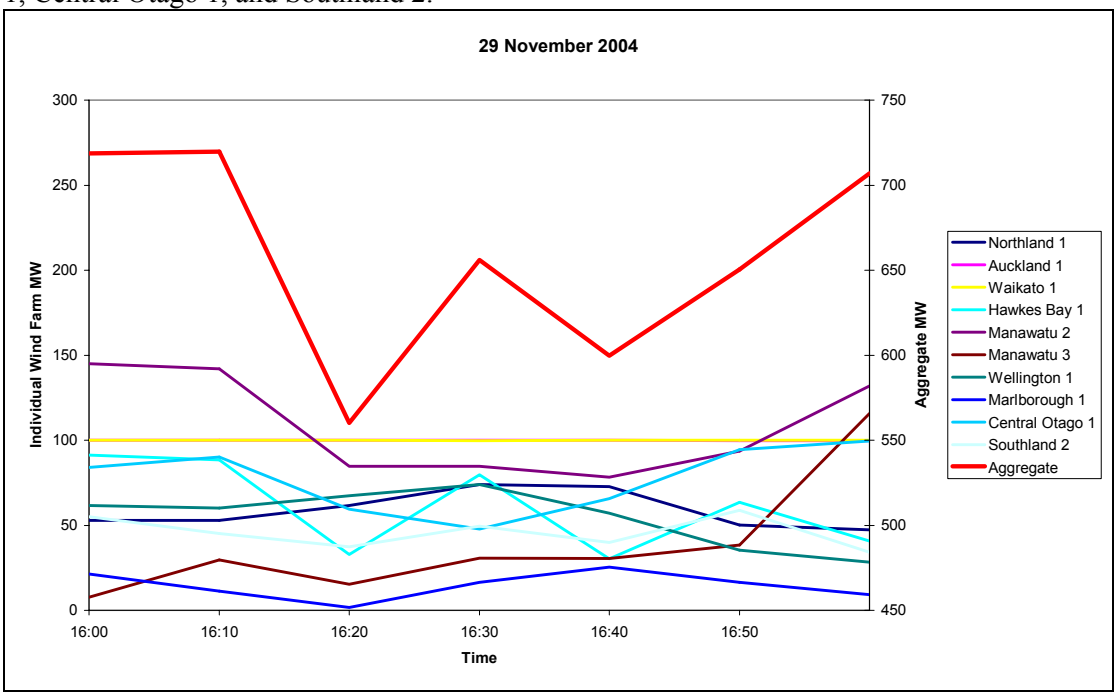


Figure 2.26 – Theoretical wind farm power outputs on 29 November 2004

From the figure below it can be seen that the decreases in theoretical power outputs are due to increases in wind speed above 25 m/s at the Hawkes Bay 1, Manawatu 2 and Manawatu 3 sites, and decreases in wind speed below 15 m/s at the Marlborough 1, Central Otago 1 and Southland 2 sites.

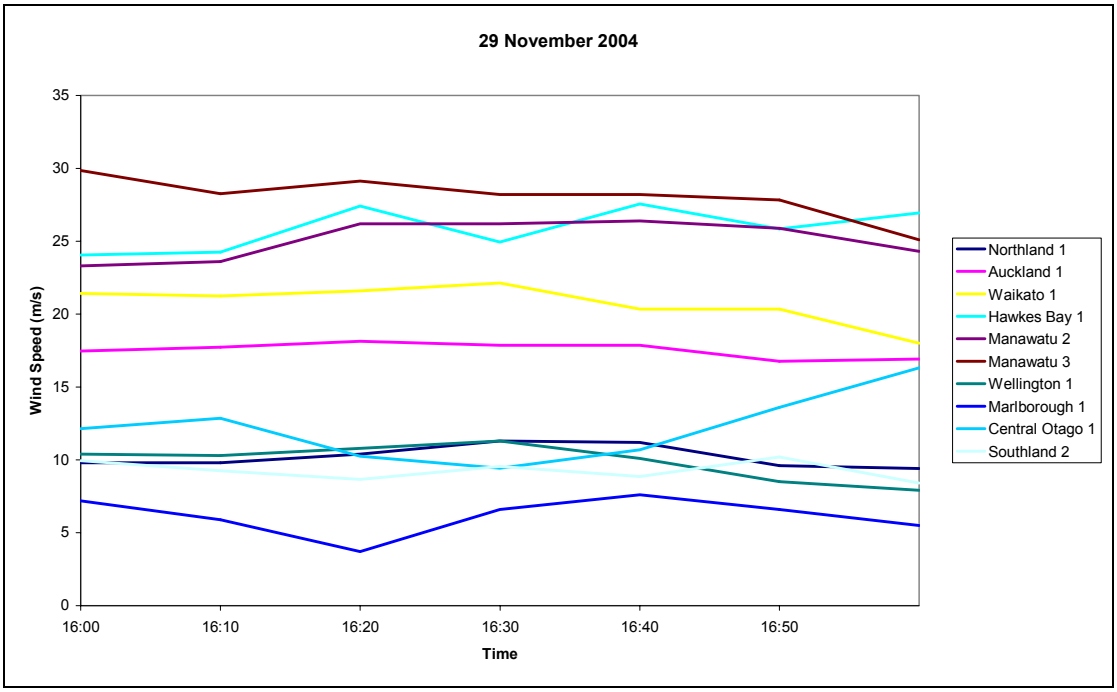


Figure 2.27 – Wind speeds recorded on 29 November 2004

23 April 2005 04:30 to 04:40

Over this time period the theoretical scenario output decreases from 543 MW at 04:30 to 384 MW at 04:40, or approximately 159 MW over 10 minutes. This is caused by a large decrease at Southland 2, in combination with smaller decreases in Northland 1, Waikato 1, Auckland 1, Manawatu 2 and Manawatu 3.

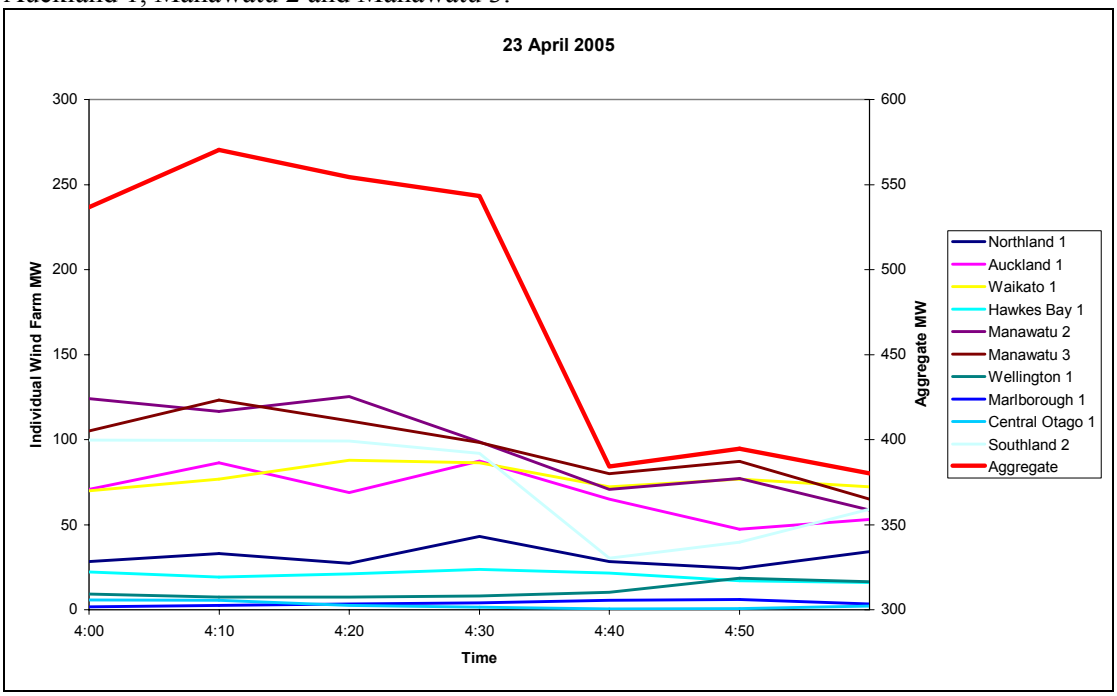


Figure 2.28 – Theoretical wind farm power outputs on 23 April 2005

From the figure below, it can be seen that decreases in theoretical outputs at these sites are all caused by decreases in wind speed below 15 m/s.

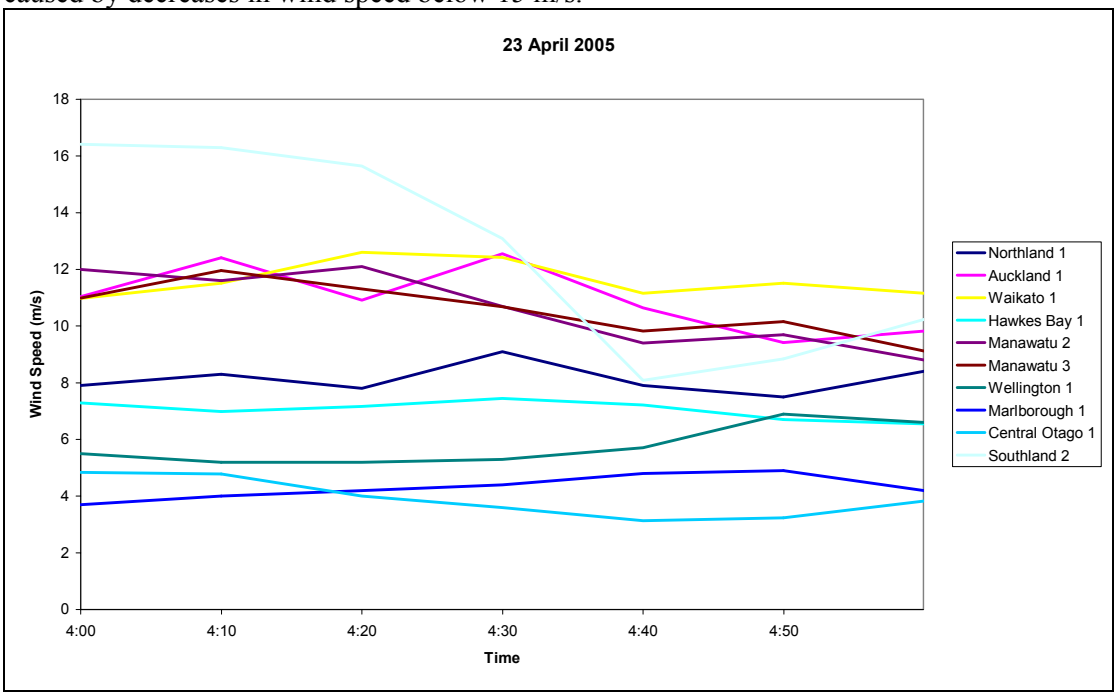


Figure 2.29 – Wind speeds recorded on 23 April 2003

2.4.4. Ten largest rates of change in theoretical output for the modelled North Island wind generation.

Since frequency is maintained separately in each Island, the EC requested that the scenario be further analysed on a North and South Island basis. The scenario was examined to identify the ten largest rates of change recorded in the 225 days of data for the modelled North Island wind farms. These are shown in the following table, and each event is examined in more detail in the following pages.

Rank	Date and Time (NZST)	MW change over 10 minutes
1	10 December 2004, 17:20	-229 MW
2	25 March 2005, 11:10	205 MW
3	30 June 2005, 05:40	-181 MW
4	28 September 2004, 11:40	-171 MW
5	3 September 2004, 16:10	165 MW
6	21 April 2005, 11:20	162 MW
7	10 December 2004, 09:00	-161 MW
8	30 June 2005, 05:50	-155 MW
9	18 December 2004, 17:00	-155MW
10	30 May 2005, 20:10	147 MW

Table 2.11 – Ten largest changes in North Island theoretical output for the scenario modelled

10 December 2004 17:10 to 17:20

Over this time period the theoretical North Island output falls from 658 MW at 17:10 to 429 MW at 17:20, or approximately 229 MW over 10 minutes. This is caused by rapid decreases in theoretical outputs at both the Waikato 1 and Manawatu 3 wind farms, coupled with more moderate decreases in theoretical output at the Auckland 1, Hawkes Bay 1, Wellington 1 and Hawkes Bay 1 wind farms. The outputs of the other wind farms were largely unchanged. These changes are shown in the figure below, the outputs of individual wind farms are referenced to the left hand scale, the aggregate (in red) to the right hand scale.

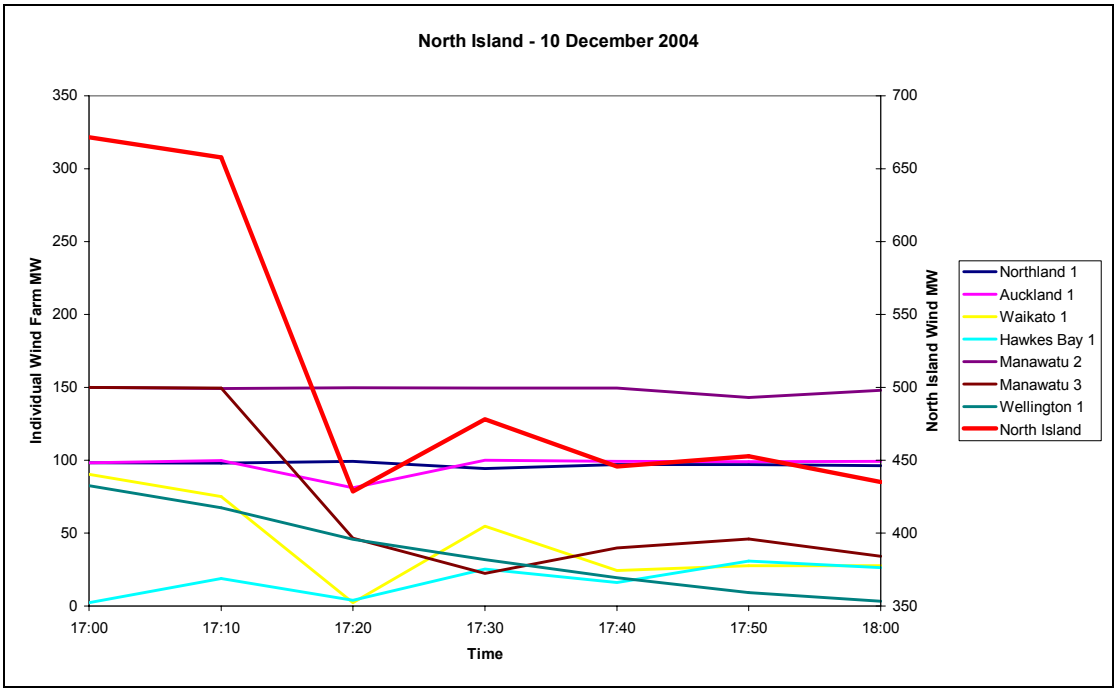


Figure 2.30 – Theoretical North Island wind farm power outputs on 10 December 2004

Looking at an equivalent plot of wind speeds it can be seen that the large decreases in the theoretical power outputs of the Waikato 1 and Manawatu 3 wind farms are an increase in wind speed above 25 m/s and a decrease in wind speed below 15 m/s respectively.

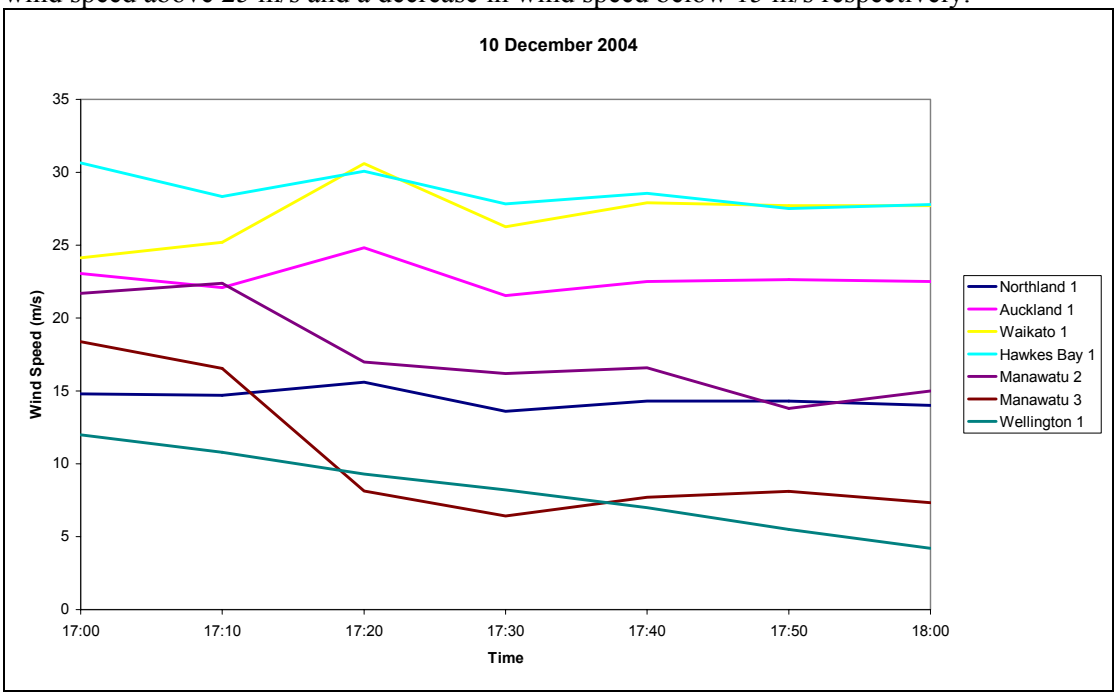


Figure 2.31 – Wind speeds recorded on 10 December 2004.

25 March 2005 11:00 to 11:10

Over this time period the theoretical North Island output increases from 381 MW at 11:00 to 586 MW at 11:10, or approximately 213 MW over 10 minutes. This change is shown in the figure below. This is driven by a large increase in the theoretical power output at Manawatu 2, combined with smaller increases at Manawatu 3 and Waikato 1.

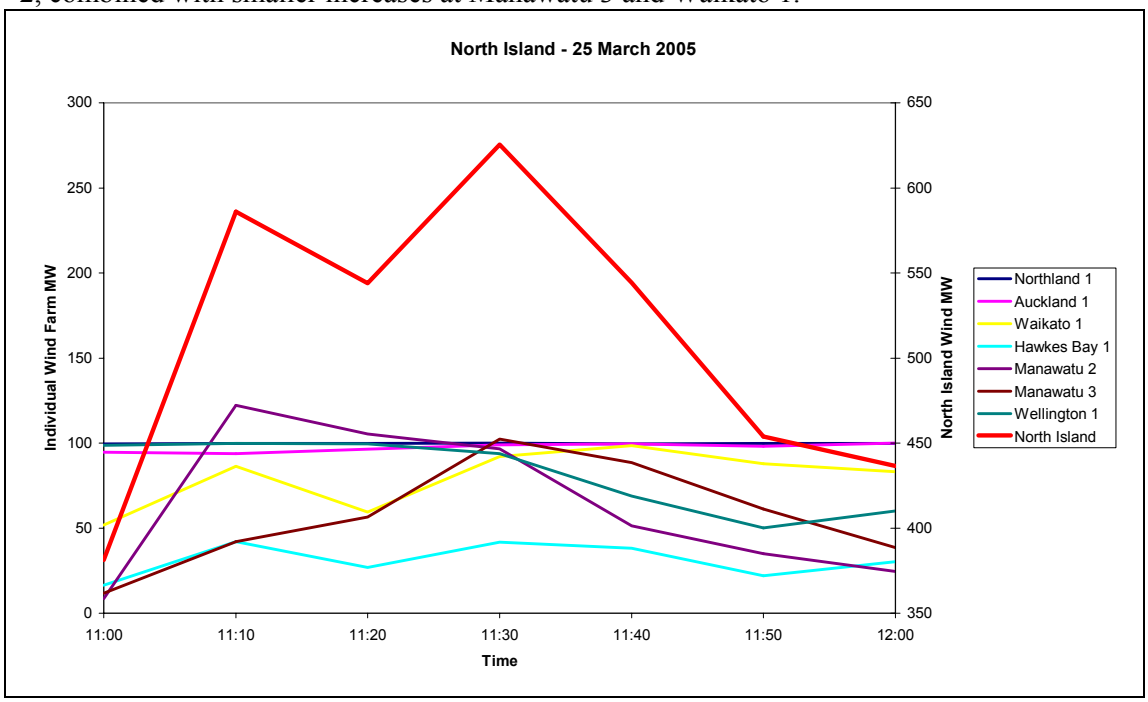


Figure 2.32 – Theoretical North Island wind farm power outputs on 25 March 2005

Looking at the corresponding wind speed plots it can be seen that the changes in theoretical power output are being driven by increases in wind speeds at the Manawatu 2 and Waikato 1 sites, and to a lesser extent at the Manawatu 3 site.

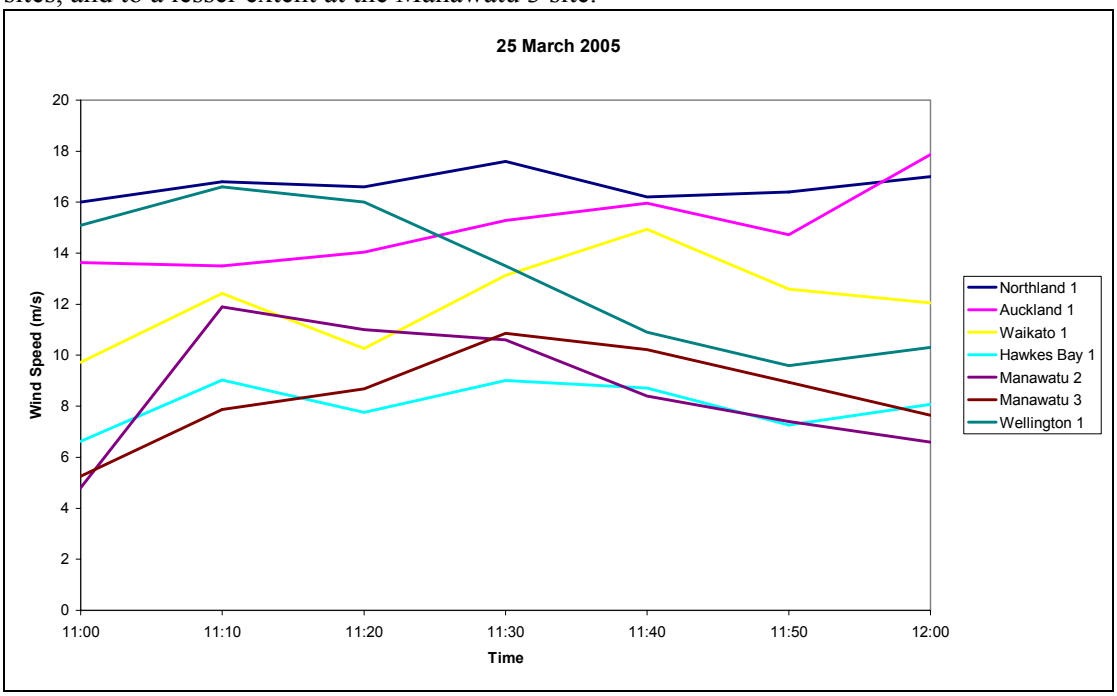


Figure 2.33 – Wind speeds recorded on 25 March 2005.

30 June 2005 5:30 to 5:50

Over this time period the theoretical North Island output decreases from 702 MW at 5:30 to 522 MW at 5:40, or approximately 181 MW over 10 minutes. This is followed by a further fall to 367 MW at 5:50, or 155 MW over 10 minutes. This change is shown in the figure below. This is driven by decreases in the theoretical power output at Manawatu 2, Manawatu 3 and Waikato 1.

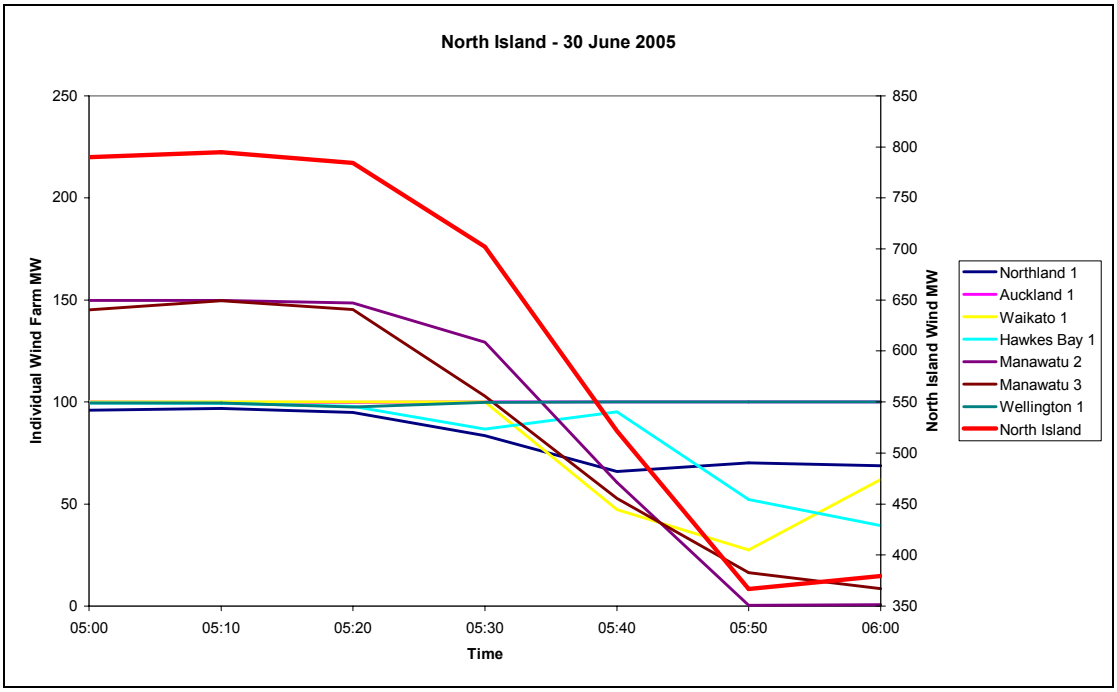


Figure 2.34 – Theoretical North Island wind farm power outputs on 30 June 2005

From the figure below, it can be seen that decreases in theoretical power outputs are caused by decreases in wind speed below 15 m/s at Manawatu 2 and Manawatu 3. While the decrease at Waikato 1 is caused by an increase in wind speed above 25 m/s.

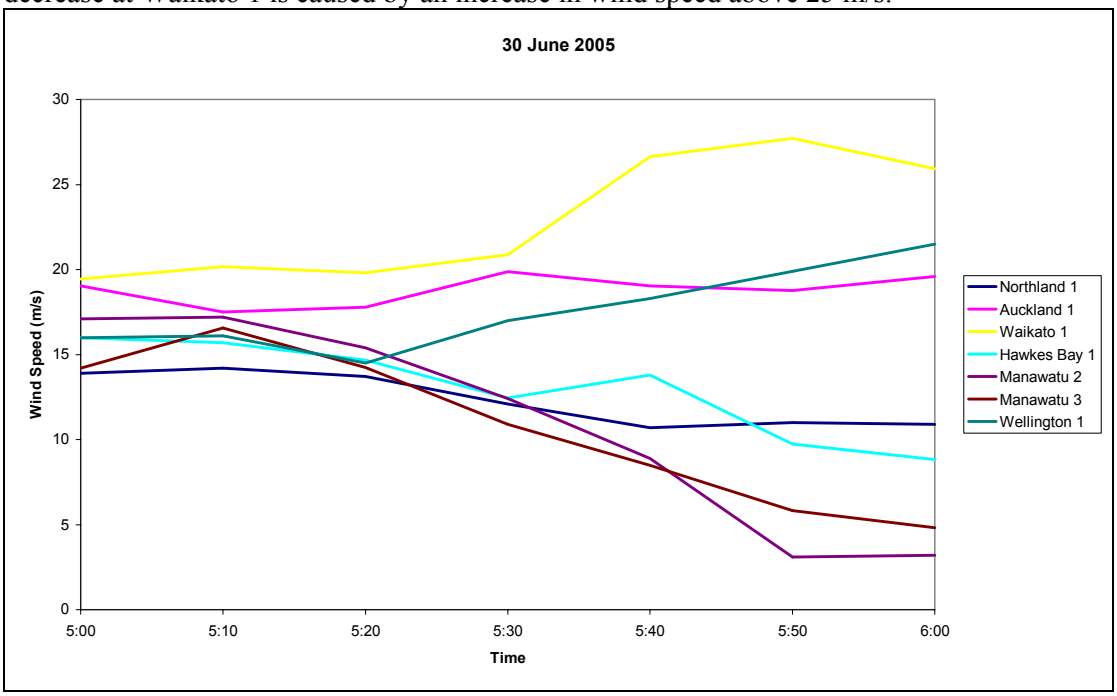


Figure 2.35 – Wind speeds recorded on 30 June 2005

28 September 2004 11:30 to 11:40

Over this time period the theoretical North Island output decreases from 717 MW at 11:30 to 547 MW at 11:40, or approximately 171 MW over 10 minutes. This change is shown in the figure below. This is driven by decreases in the theoretical power output at Manawatu 2 and Manawatu 3.

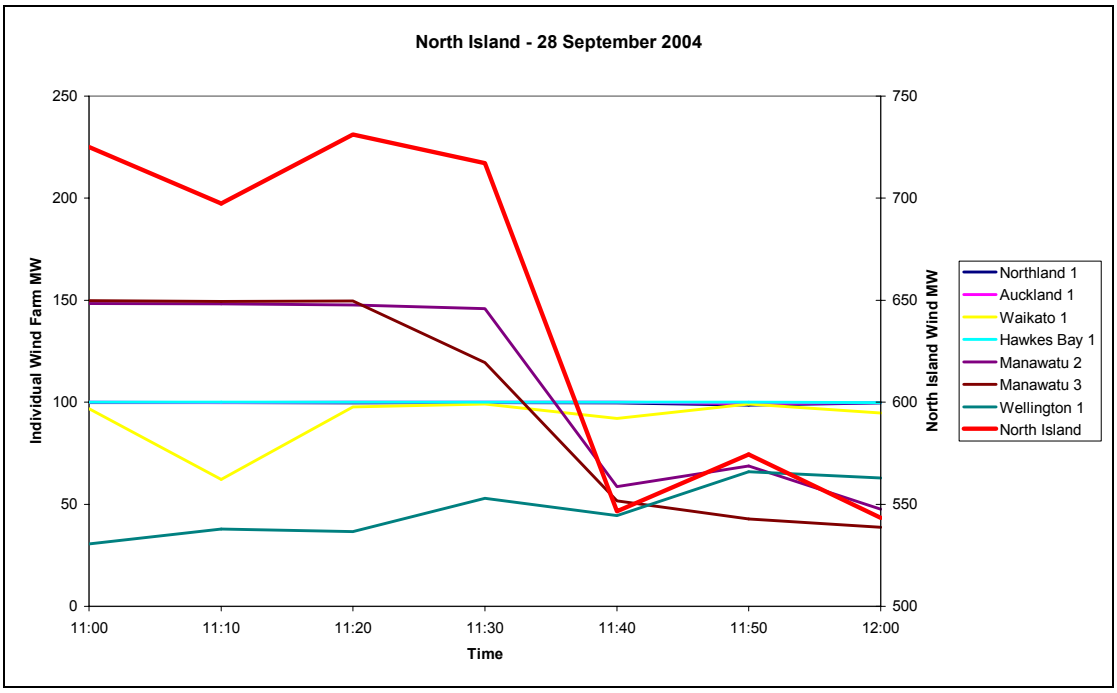


Figure 2.36 – Theoretical North Island wind farm power outputs on 28 September 2004

From the plot of wind speeds, below, it can be seen that the wind speed at both Manawatu 2 and Manawatu 3 decrease below 15 m/s.

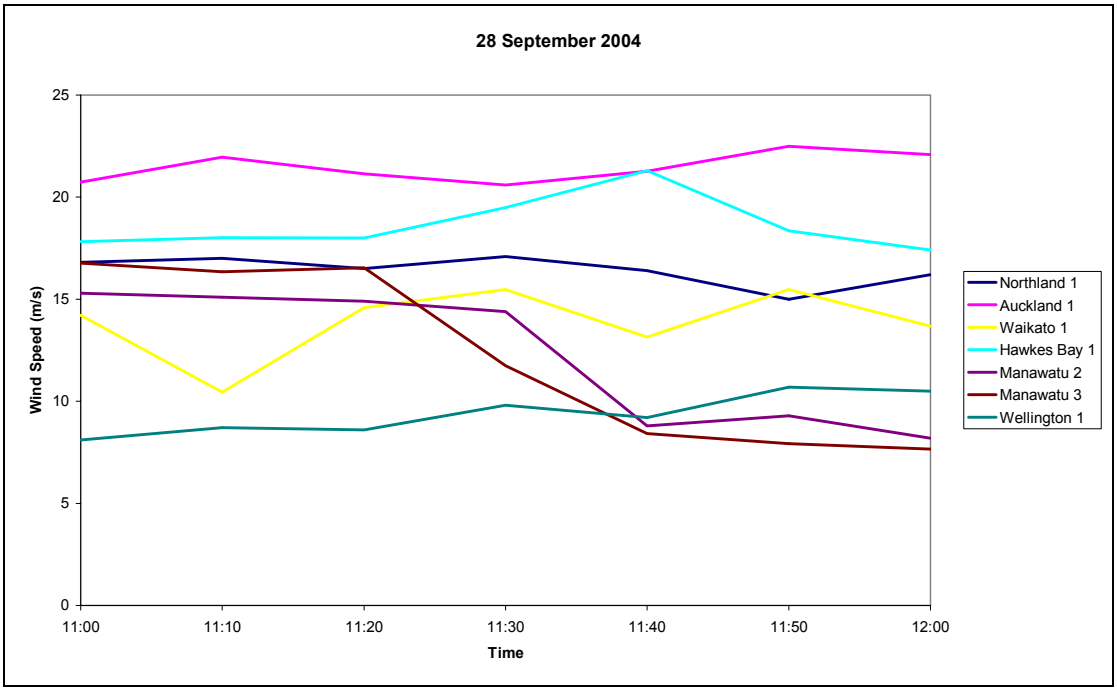


Figure 2.37 – Wind speeds recorded on 28 September 2004

3 September 2004 16:00 to 16:10

Over this time period the theoretical North Island output increases from 368 MW at 16:00 to 533 MW at 16:10, or approximately 165 MW over 10 minutes. This change is shown in the figure below. This is driven by increases in the theoretical power output at Manawatu 2, Manawatu 3 and Auckland 1.

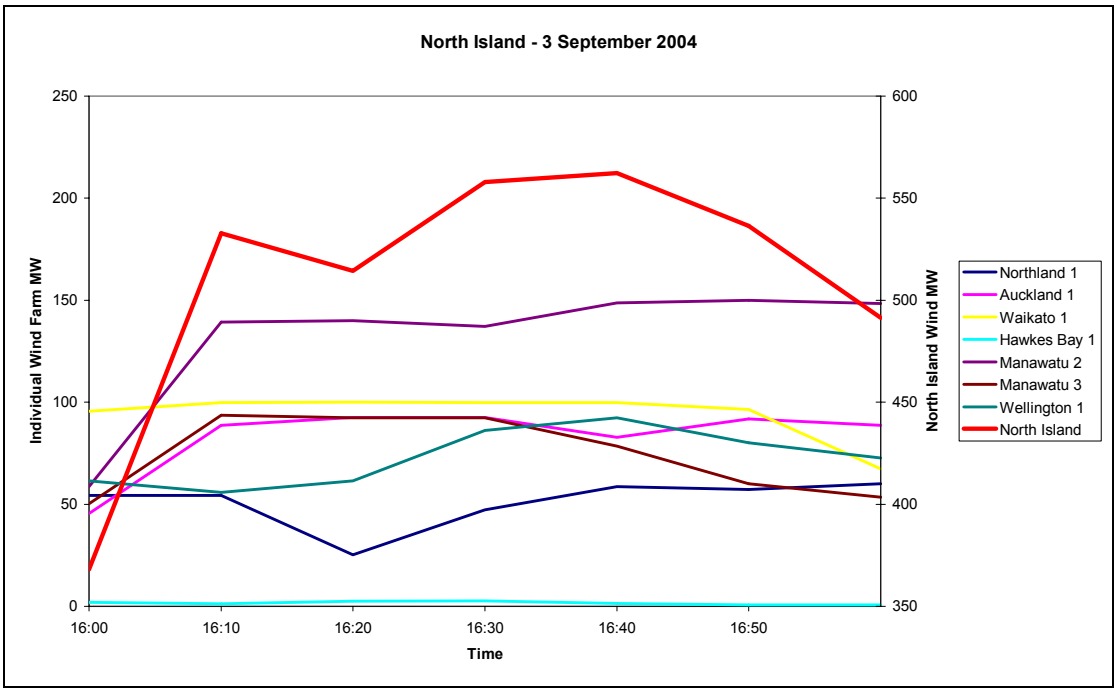


Figure 2.38 – Theoretical North Island wind farm power outputs on 3 September 2004

From the plot below, it can be seen that the increases in theoretical power output at these sites are all driven by increases in wind speeds (below 15 m/s) occurring at the sites.

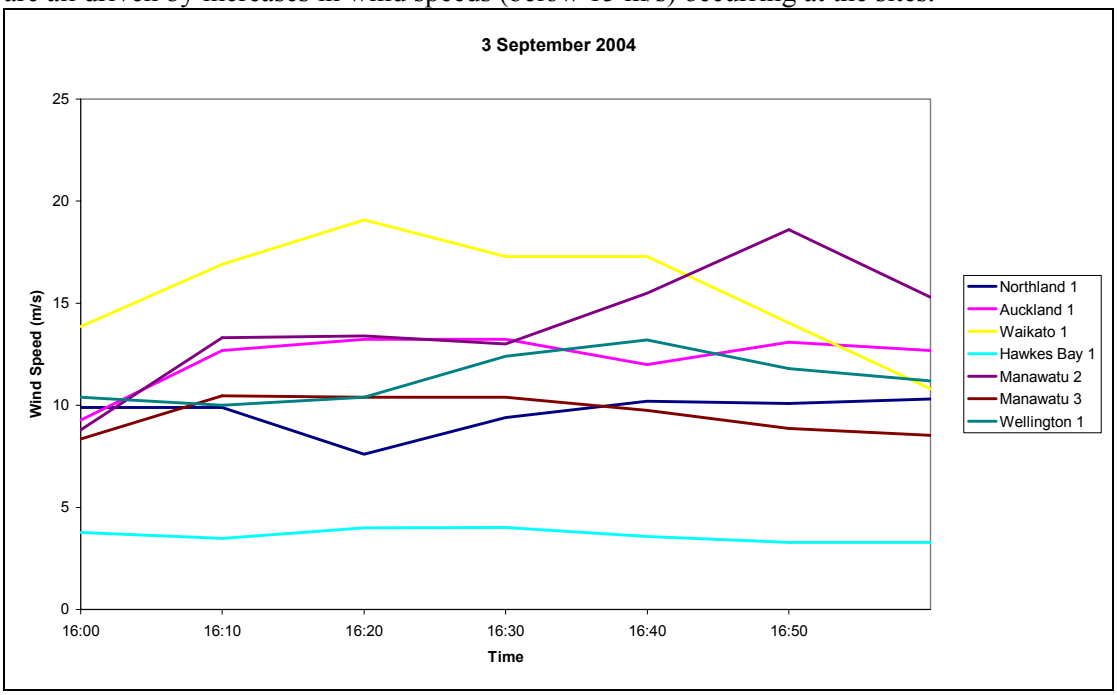


Figure 2.39 – Wind speeds recorded on 3 September 2004

21 April 2005 11:10 to 11:20

Over this time period the theoretical North Island output increases from 368 MW at 11:10 to 531 MW at 11:20, or approximately 162 MW over 10 minutes. This is caused by increases in the theoretical power outputs at Manawatu 2 and Manawatu 3

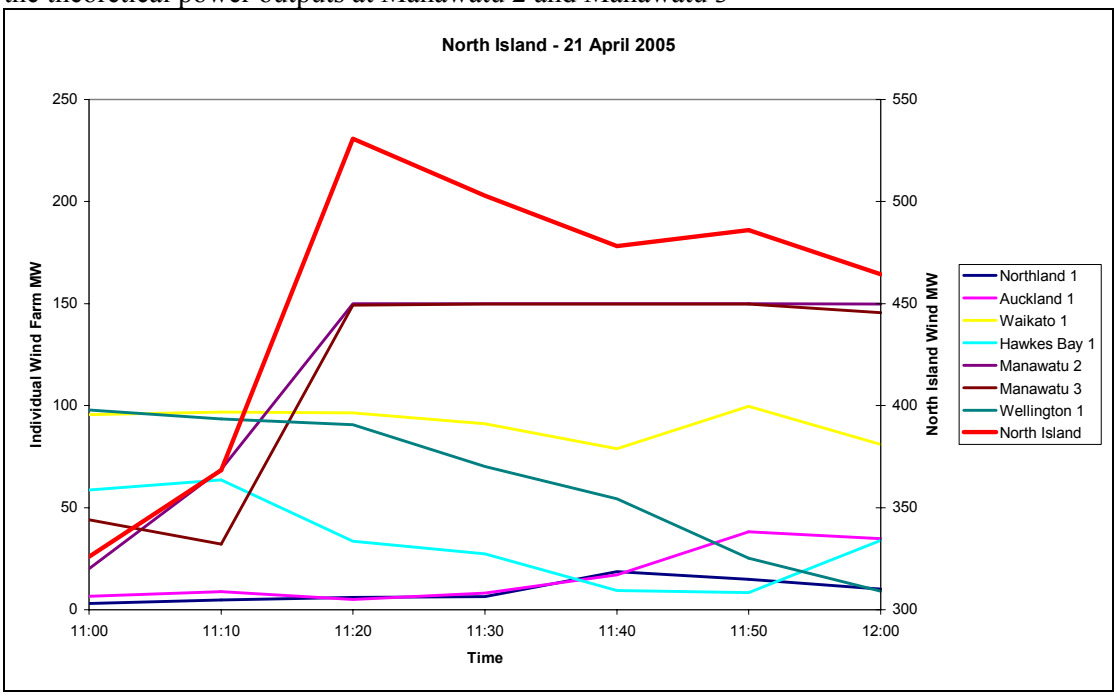


Figure 2.40 – Theoretical North Island wind farm power outputs on 21 April 2005

As can be seen from the figure below, the increases in theoretical power output at the Manawatu 2 and Manawatu 3 sites are driven by increases in wind speed at the sites from below 15 m/s.

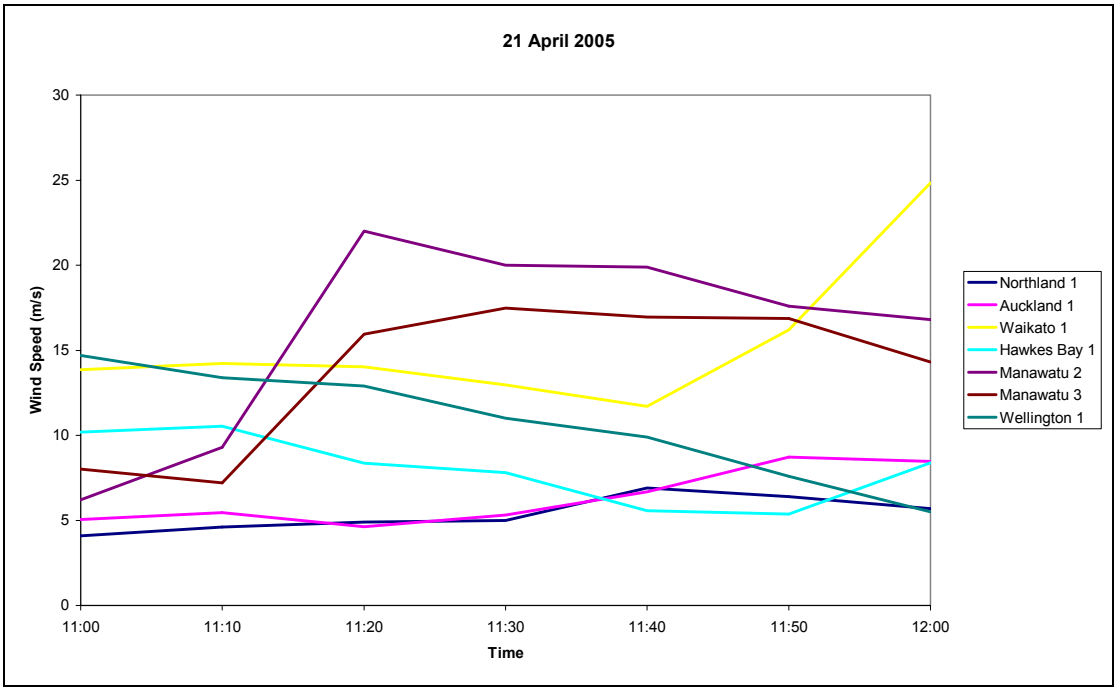


Figure 2.41 – Wind speeds recorded on 21 April 2005

10 December 2004 08:50 to 09:00

Over this time period the theoretical North Island output decreases from 754 MW at 08:50 to 592 MW at 09:00, or approximately 161 MW over 10 minutes. This is caused by decreases in the theoretical power outputs at Waikato 1, Hawkes Bay 1 and Manawatu 3

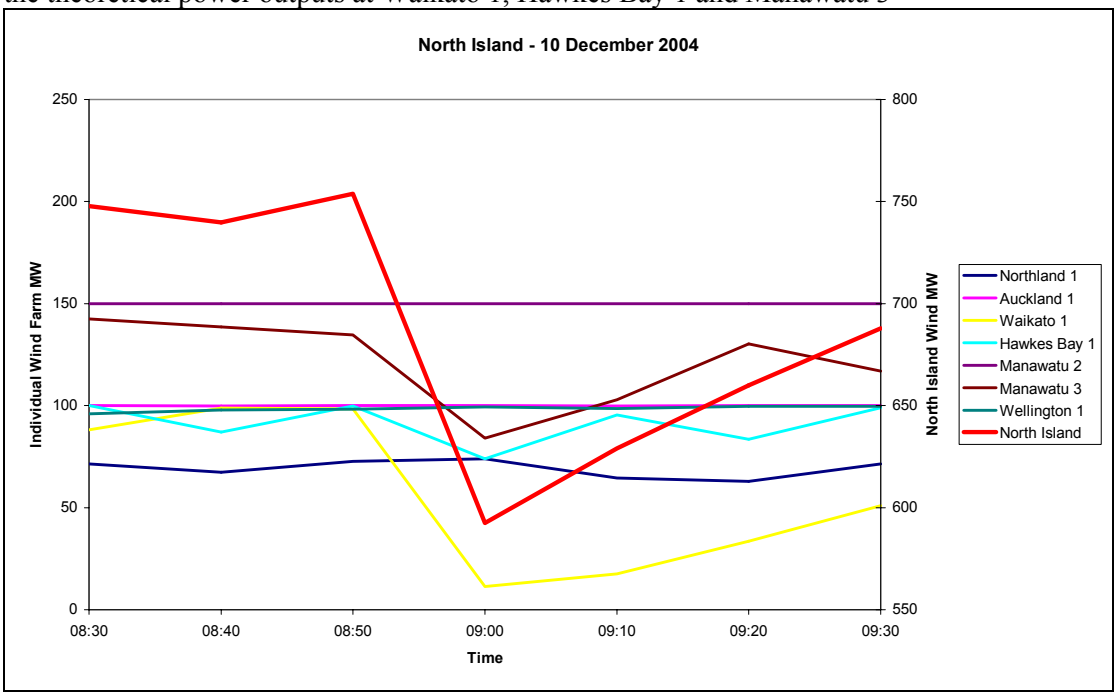


Figure 2.42 – Theoretical North Island wind farm power outputs on 10 December 2004

As can be seen from the figure below, the decreases in theoretical power output at the Waikato 1, Hawkes Bay 1 and Manawatu 3 sites are driven by increases in wind speed at the sites above 25 m/s.

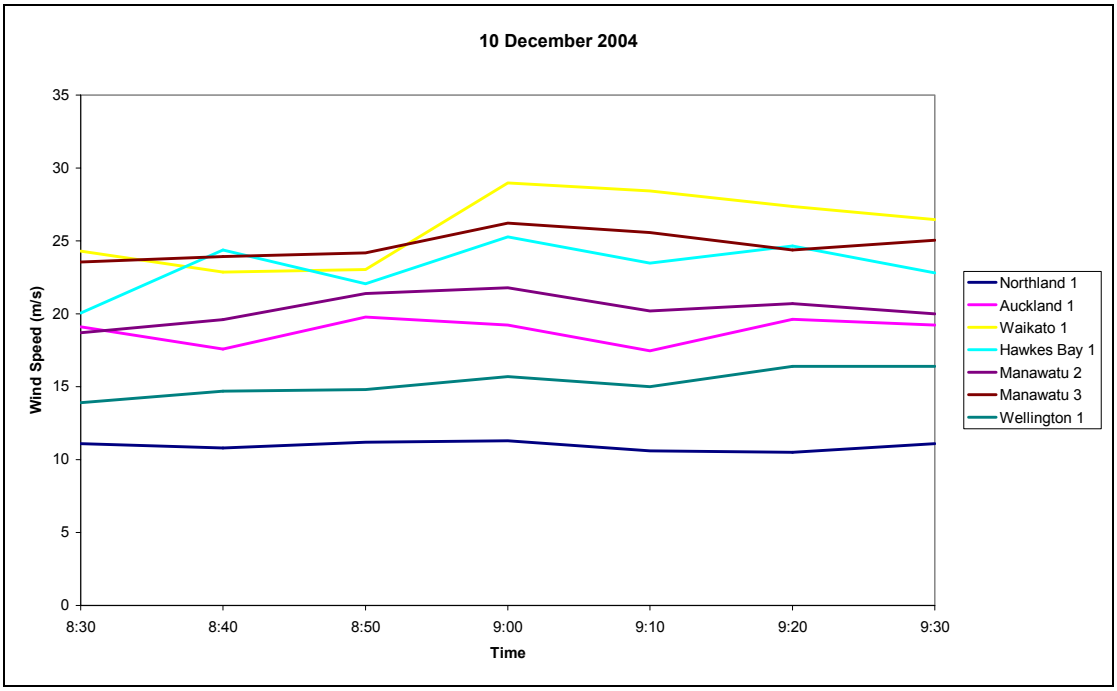


Figure 2.43 – Wind speeds recorded on 10 December 2004

18 December 2004 16:50 to 17:00

Over this time period the theoretical North Island output decreases from 485 MW at 16:50 to 331 MW at 17:00, or approximately 155 MW over 10 minutes. This is caused by decreases in the theoretical power outputs at Auckland 1, Waikato 1 and Hawkes Bay 1.

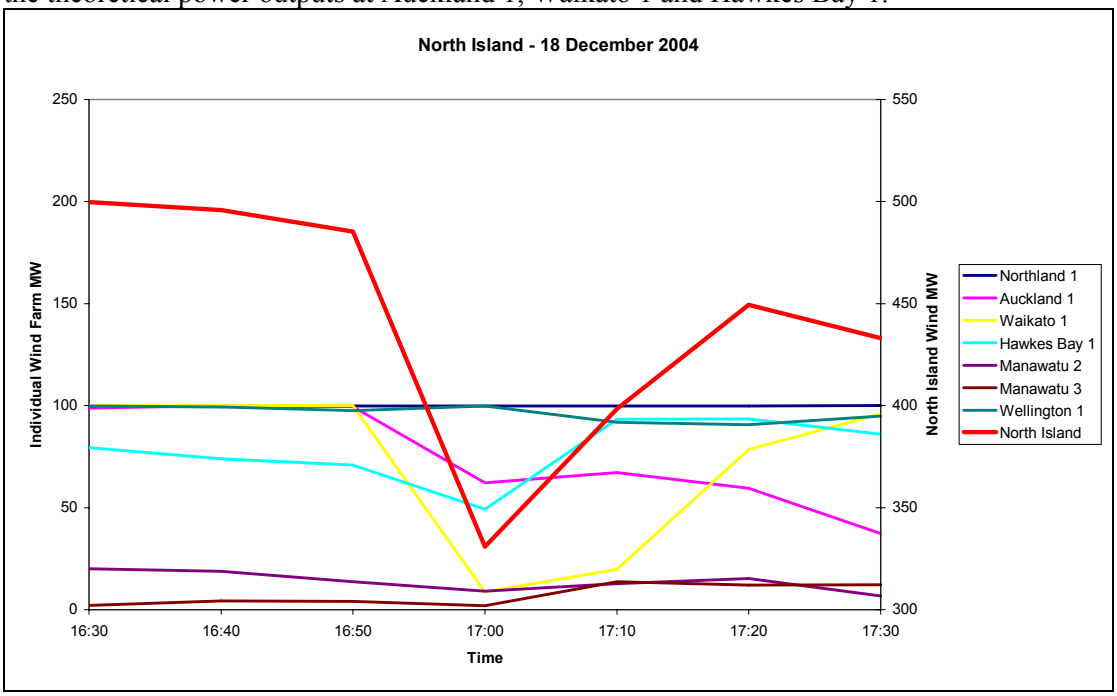


Figure 2.44 – Theoretical North Island wind farm power outputs on 18 December 2004

As can be seen from the figure below, the decreases in theoretical power output at the Auckland 1, Waikato 1 and Hawkes Bay 1 sites are driven by increases in wind speed at the sites above 25 m/s at Auckland 1 and Waikato 1 and a decrease in wind speed below 15 m/s at Hawkes Bay 1.

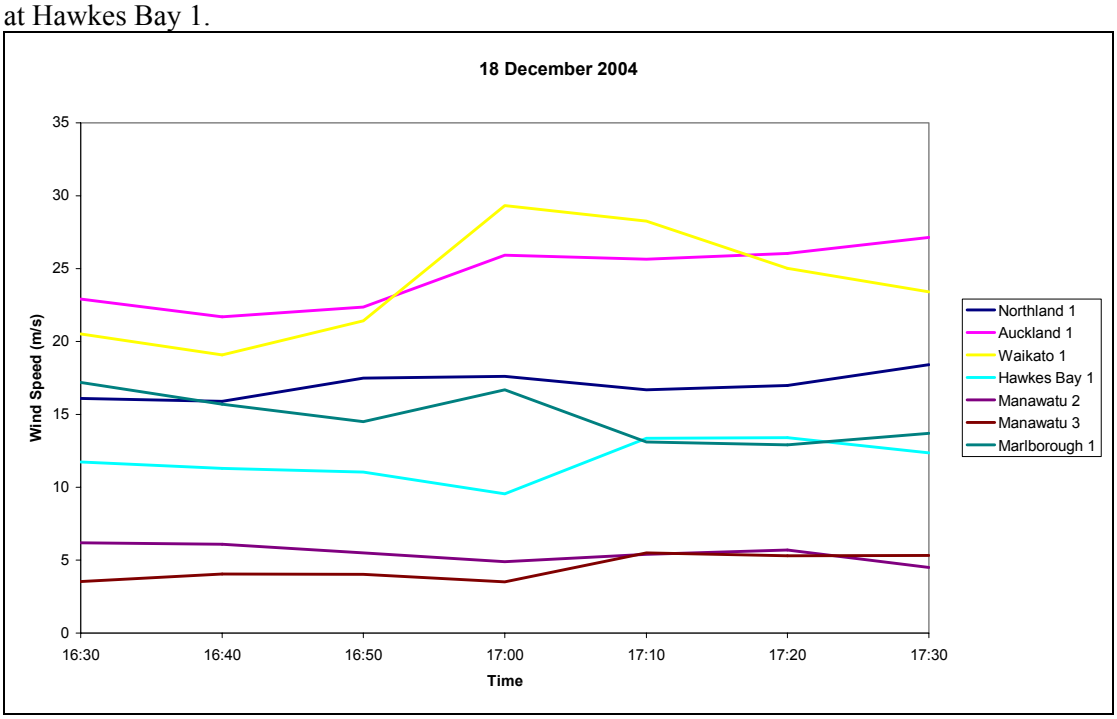


Figure 2.45 – Wind speeds recorded on 18 December 2004

30 May 2005 20:00 to 20:10

Over this time period the theoretical North Island output increases from 527 MW at 20:00 to 674 MW at 20:10, or approximately 147 MW over 10 minutes. This is caused by decreases in the theoretical power outputs at Auckland 1, Manawatu 2 and Manawatu 3.

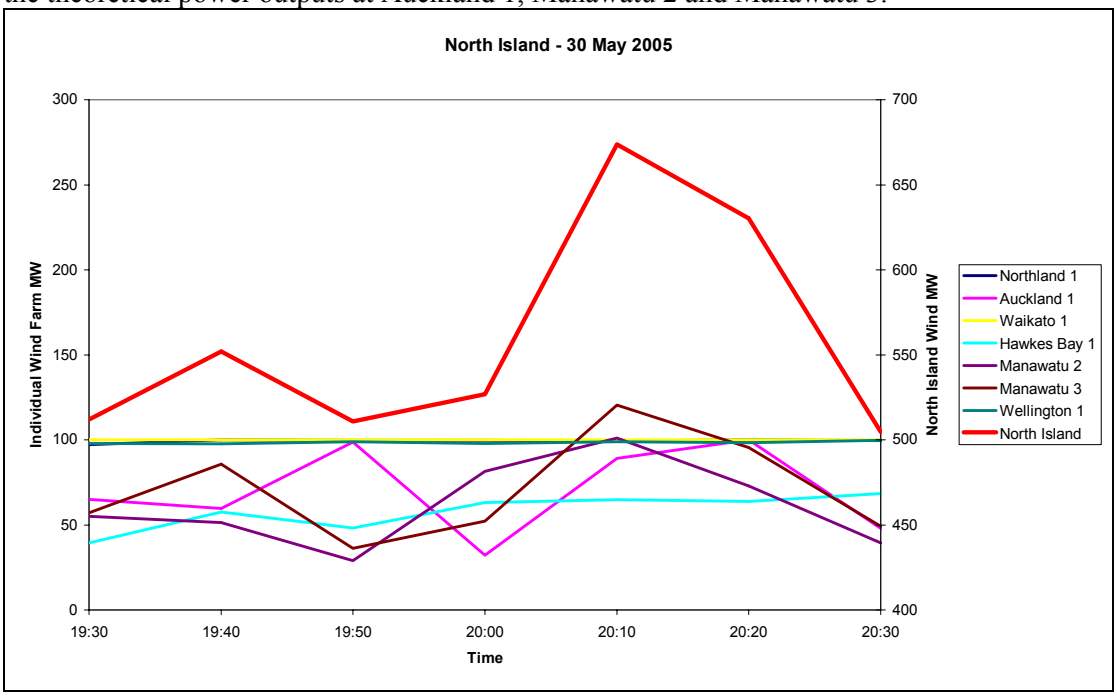


Figure 2.46 – Theoretical North Island wind farm power outputs on 30 May 2005

As can be seen from the figure below, the increases in theoretical power output at the Auckland 1, Manawatu 2 and Manawatu 3 sites are driven by increases in wind speed at the sites from below 15 m/s at Manawatu 2 and Manawatu 3 and a decrease in wind speed from above 25 m/s at Auckland 1.

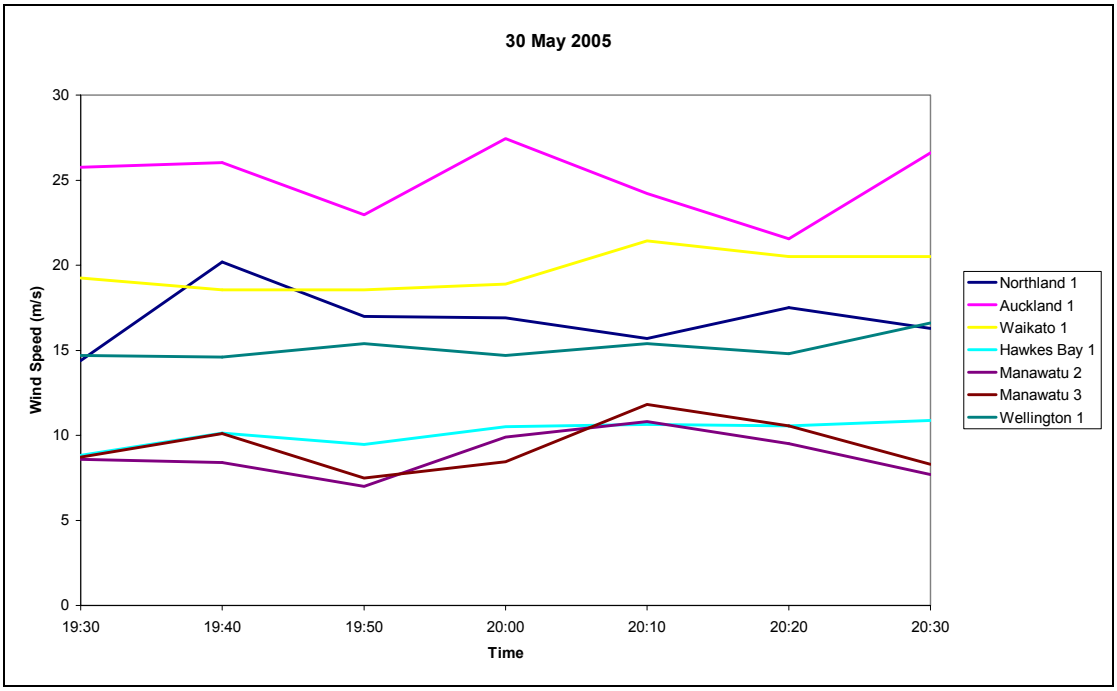


Figure 2.47 – Wind speeds recorded on 30 May 2005

2.4.5. Ten largest rates of change in theoretical output for the modelled South Island wind generation.

The scenario was examined to identify the ten largest rates of change recorded in the 225 days of data for the modelled South Island wind farms. These are shown in the following table, and each event is examined in more detail in the following pages.

Rank	Date and Time (NZST)	MW change over 10 minutes
1	30 June 2005, 01:40	103
2	12 December 2004, 19:50	103
3	27 February 2005, 08:30	-93
4	18 December 2004; 11:50	-92
5	14 May 2005, 06:20	91
6	27 February 2005, 08:50	91
7	30 May 2005, 13:00	90
8	25 November 2004, 11:50	-88
9	1 June 2005, 06:40	88
10	24 November 2004, 10:50	86

Table 2.12 – Ten largest changes in South Island theoretical output for the scenario modelled

30 June 2005 01:30 to 01:40

Over this time period the theoretical South Island output increases from 172 MW at 01:30 to 275 MW at 01:40, or approximately 103 MW over 10 minutes. This is caused by a large increase at Marlborough 1, in combination with a smaller increase at Central Otago 1.

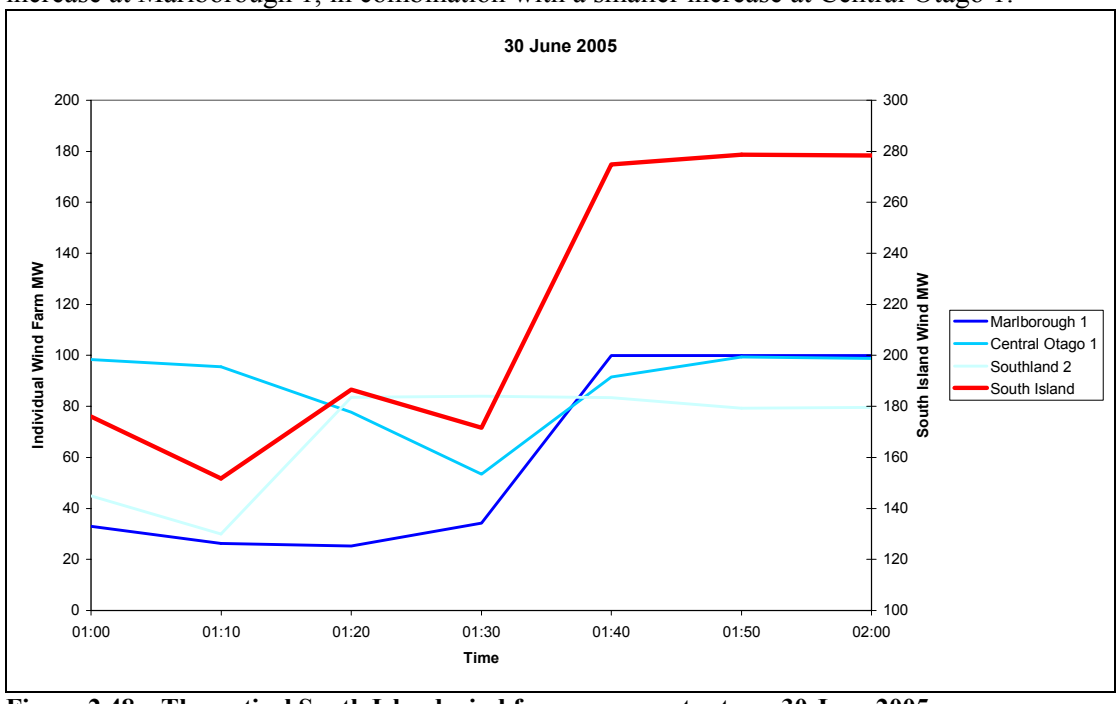


Figure 2.48 – Theoretical South Island wind farm power outputs on 30 June 2005

As can be seen from the figure below, the increases in theoretical power outputs at the Marlborough 1 and Central Otago 1, are driven by increases in wind speed at the sites from below 15 m/s.

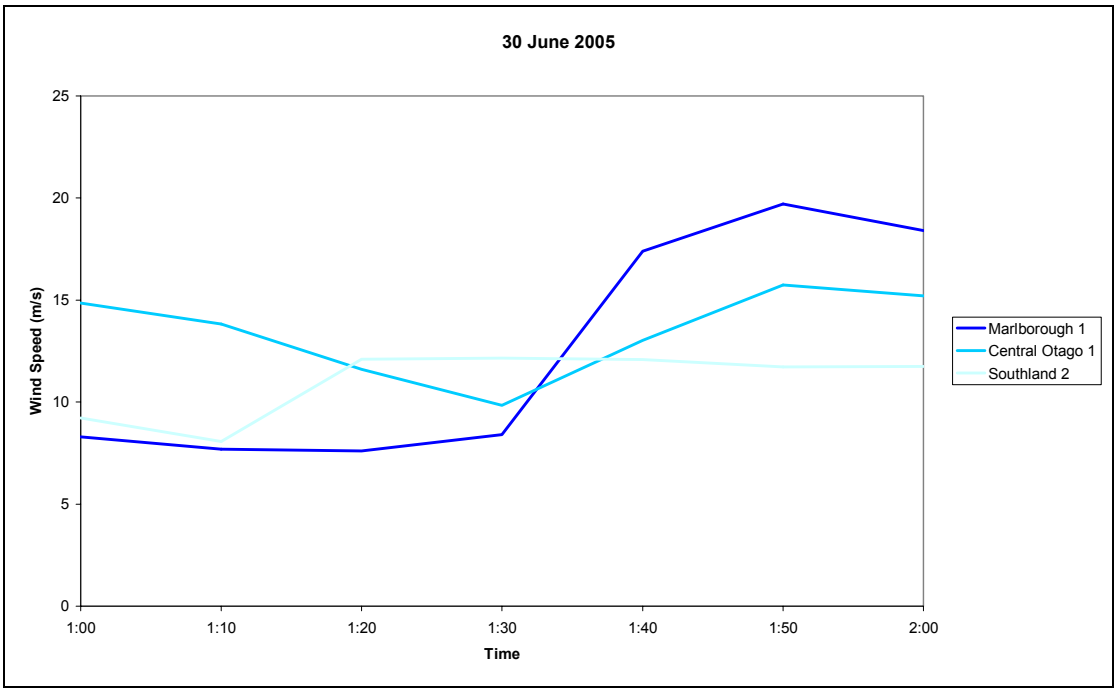


Figure 2.49 – Wind speeds recorded on 30 June 2005

12 December 2004 19:40 to 19:50

Over this time period the theoretical South Island output increases from 121 MW at 19:40 to 224 MW at 19:50, or approximately 103 MW over 10 minutes. This is caused by a large increase at Marlborough 1, in combination a smaller increase at Central Otago 1.

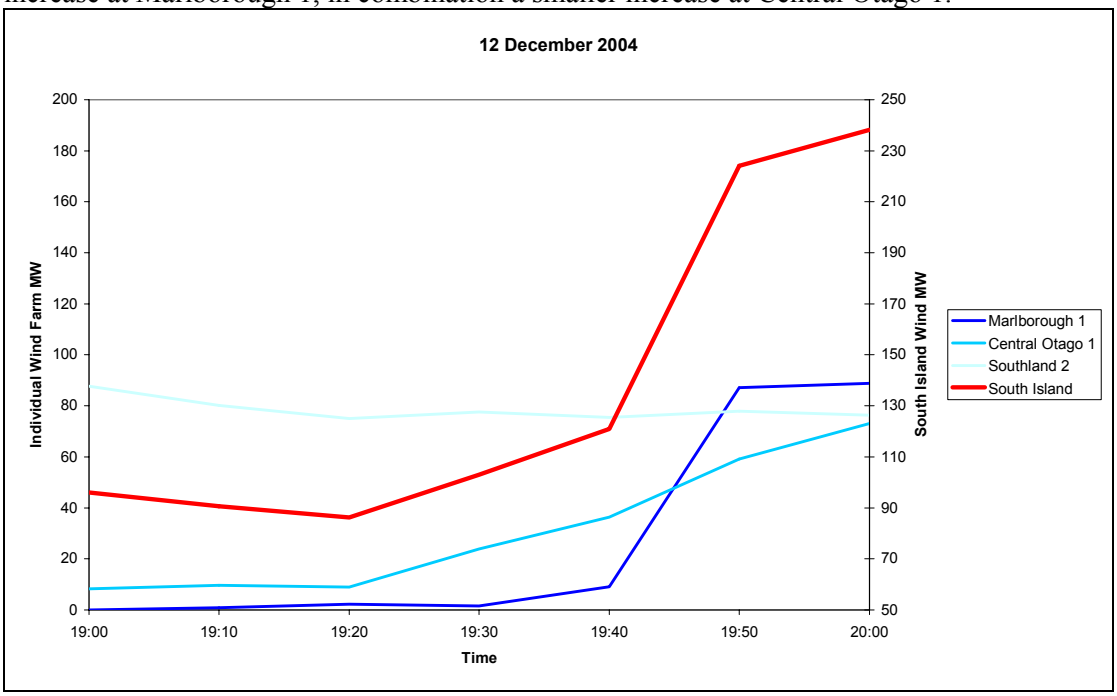


Figure 2.50 – Theoretical South Island wind farm power outputs on 12 December 2004

As can be seen from the figure below, the increases in theoretical power output at the Marlborough 1 and Central Otago 1 sites are driven by increases in wind speed at the sites from below 15 m/s.

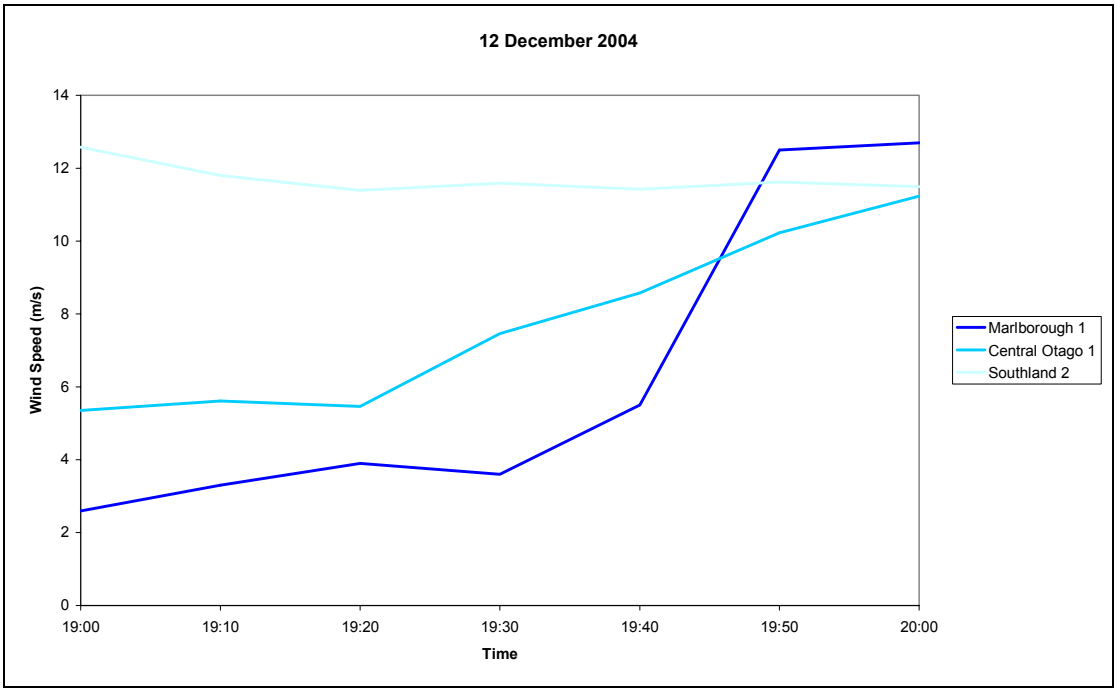


Figure 2.51 – Wind speeds recorded on 12 December 2004

27 February 2005 08:20 to 08:30 and 8:40 to 8:50

Over this time period the theoretical South Island output decreases from 124 MW at 08:20 to 32 MW at 08:30, or approximately 93 MW over 10 minutes. This is caused by a large decrease at Southland 2. This event is followed by an increase in generation from 8 MW at 08:40 to 99 MW at 08:50, or approximately 91 MW over 10 minutes

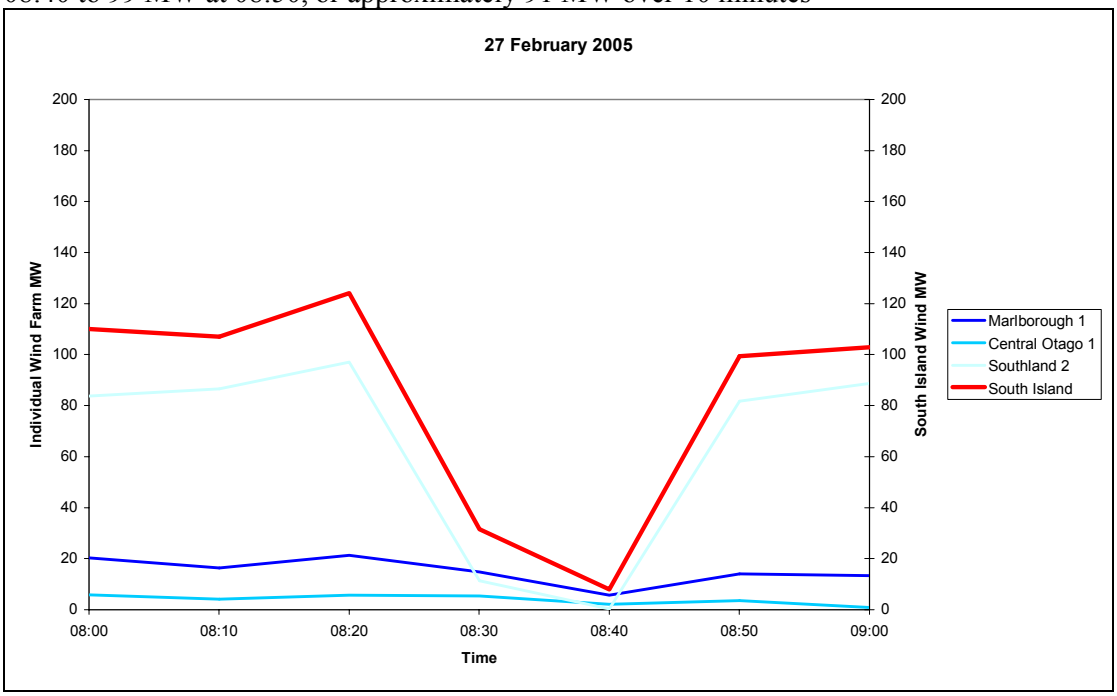


Figure 2.52 – Theoretical South Island wind farm power outputs on 27 February 2005

As can be seen from the figure below, the changes in theoretical power output at the Southland 2 site, are driven by a changes in wind speed at the site below 15 m/s.

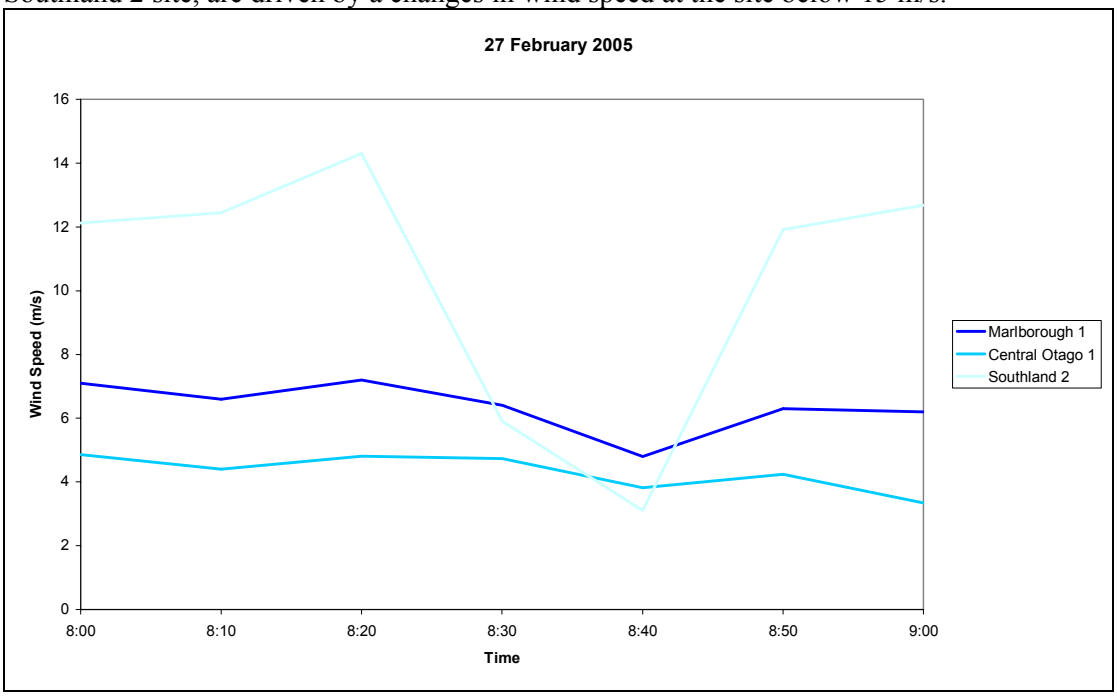


Figure 2.53 – Wind speeds recorded on 27 February 2005

18 December 2004 11:40 to 11:50

Over this time period the theoretical South Island output decreases from 255 MW at 11:40 to 164 MW at 11:50, or approximately 92 MW over 10 minutes. This is caused by decreases in generation at all 3 South Island sites.

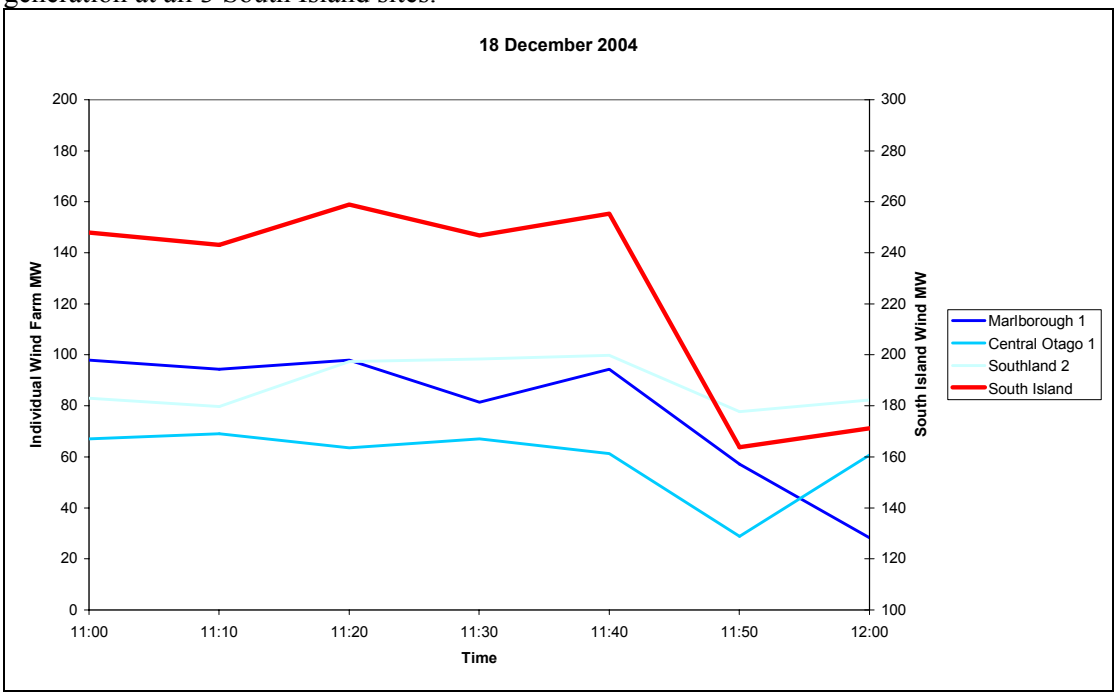


Figure 2.54 – Theoretical South Island wind farm power outputs on 18 December 2004

As can be seen from the figure below, the decreases in theoretical power output at the sites, are driven by a decreases in wind speed at the sites below 15 m/s.

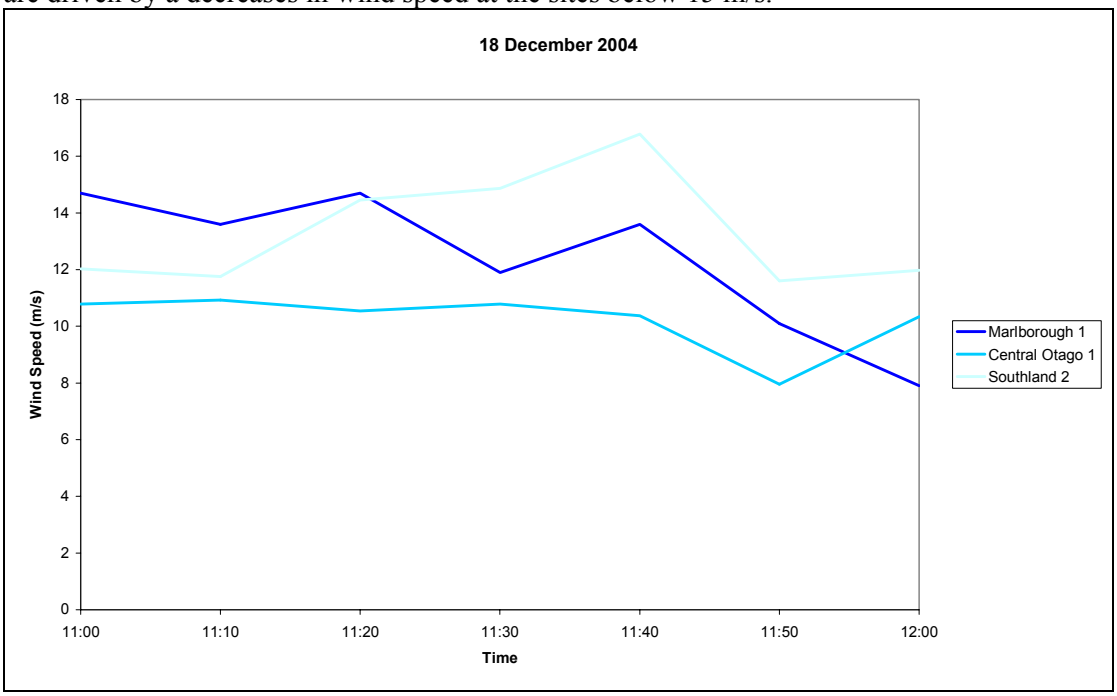


Figure 2.55 – Wind speeds recorded on 18 December 2004

14 May 2005 06:10 to 06:20

Over this time period the theoretical South Island output increases from 139 MW at 06:10 to 231 MW at 06:20, or approximately 91 MW over 10 minutes. This is caused by a large increase at Southland 2, in combination with smaller increases at Marlborough 1 and Central Otago 1.

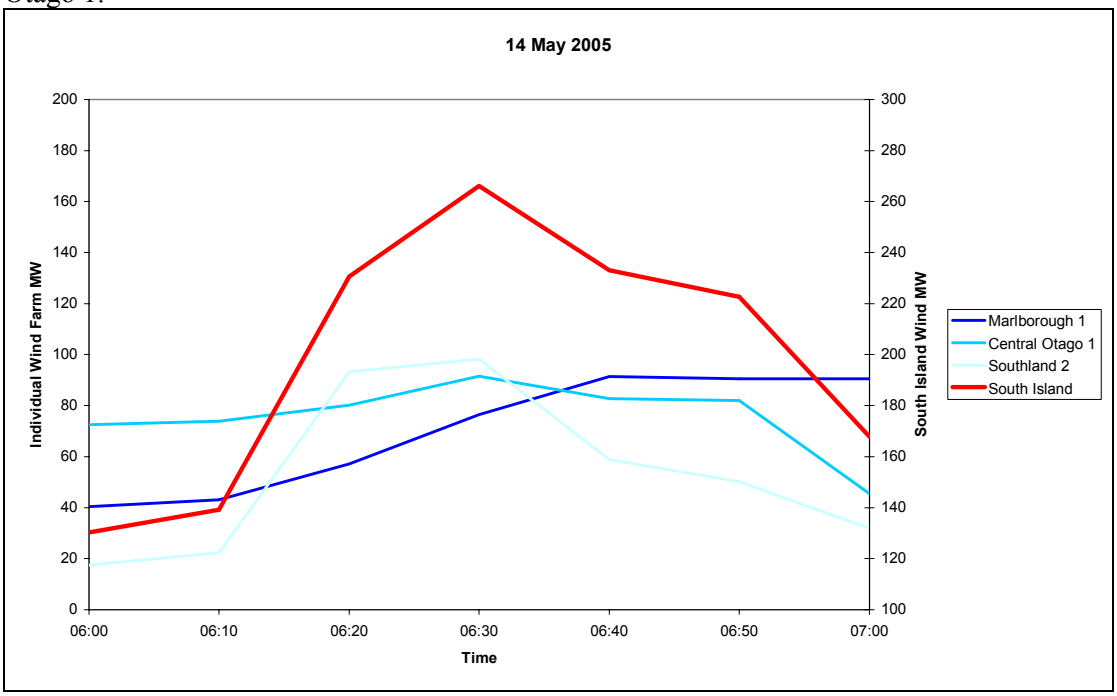


Figure 2.56 – Theoretical South Island wind farm power outputs on 14 May 2005

As can be seen from the figure below, the increases in theoretical power output at the sites, are driven by increases in wind speed at the sites from below 15 m/s.

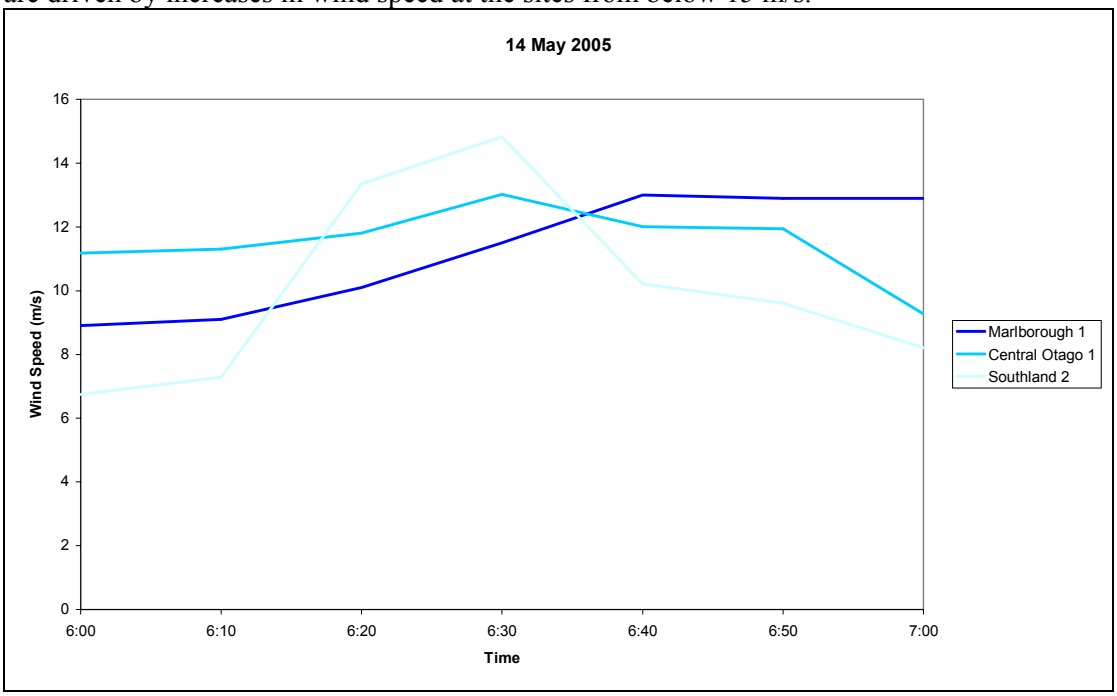


Figure 2.57 – Wind speeds recorded on 14 May 2005

30 May 2005 12:50 to 13:00

Over this time period the theoretical South Island output increases from 130 MW at 12:50 to 220 MW at 13:00, or approximately 90 MW over 10 minutes. This is caused by increases in generation at all the South Island sites.

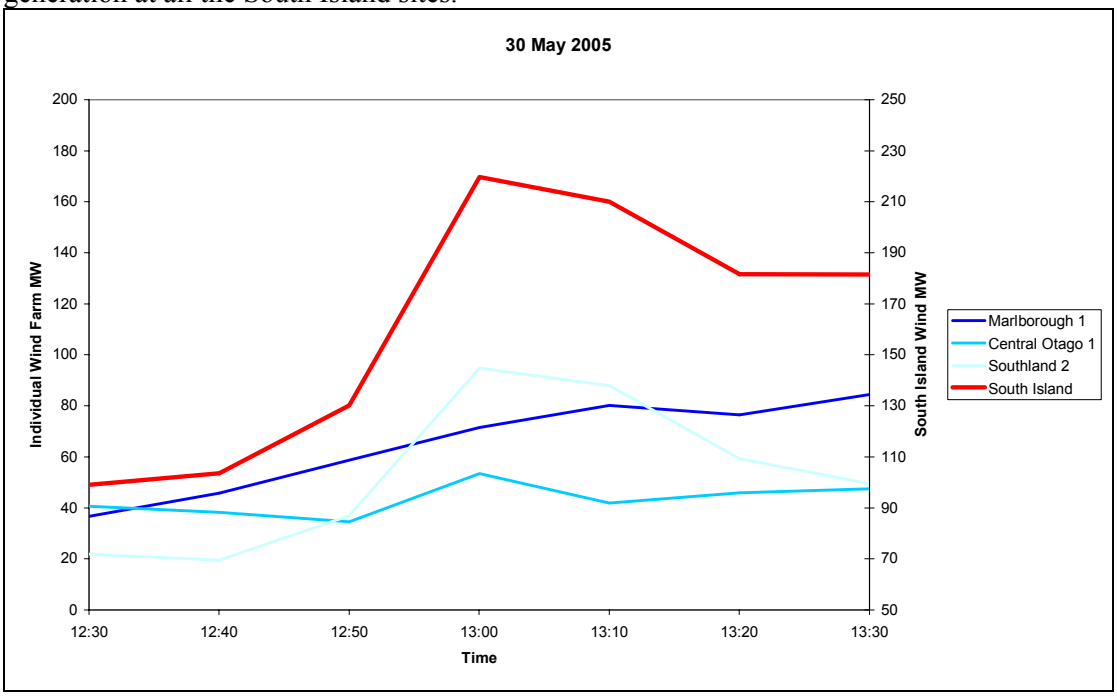


Figure 2.58 – Theoretical South Island wind farm power outputs on 30 May 2005

As can be seen from the figure below, the increases in theoretical power output at the sites, are driven by increases in wind speed at the sites from below 15 m/s.

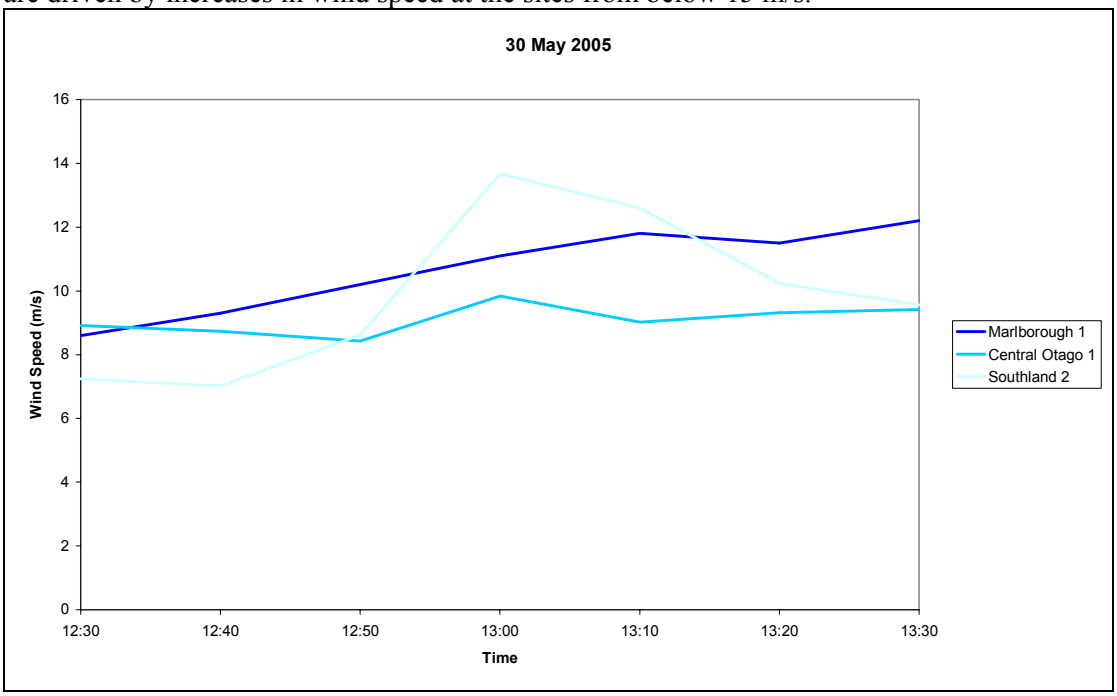


Figure 2.59 – Wind speeds recorded on 30 May 2005

25 November 2004 11:40 to 11:50

Over this time period the theoretical South Island output decreases from 252 MW at 12:50 to 163 MW at 13:00, or approximately 88 MW over 10 minutes. This is caused by decreases in generation at all the South Island sites.

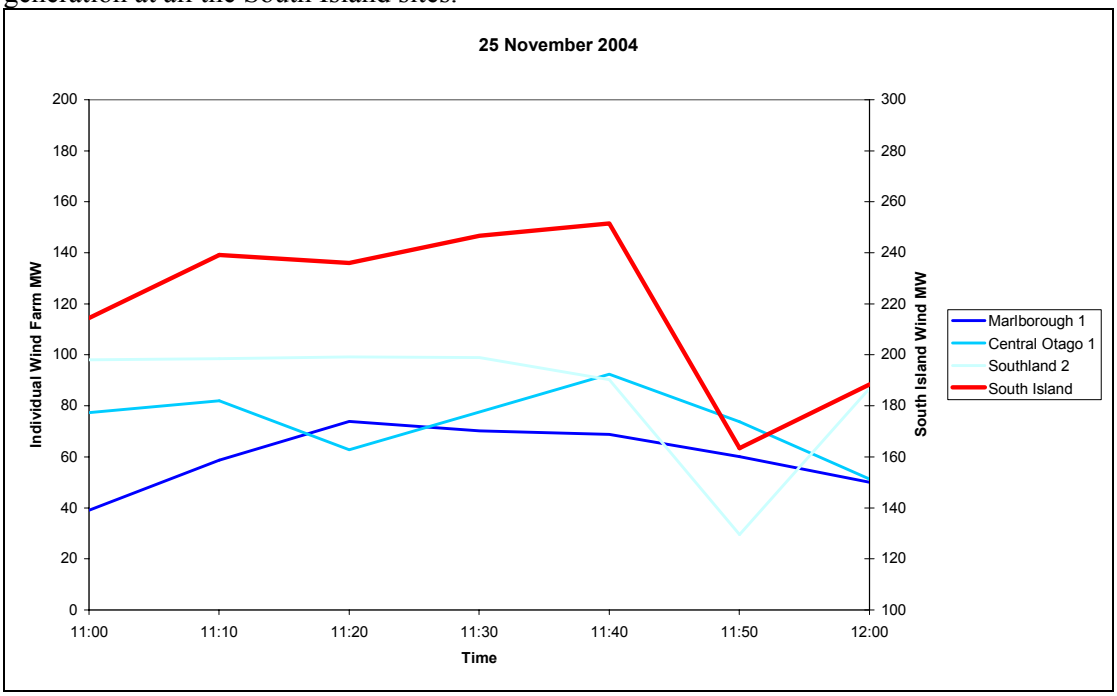


Figure 2.60 – Theoretical South Island wind farm power outputs on 24 November 2004

As can be seen from the figure below, the decreases in theoretical power output at the sites are driven by decreases in wind speed at the sites below 15 m/s.

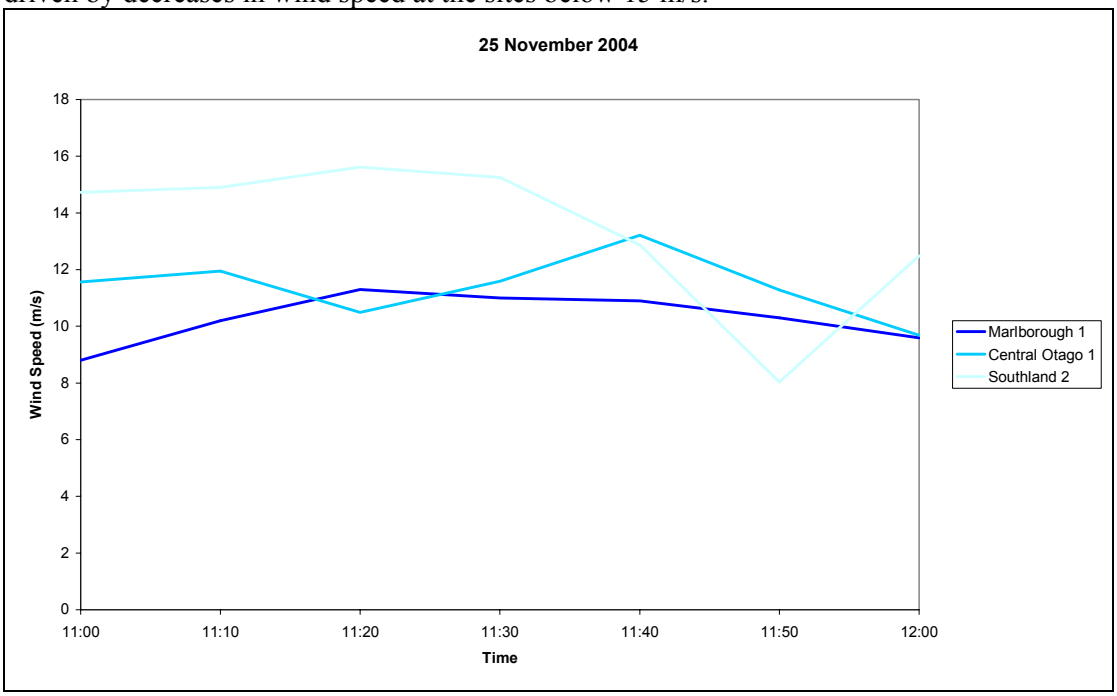


Figure 2.61 – Wind speeds recorded on 25 November 2004

1 June 2005 06:30 to 06:40

Over this time period the theoretical South Island output increases from 109 MW at 06:30 to 197 MW at 06:40, or approximately 88 MW over 10 minutes. This is caused by increases in generation at Marlborough 1 and Southland 2.

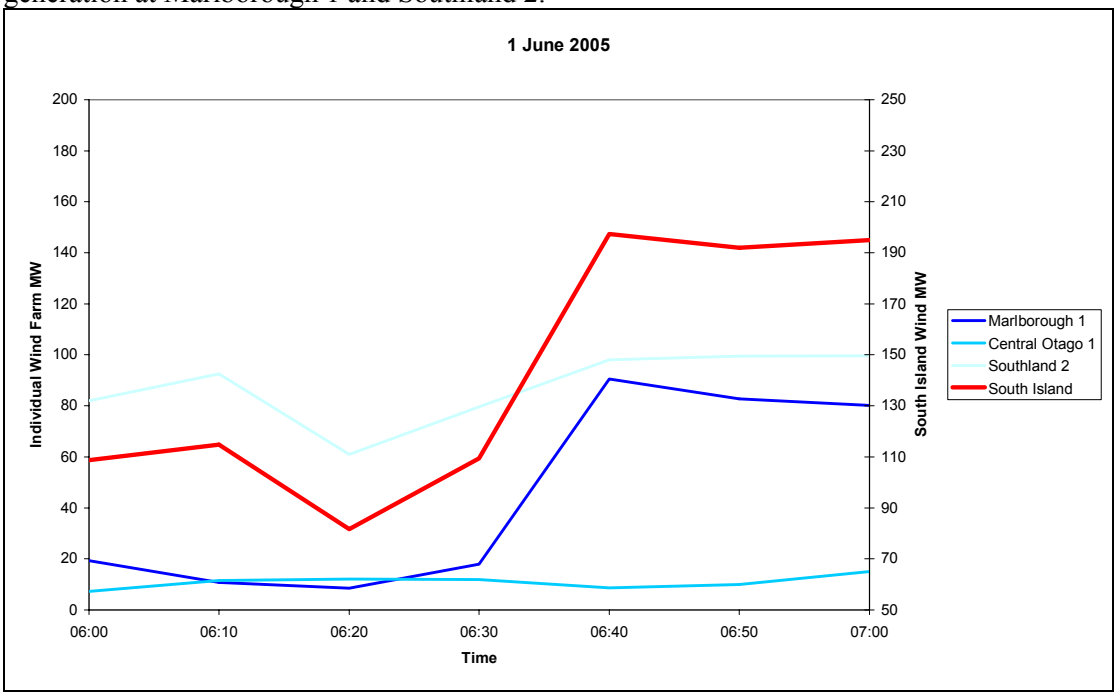


Figure 2.62 – Theoretical South Island wind farm power outputs on 1 June 2005

As can be seen from the figure below, the increases in theoretical power output at Marlborough 1 and Southland 2 are driven by increases in wind speed at the sites from below 15 m/s.

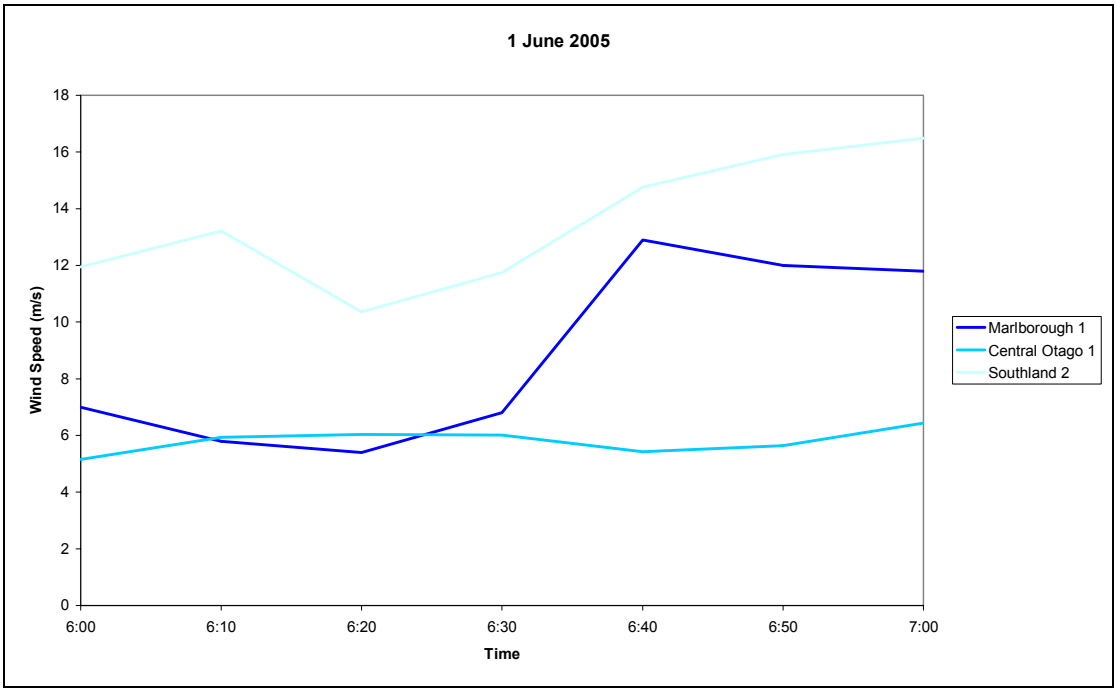


Figure 2.63 – Wind speeds recorded on 1 June 2005

24 November 2004 10:40 to 10:50

Over this time period the theoretical South Island output increases from 71 MW at 10:40 to 157 MW at 10:50, or approximately 86 MW over 10 minutes. This is caused by increases in generation at Marlborough 1 and Southland 2

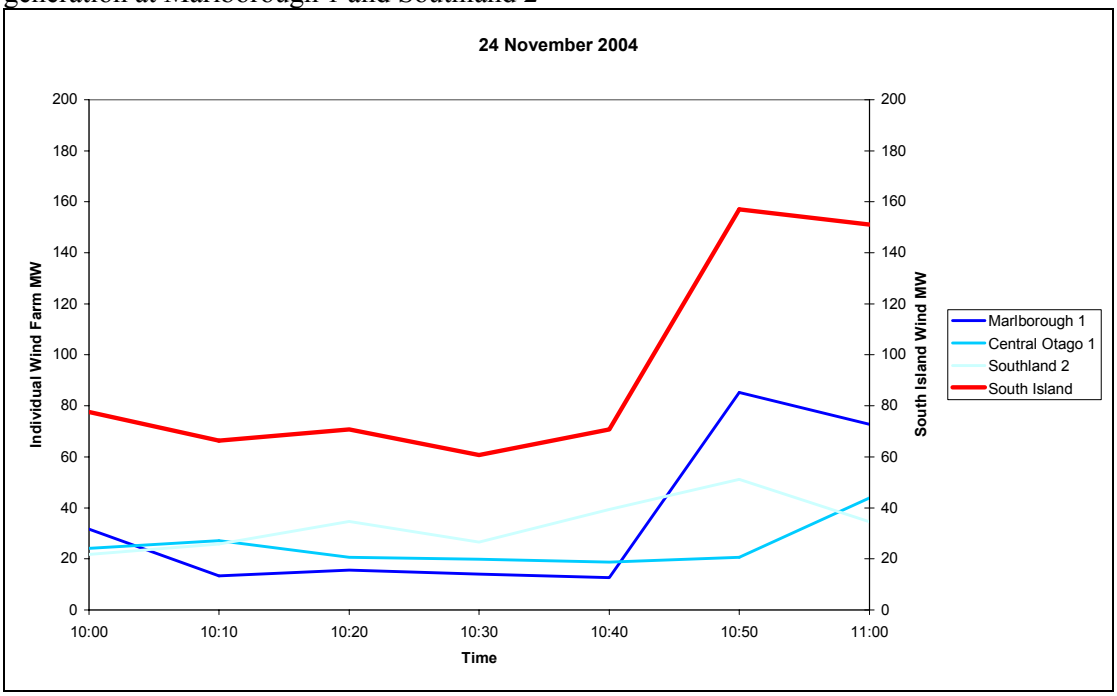


Figure 2.64 – Theoretical South Island wind farm power outputs on 24 November 2004

As can be seen from the figure below, the increases in theoretical power output at Marlborough 1 and Southland 2 are driven by increases in wind speed at the sites from below 15 m/s.

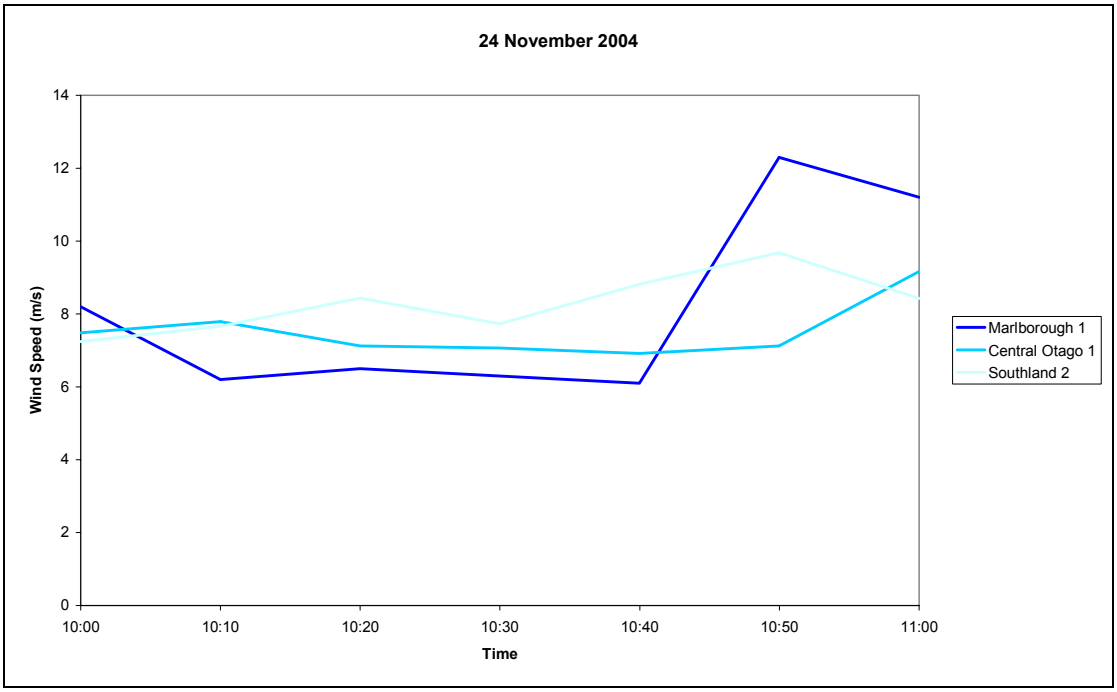


Figure 2.65 – Wind speeds recorded on 24 November 2004

3. DISCUSSION AND CONCLUSIONS

3.1. Correlation between sites

From the analysis of the correlation relationships, the following conclusions can be drawn;

- The correlation between sites generally increases for longer averaging periods.
- The correlation of theoretical wind power output is generally lower than the corresponding correlation in wind speed.
- The correlation of rate of change of theoretical power output is generally very low between sites.

In the context of this study, the r-squared values can be interpreted as the proportion of deviation from the average that the data sets have in common For example if the r-squared value is 0.5, half of the deviation from the mean in the data sets is in common. An r-squared value of 0 would imply no deviation in common, while 1 would imply all the deviation from the mean is in common.

For the 10 minute wind speed data, r-squared values between sites that are not in the same regions are generally below 0.5, the exception being the Auckland 1 site, which has r-squared values higher than this level for sites in the neighbouring regions of Northland and Waikato. R-squared values generally decrease with increasing distance between the regions, for example the Northland sites have r-squared values below 0.1 for all the regions examined south of the Waikato.

Within regions, r-squared values can be quite high, in excess of 0.7 in some cases. This is thought to be driven primarily by the proximity of the sites to each other. Some regions show quite low correlation within the region, for example, no Southland site had an r-squared value greater than 0.3 even with another site in the same region.

Moving to longer averaging periods, the r-squared values between the sites increase. It is relatively common for sites in neighbouring regions to have r-squared values in the order of 0.7 for a 24 hour averaging period, while r-squared values for sites within the same region can be in excess of 0.9. The same general trends of decreasing correlation with increasing distance remain.

Looking at the correlation between the theoretical power outputs at the sites, the r-squared values are generally lower than the corresponding wind speed values. Generally similar patterns can be seen in the correlation relationships, they tend to increase with increasing averaging time, and decrease with increasing distance.

The correlation of rates of change of theoretical power outputs is low, even for sites within the same region. This is not all together surprising, since the sites are known to be several kilometres apart, and for the rates of change to be correlated, increases or decreases in wind speed would have to occur within the same time period. From the values, which are close to zero, it would seem to be reasonable to postulate that the theoretical rate of change at one site is independent of the theoretical rate of change at the other sites that have been examined in this report.

3.2. The scenario

The generation duration curve developed from the 1100 MW scenario for the 225 days modelled shows that;

- Theoretical output from the scenario was above 100 MW approximately 95% of the time.
- Theoretical output from the scenario was above 1000 MW approximately 1% of the time.
- The average output from the scenario was approximately 460 MW.

The rates of change in theoretical output from the scenario seem broadly in line with the postulation that rates of change at the sites are independent. Using this assumption the magnitude of the rates of change for the overall scenario for a given frequency of occurrence is able to be calculated as the square root of the sum of the squares. For the scenario analysed, this would imply that the scenario rates of change would be in the order of 2.4 times the rates of change for a theoretical 150 MW Manawatu wind farm. Figure 2.11 appears to be broadly in line with these expectations.

Transpower as System Operator has reported an asymmetric rate of change distribution from wind generation in the Manawatu [1], with increases in output occurring more rapidly than decreases in output. These increases in output have generally been sustained for periods less than 10 minutes (of the order of 5 minutes). The theoretical rate of change distributions derived in this report are largely symmetric. This may be because 10 minute data have been used, and so changes that occur in shorter timeframes than this are not fully reflected in the wind data.

From Figure 2.11; it is the sites with the largest installed capacity (Manawatu 2 and Manawatu 3) which contribute most to the overall scenario rate of change of output. This is expected by GH, as contributions would be expected to be broadly proportional to the wind farms. Waikato 1 also makes a comparable contribution, however this may be due to scaling of the data set supplied to the EC (data suppliers were permitted to scale their data sets). In a real world situation, larger wind farm sites could be expected to contribute to overall rates of change in output in a slightly less than proportional manner, as diversity within a large wind farm site becomes more significant. (For example, it may take several minutes or even tens of minutes for a weather system to traverse a large site such as the proposed project West Wind).

Looking at the individual events, large changes in theoretical wind farm output tend to occur with large changes in wind speed when the wind speed is in the range 5-15 m/s and 25-30 m/s. This is to be expected from the shape of the wind farm power curve. When the wind speed is in these ranges, the theoretical output of the wind farm changes rapidly with changes in wind speed. Outside those wind speed ranges, wind farm output is relatively unresponsive to changes in wind speed.

The scenario has been further analyses by looking separately at the theoretical wind generation installed in both islands. As the North Island contains most of the theoretical wind generation in the scenario, many of the events represented in the overall scenario are also evident in the analysis of the theoretical North Island generation.

4. REFERENCES

1 Manawatu wind generation - Observed impacts on the scheduling and dispatch processes, Second revision, 28 September 2005, Transpower NZ Ltd.