Correlation between wind generation output and hydro inflows

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Executive summary

Integration of wind generation is seen as a key issue for the power system. One area of concern is the possible interaction between wind and hydro generation.

New analysis shows that:

- New Zealand wind generation appears to be seasonal – with output typically being high from October to January and low from April to July;
- there is a moderate correlation between wind generation output and national hydro inflows (i.e. a “dry period” is more likely to be a “calm period”). This correlation holds for wind farms throughout most of New Zealand, with the exception of Taranaki and the upper North Island.

In assessments of dry-winter security, the assumed contribution of wind should be reduced by 10% to reflect these findings.

There may also be implications for the economics of wind generation.

Acknowledgements

The Commission thanks Meridian Energy for providing the synthetic wind dataset used in this work.

The Meridian dataset was prepared using NIWA weather station data, available from the National Climate Database (cliflo.niwa.co.nz).

Thanks also to Grant Telfar (Meridian Energy) for his advice and assistance, to Steve Torrens and other EECA staff for feedback, and to Richard Turner, Roddy Henderson and Mike Revell (NIWA) for their comments on this paper and on the 2008 NZIER study.

Introduction

Integration of wind generation is seen as a key issue for the power system. Wind generation brings challenges[1] in areas including:

- variability and uncertainty on generation scheduling time frames;
- frequency management;
- voltage management; and
- power system stability.

On the other hand, modern wind generation can also bring benefits in several of the above areas. For more information on Electricity Commission work on wind integration, see the Commission website.[2]

One area of concern is the possible interaction between wind and hydro generation. It has been suggested that a "dry year" (period of low inflows into key hydro systems) may be more likely to be a "calm year" (period of low wind generation output) – i.e. there may be correlations between wind and hydro generation.

It has also been suggested that wind generation may be seasonal – producing less power at times of year where it is most needed.

If these hypotheses are true, then they have implications in terms of:

- economics of wind generation – i.e. owners of wind farms should expect less revenue at times when prices are high; and
- security assessment – i.e. parties attempting to assess "dry-year security" (the ability of the power system to manage periods of low hydro inflows) should consider that wind output is likely to be lower than average at these times.

Indeed, the Commission's Annual Security Assessment 2009[3] included a sensitivity scenario in which wind generation output was assumed to be 10% lower than average during extended energy shortages. (The effect on projected energy margins was relatively minor compared to other sensitivity scenarios.)

The Commission has sought to test both the above hypotheses; this report sets out the results.

In 2008, the New Zealand Institute of Economic Research (NZIER) published a study 'Exploring wind-hydro correlation – Report to NZ Steel and the Major Electricity Users' Group'.[4] The NZIER study investigates correlations between hydro lake levels and wind speeds at four weather stations. Although the exposition is interesting, there are some concerns about the methodology used (Appendix 1).

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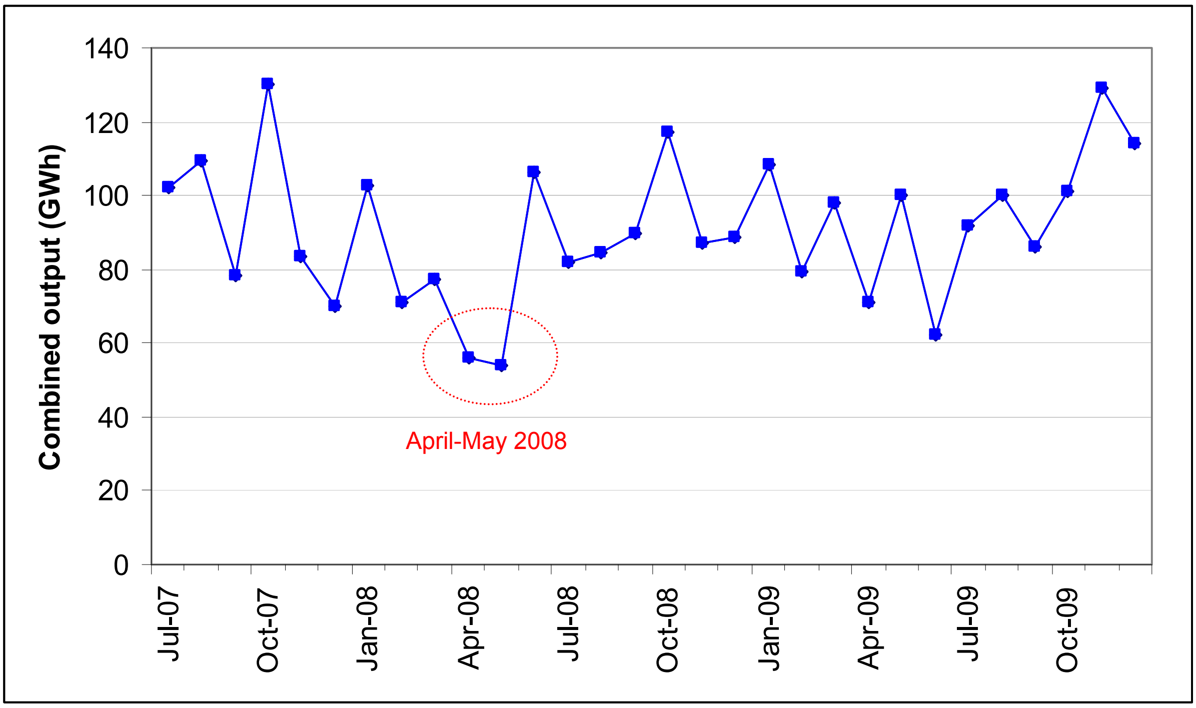
1 http://www.electricitycommission.govt.nz/opdev/comqual/windgen/wgip
2 http://www.electricitycommission.govt.nz/opdev/comqual/windgen
3 http://www.electricitycommission.govt.nz/pdfs/opdev/secsupply/policy/ASA-2009-final.pdf
4 http://www.meug.co.nz/includes/download.aspx?ID=97686

Methodology

Wind generation output was observed to be low during April and May 2008 (Figure 1). These were the two driest months of the 2008 dry winter (in terms of national hydro inflows).

Figure 1: Combined output from White Hill, Tararua and Te Apiti wind farms



Some imputed data used for mid-2007 data points

However, this is only one case and not a reliable guide to what may happen in other years. Therefore, a statistical analysis was undertaken, using longer-term synthetic (i.e. artificial, simulated) records to examine the linkages between wind resource and hydro inflows.

The underlying assumption of this analysis is that future climate conditions will be similar to recent history. The results shown here are only as reliable as this assumption.

The analysis consisted of six steps:

- obtaining a synthetic dataset of inflows to major hydro systems (cumecs);
- converting this into energy yields (GWh);
- obtaining a synthetic dataset of wind speeds (m/s) at actual and potential wind sites;
- converting this into the energy that would have been produced (GWh) by various possible wind generation portfolios;
- assessing the seasonality of wind generation output; and
- investigating correlations between the wind and hydro datasets.

Note that the analysis focuses on the correlation between hydro *inflows* with wind *energy output*, as opposed to the NZIER study which compared hydro *lake levels* with wind *speeds* (Appendix 1).

Synthetic hydro inflow data

The hydro inflow data prepared by OPUS International and published in the Centralised Dataset[5] were used in this work.

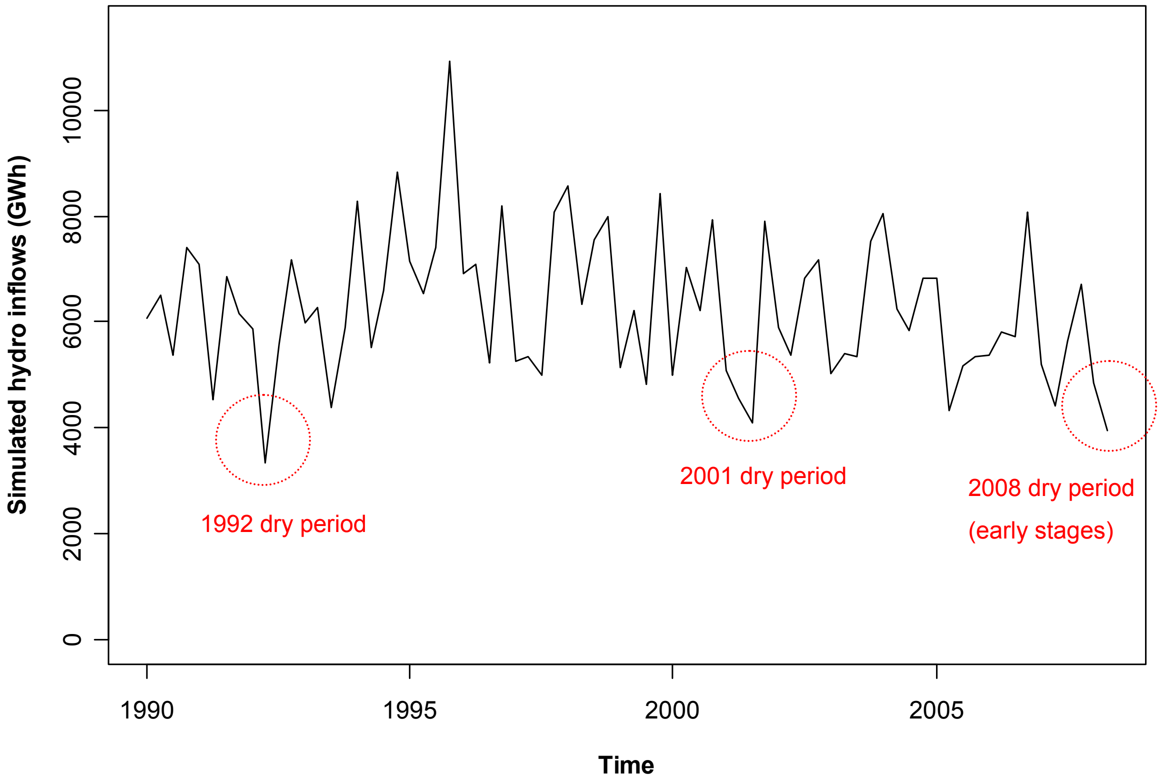
The data used were the monthly inflows to major hydro systems that *would* have occurred over 1990-2008 if current hydrological structures were in place. They should be considered as a simulated or synthetic dataset, because in some cases OPUS used models to estimate flows from the available information. (The full OPUS dataset covers a longer record from 1932 to 2008 with daily resolution, and also includes 'natural' flow series, i.e. simulated data derived assuming the hydrological structures that were in place at the time.)

Simple conversion factors were used to convert these inflows from cumecs (as provided by OPUS) to GW and integrate them into GWh.[6] These conversion factors were derived assuming current hydro generation assets (rather than those that were in place at the time).

Inflows (in GWh) were aggregated over the following hydro systems: Waikato, Waikaremoana, Tongariro Power Development, Matahina, Mangahao, Kaimai, Aniwhenua, Wheao/Flaxy, Patea, Waitaki, Clutha, Manapouri / Te Anau, Cobb, Coleridge, Waipori, Highbank, Branch.

Aggregated inflows for the period 1990-2008 are shown in Figure 2. As can be seen, hydro inflows are seasonal and have considerable month-to-month and year-to-year variability.

Figure 2: Total monthly hydro inflows for listed catchments, 1990-2008



[5] http://www.electricitycommission.govt.nz/opdev/modelling/centraliseddata/inflows
[6] http://www.electricitycommission.govt.nz/pdfs/opdev/modelling/pdfsmodelling/pdfscds/inflows/summarised-flows.zip

<u>Synthetic wind speed data</u>

It is generally difficult to obtain wind speed data for wind generation sites, particularly if a long record is required. The data are typically owned by the developer and not made public – and, in any case, will not cover a long time span (i.e. more than a year or two) for most sites.

One approach to this problem is to use a synthetic dataset – i.e. a dataset that takes the form of an actual wind speed record, but actually contains estimated speeds based on some other source of meteorological information. The preparation of a synthetic wind dataset is a fairly technical exercise; the main difficulty lies in preserving the key features of real wind speed data (intertemporal correlation, spatial correlation, daily and seasonal cycles).

A synthetic wind dataset, prepared by NIWA for the Electricity Commission, has been available for use in wind integration studies since 2009.[7] The NIWA dataset has a ten-minute time step and covers a five-year span, which means it is suitable for modelling wind variability over minutes to days. However, due to its short length, it is not suitable for modelling variability over months to years.

This study uses a new synthetic wind dataset, kindly provided by Meridian Energy for public use. It consists of daily mean wind speeds at twelve different sites distributed around New Zealand, and covers a nineteen-year span (1990-2008), which means it can be used for analysis of longer-term wind variability.

The Meridian dataset was derived using two sources of information: Meridian wind monitoring mast data and NIWA station data available from the National Climate Database[8]. The methodology used is described on the Commission's website. [9]

A peer review carried out by NIWA supports the methodology used by Meridian, compares the synthetic dataset with other available wind datasets (to the extent possible), and concludes that the dataset is fit for the purpose of gaining a high level understanding of long-term variability in wind generation output.

The twelve sites have been labelled Auckland, Canterbury, Central NI, Hawkes Bay, Northland, Otago, Southland 1, Southland 2, Taranaki, Tararua, Wairarapa and Wellington. Some are established wind farms; others are potential wind farm sites.

In order to protect Meridian intellectual property, the synthetic data for each site have been scaled to a mean of 8 m/s. This makes it impossible to distinguish sites with high wind speeds from low wind speeds. This rescaling has little impact on the results of the analysis (because the assumed relationship between mean wind speed and wind farm output is linear, as set out in the next section – therefore rescaling has minimal effect on wind/hydro correlation for a single farm, and affects correlations for portfolios of farms only by changing the relative weighting of each farm).

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7 http://www.electricitycommission.govt.nz/opdev/modelling/synthetic-wind
8 http://cliflo.niwa.co.nz
9 http://www.electricitycommission.govt.nz/opdev/modelling/long-term-synthetic-wind

<u>Conversion to synthetic wind generation output data</u>

Correlations between wind and hydrology, and the consequent effects on the power system, will depend on the amount of wind generation installed and the locations of wind farms. Since there is considerable uncertainty about the pace of development of the wind industry and the likely locations of future wind farms, several scenarios have been considered in this work:

- 'near-future' (all major existing and committed farms);
- 'diversified' (extensive growth in large-scale wind generation, with new farms spread around the country);
- 'Tararua-based' (substantial new wind generation in the lower North Island, close to most existing farms); and
- 'Southern' (major new farms in the lower South Island).

The composition of each of these wind portfolios is shown in Table 1.

Table 1: Four wind generation portfolios – capacity per site (MW)

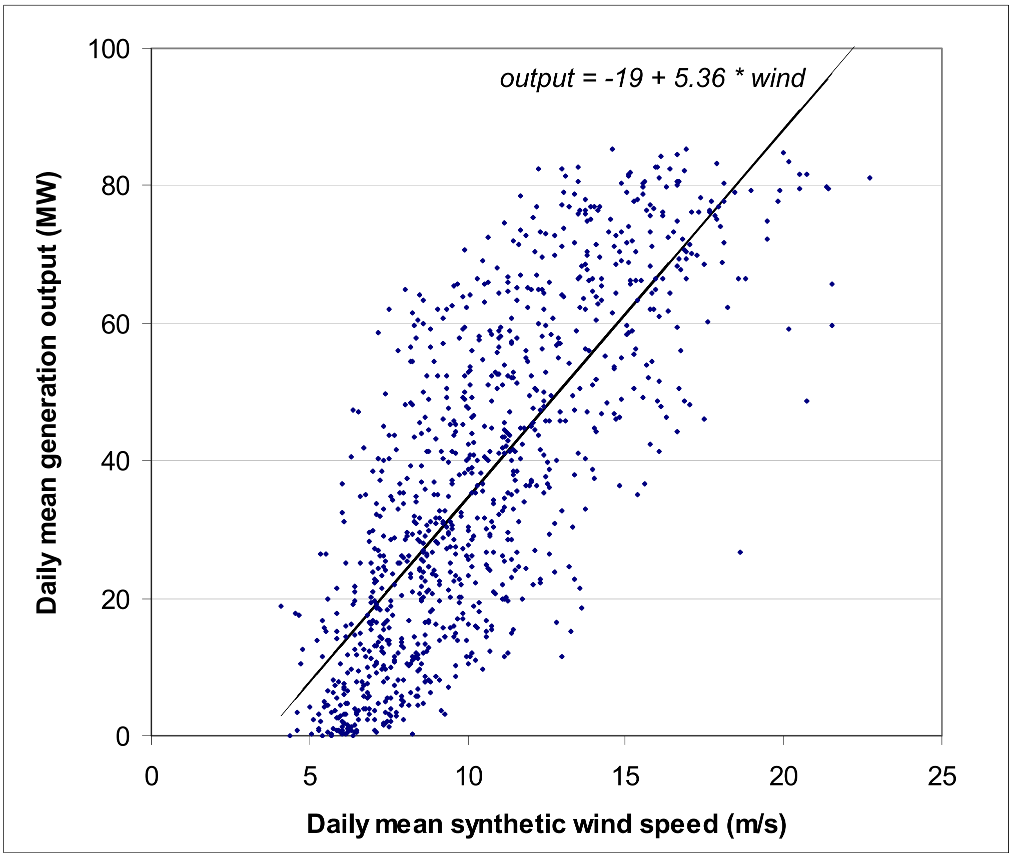
Site	Near-future	Diversified	Tararua-based	Southern
Auckland	(Te Uku–nearest site) 70	70	70	70
Canterbury				
Central NI			130	
Hawkes Bay		200		
Northland		100		
Otago		200		600
Southland 1		200		
Southland 2	60	60	60	60
Taranaki				
Tararua	250	250	500	250
Wairarapa				
Wellington	130	130	200	130
Total	**510**	**1,210**	**960**	**1,110**

For each of these portfolios, daily synthetic wind generation output data was produced. These data represent the estimated output that would have been produced by the specific wind farms, if they had been in operation since 1990.

In theory, the power produced by a wind turbine is proportional to the cube of wind speed. However, turbines are limited to a certain maximum output, and will stop producing energy at very low or very high speeds. In a farm of multiple turbines, some will be producing more or less than average. When these factors are considered, it turns out that over longer time frames, the electrical output of a wind farm is roughly linearly related to mean wind speed.[10]

This linear relationship is clearly seen for Meridian's Te Apiti wind farm (Figure 3).

Figure 3: Relationship between wind speed and generation at Te Apiti, 2004-08



Periods when the wind farm was still under construction, or where a significant proportion of turbines were out for maintenance, have been excluded from the relationship

The observed relationship for Te Apiti has been applied to each site in the wind generation portfolios[11]:

*Synthetic output (MW) from wind farm with capacity of X MW = max(0, min(0.95 X, X/90 * [-19 + 5.36 * synthetic wind (m/s)]))*

Daily mean power was then converted into daily energy, for each wind farm and each portfolio. This yielded a synthetic wind generation output dataset extending for 19 years (1990-2008).

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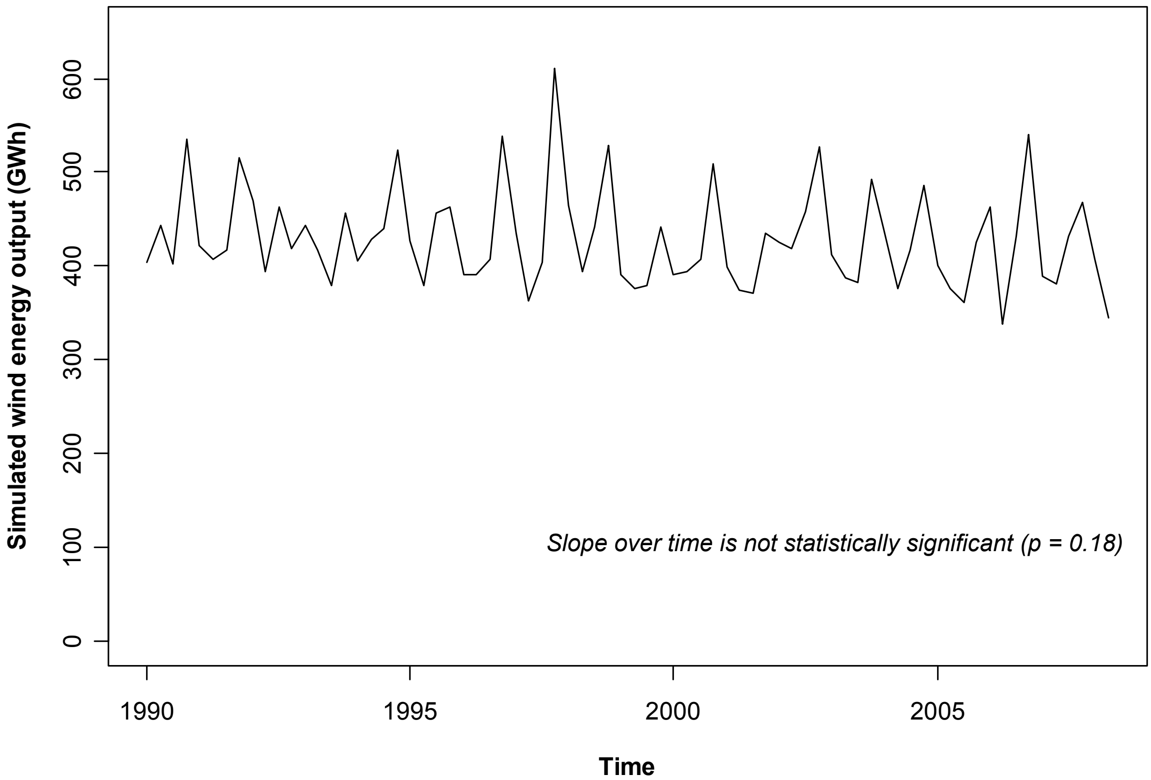
[10] http://www.electricitycommission.govt.nz/pdfs/opdev/modelling/workshops/wind-hydrology/Wind-to-power.pdf

[11] It would have been better to determine a separate wind speed / generation relationship – which might or might not be linear – for each site. However, there was insufficient data to do so.

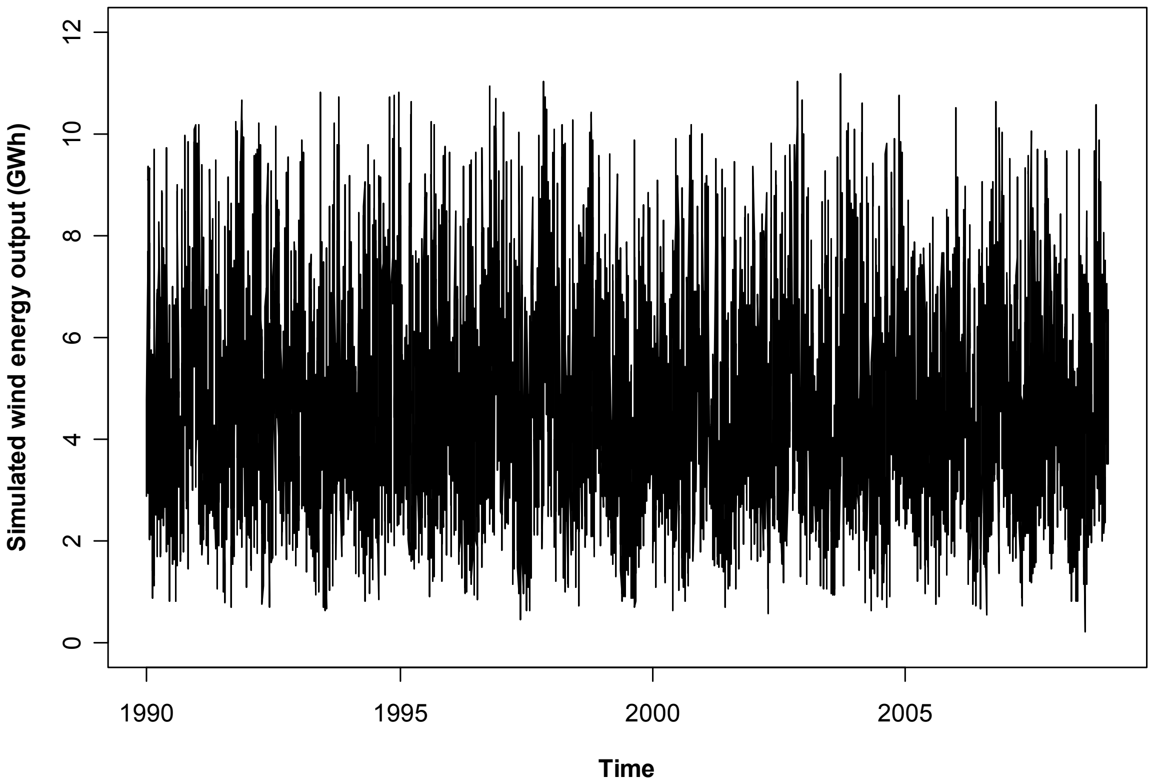
The synthetic wind energy data do not show a statistically significant trend over time, for any site or portfolio. (This is reassuring, as a trend might suggest instrumental drift over the years.)
An example is shown for the “near-future portfolio” in Figure 4.

Figure 4: Monthly synthetic wind generation output for the 'near-future portfolio'



It will be noted that there is relatively little variation in wind generation output from month to month. Day-to-day variation is much higher (Figure 5).

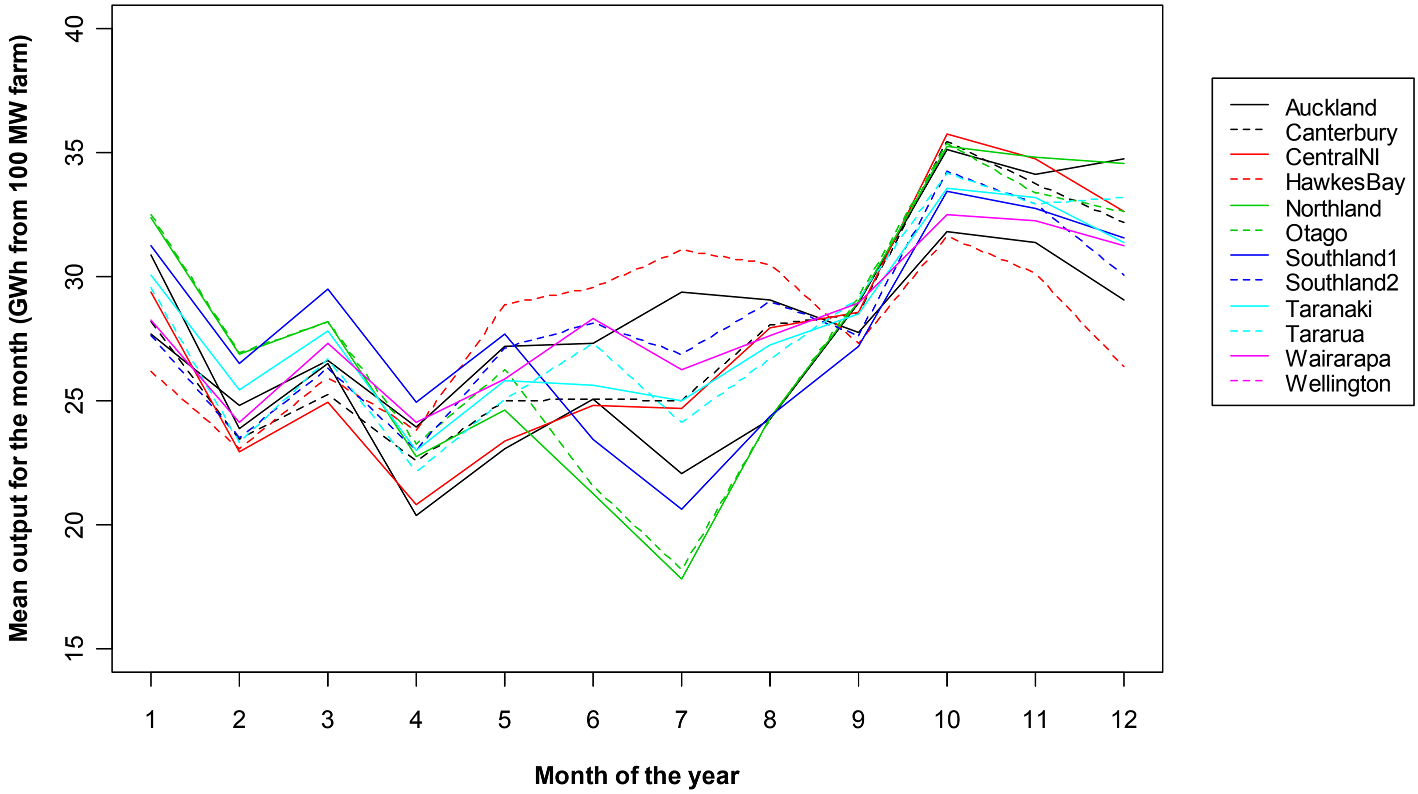
Figure 5: Daily synthetic wind generation output for the 'near-future portfolio'



Seasonality

Wind generation output has moderate seasonality (Figure 6).[12]

Figure 6: Seasonal patterns in synthetic wind generation output



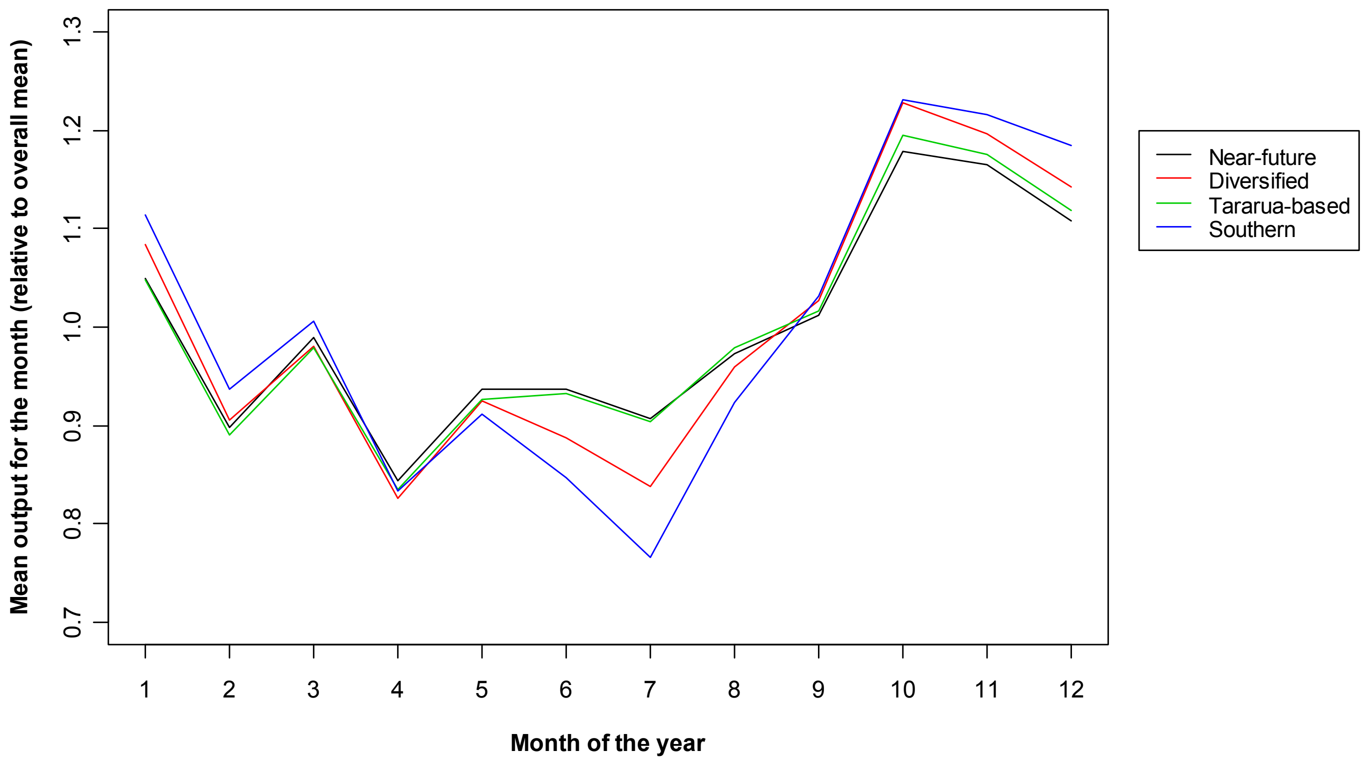
The exact seasonal pattern varies from site to site, but over each of the four portfolios considered, simulated output over winter (April-September) is lower than over summer (October-March) – see Table 2, Figure 7. The difference is statistically significant.

Table 2: Seasonality of synthetic wind generation output

Portfolio	Ratio of mean winter output (Apr-Sep) to year-round mean output	Apr-Jun only	Jul-Sep only
Near-future	0.94	0.91	0.97
Diversified	0.91	0.88	0.94
Tararua-based	0.93	0.90	0.97
Southern	0.89	0.87	0.91

[12] There is more discussion of the seasonality of wind in the NIWA research report on the preparation of the shorter-term synthetic wind dataset - http://www.electricitycommission.govt.nz/opdev/modelling/synthetic-wind.

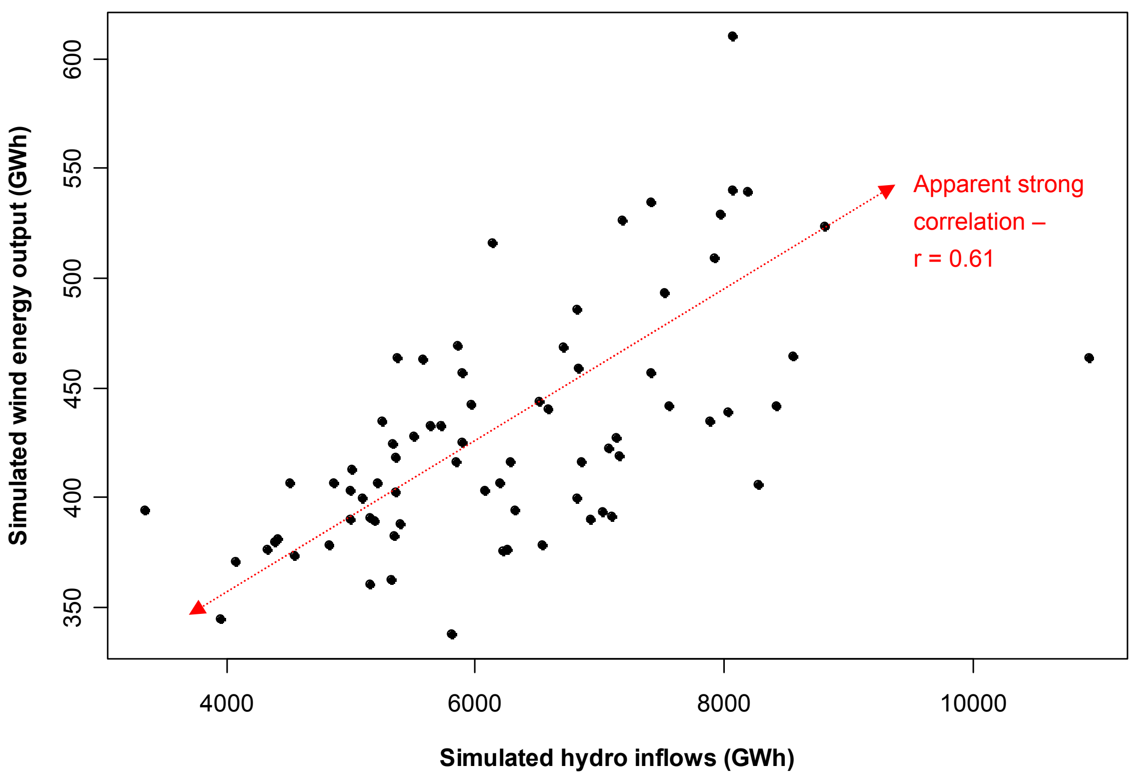
Figure 7: Seasonal patterns in synthetic wind generation output – by portfolio



Correlation analysis

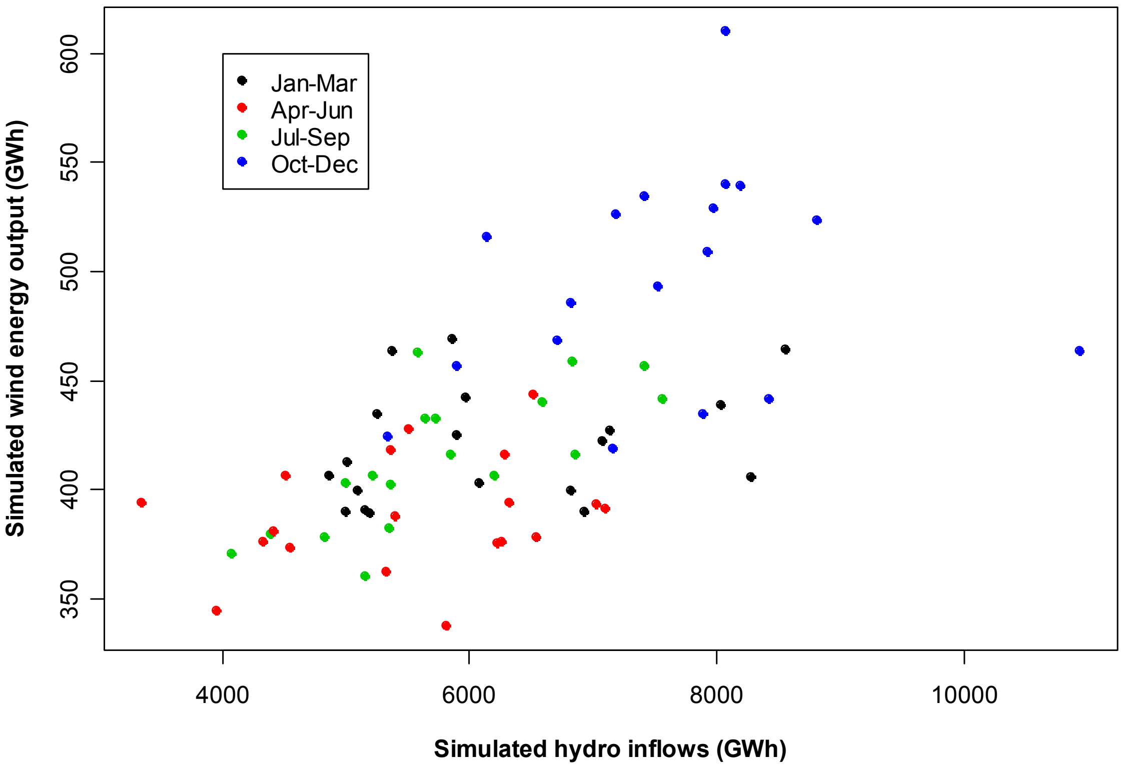
There is a correlation between wind and inflows (Figure 8).

Figure 8: Spurious correlation - quarterly inflows vs wind ('near-future portfolio')



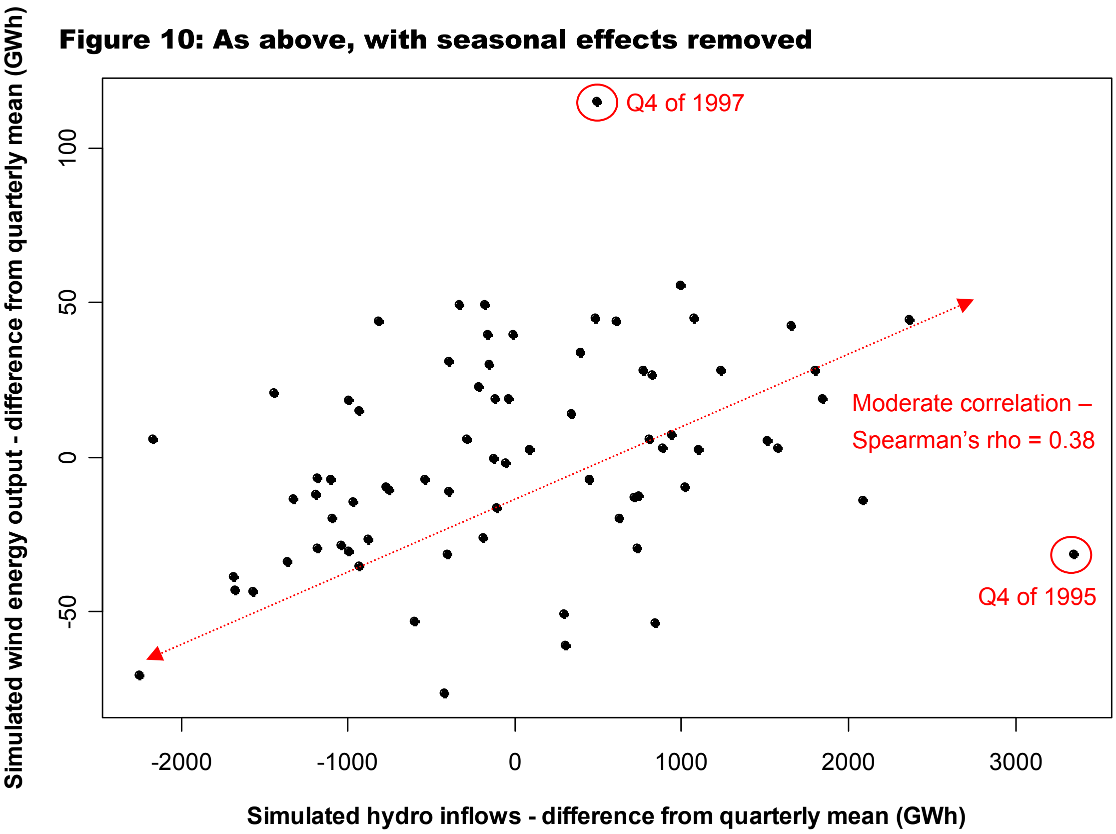
The main source of the correlation can readily be seen when seasons are distinguished (Figure 9). Both wind and inflows are typically lower in winter than in summer.

Figure 9: As above, with seasons distinguished



Once seasonal effects are removed, the correlation is weaker (Figure 10). With two major outliers, the use of Spearman's rank correlation is appropriate.

Figure 10: As above, with seasonal effects removed



Correlations with national hydro inflows vary substantially between wind generation sites and portfolios (Figure 11, Table 3).

For ten out of twelve wind sites, there is a moderate correlation with inflows. The exceptions are the Auckland and Northland sites, which are near-independent of inflows – it appears wind in these latitudes is driven by different climate factors. (NIWA has commented that "these sites are less influenced by the midlatitude westerly belt and have a more convective subtropical climate".)

For all four portfolios, there is a moderate correlation with inflows. In other words, while spreading wind farms throughout New Zealand might produce useful diversity on short time scales, it would not evade the correlation with hydro.

Figure 11: Correlations between inflows and wind

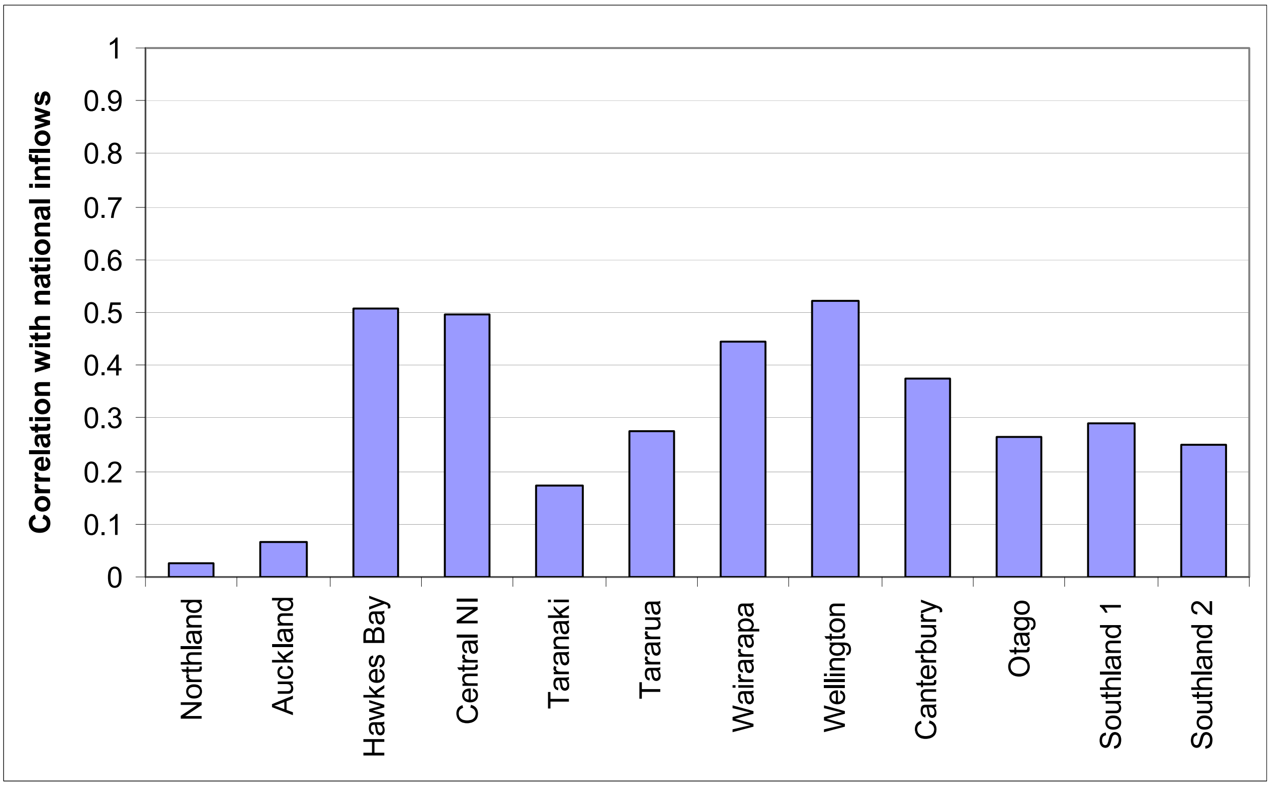


Table 3: Correlations between inflows and wind

Portfolio	Correlation
Near-future	0.38
Diversified	0.42
Tararua-based	0.44
Southern	0.33

In the Figure and Table above, numbers shown are rank correlations between quarterly synthetic datasets. Both datasets are deseasonalised (i.e. represented as the difference from the mean figure in the quarter.

Given that a correlation between hydro and wind has been demonstrated, it is useful to consider how expected wind output differs between a 'dry year' and a 'wet year'.

Simple linear regression analysis was used to estimate the relationship between wind and hydro, for each of the four wind portfolios. The model equation was (for years *y* and quarters *q*):

$$wind\_energy\_output_{q,y} = \alpha + seasonal\_effect_q + \beta * hydro\_inflows_{q,y} + \varepsilon_{q,y}$$

Other simple models were tested (e.g. including interaction terms, or using North and South Island inflows as separate predictor variables) and found not to be superior.

The two outlying data points were removed (quarter 4 of 1995 and 1997), since they would otherwise have a disproportionate effect on results – otherwise the data met the assumptions of simple linear regression.

Table 4 shows model predictions of wind energy output in the Apr-Jun quarter, for:

- dry conditions (quarterly inflows of 4500 GWh, as per Apr-Jun 2001);
- average conditions; and
- wet conditions (quarterly inflows of 6500 GWh, as in Apr-Jun 1995)[13].

Table 4: Model predictions of expected wind energy output, given hydro inflows

Portfolio	Expected output (GWh) in Apr-Jun quarter			
	Dry conditions	Average conditions	Wet conditions	% difference between dry and average
Near-future	376	388	400	3.0%
Diversified	851	888	926	4.2%
Tararua-based	697	725	752	3.9%
Southern	770	793	833	2.9%

(The table shows Apr-Jun for ease of interpretation, but exactly the same trend applies to Aug-Sep, since the model does not include an interaction between time and inflow effect.)

The difference in expected wind output between a dry winter and an average winter is statistically significant, but relatively small:

- it is smaller than the difference in expected wind output between winter and summer; and
- in terms of multi-year security assessments, it is well below the margin of error.

As previously noted, diversifying the wind portfolio does not reduce the correlation with hydro.

[13] These are roughly the 15th and 85th percentiles of the historical range.

By contrast, there is a much greater difference between national hydro inflows in a 1-in-10 dry Apr-Jun quarter and those in an average Apr-Jun quarter – approximately 1100 GWh, or 20% of average Apr-Jun inflows.

Conclusions

It appears that New Zealand wind generation is seasonal. The exact seasonal pattern varies between regions, but is typically high from October to January and low from April to July.

There is also a moderate correlation between wind generation output and national hydro inflows. This correlation holds for most of New Zealand (with rank correlation in the 0.25 – 0.5 range), but wind resources in Northland, Auckland and to a lesser extent Taranaki are approximately independent of hydro inflows.

These observations should be taken into account in assessments of dry-winter security. An appropriate adjustment would be to reduce the assumed load factor of wind during "dry winters" by 10% - roughly 6% for seasonality (Table 2) and 4% for correlation with hydro inflows (Table 4). A smaller derating might be appropriate for any new wind farms in Taranaki or the Upper North Island.

Currently there are two dry-year energy security standards – a New Zealand winter energy margin (NZ-WEM) of 17% and a South Island winter energy margin (SI-WEM) of 30%.[14] When these standards are next revised, the seasonality of wind and the correlation with hydro generation should be taken into account.

There may also be implications for the economics of wind generation.

All these conclusions assume that climate over the next few years will be roughly similar to those over the last 20 years. The results shown here are only as reliable as this assumption.

It would be possible to extend this work by obtaining a longer synthetic wind speed record. At this point it is not clear that the benefit of doing so would justify the cost, but it might be worth looking at when a significant amount of new wind generation has been added to the system.

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[14] See the Electricity Commission's Security of Supply Policy, available at http://www.electricitycommission.govt.nz/opdev/secsupply/.

Appendix 1: 'Exploring wind-hydro correlation' (NZIER) – comments on methodology

In 2008, NZIER published a study 'Exploring wind-hydro correlation – Report to NZ Steel and the Major Electricity Users' Group'.[15] This Appendix notes some concerns about the methodology used, based on a peer review by NIWA.

The NZIER study analyses correlations over 1990-2008 between:

- actual wind speeds at four weather stations (Manukau Heads 2, Palmerston North Aero, Kaukau Top, and Dunedin Aero) from NIWA's National Climate Database;
- Te Apiti generation from July 2004 to June 2008; and
- key hydro lake levels.

The four weather stations can be expected to be reasonably well correlated with nearby wind frm sites, although there may be some important differences (for example, some of the weather stations are low-lying and would be affected more by morning temperature inversions than nearby wind farm sites). However, considering only four weather stations is probably insufficient to give a full description of the dynamics of wind farms distributed throughout New Zealand.

Unfortunately, changes in measurement methods led to step changes in two of the four weather station series in the mid-1990s.[16] These measurement changes were mistakenly interpreted as genuine trends in wind speed by NZIER. This is likely to have introduced bias.

The Te Apiti generation series also has problems;

- it is too short for meaningful analysis of medium- to long-term correlations;
- it was low for much of 2004 because the station was not yet fully constructed; and
- it was low during some periods later in the series because turbines were out for maintenance.

In terms of the hydro data, it would have been better to use inflows rather than lake levels. The reason is that lake levels are dependent on how controlled lakes are operated, which has changed significantly over the study period. Factors affecting lake operation include thermal generation, demand, transmission constraints, and market dynamics. Using (synthetic) inflows would remove all these effects.

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[15] http://www.meug.co.nz/includes/download.aspx?ID=97686

[16] The method by which the wind speeds were read off the anemograph at Kaukau was changed in 1994 – previously speeds were read off assuming a log relationship between gridlines on the vertical scale, thereafter assuming a linear relationship. This caused a decrease in mean speed of approx. 1 m/s. Similar concerns apply to Manukau Heads. These measurement changes are not well documented in the National Climate Database.