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New Zealand Renewable Generation Diversity Investigation

A report prepared for New Zealand Wind Energy Association

27 July 2022

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Executive summary

Concept Consulting was engaged by the New Zealand Wind Energy Association to investigate some of the opportunities and challenges that might arise for the New Zealand electricity system due to increasing amounts of wind and solar generation. In particular, we looked at how diversity, both in technology type and location, might assist with reducing the inherent intermittency of these generation types.

The variability of most renewable generation (i.e. wind, solar, and hydro, but not geothermal) will create some significant challenges as New Zealand transitions to an electricity system with very high levels of renewables. It will need to manage periods of low generation, particularly if they coincide with periods of high demand. Similarly, periods of high intermittent generation that coincide with low demand will result in increased levels of 'spill'. While it is impractical to avoid spill altogether, it is important to minimise spill where it is economic to do so.

This report investigates how increasing amounts of variable renewable generation plant might result in prolonged periods of low generation, and the extent to which diversity – both geographical location of schemes, and diversity of different types of renewable generation – can reduce the extent of such tight supply periods. To do this we have used forty years of 'modelled historical' wind and solar data for fourteen different sites around the country.

Our analysis indicates that – all other things being equal[1] – having a diverse portfolio of renewable generation is likely to enable New Zealand to meet this challenge at lower cost:

- Having a diversity between different *types* of variable renewables (i.e. having a mix of wind and solar) materially reduces the extremes of low and high generation that would occur if additional renewable development was only wind or only solar. This is because of a general anti-correlation between the output of these two technologies.

  Further, wind and solar have different strengths and weaknesses in terms of their correlations with demand and hydro inflows, and thus their suitability at meeting the need for generation (or at least, not giving rise to the need for balancing generation) at different times:

  - Solar's relative lack of generation in winter and early mornings & evenings make it poorly suited for meeting the need for seasonal and peaking generation. However, on the positive side, it has less variability than wind over week-to-week timeframes, which is a timeframe that is difficult to address with lithium-ion batteries.
  - On the other hand, wind's average output is well matched to daily and seasonal demand shapes, meaning that, on average, there will be reduced need for additional balancing energy for daily peaks and over winter in a wind-heavy future compared to a solar heavy future. However, one drawback for wind is that its positive correlation with winter hydro inflows means it will often exacerbate the need for dry-year firming energy (i.e. in some years the seasonal bias toward winter production will be less than the long-term average).

- Having a diversity in the *geographical spread* of renewables will further reduce the extent of extremes of both high and low generation.

  This geographical diversity benefit appears greatest for wind, relative to solar, with the extent of benefit varying with different timeframes. It appears to deliver greatest benefit for seasonal and

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[1] Any significant variations in the costs of different schemes in different locations will tend to counter-act the benefits of diversity.

dry-year requirements, with the top of the North Island in particular appearing to have significantly different wind patterns relative to much of the rest of the country.

The geographical diversity benefit for shorter time periods (e.g. over a day or week) is less than for the seasonal benefits.

That said, we note that the apparent scale of geographical diversity benefit for wind (as indicated by the extent of reduction of extremes of both low and high generation) is less than might be expected when looking at the observed price benefit of smaller wind schemes located distant from the main Tararua concentration of wind generation. Schemes such as White Hill (located in Southland) have achieved much higher ratios of their generation-weighted average price to the time-weighted average market price (GWAP/TWAP) compared to Tararua schemes.

We believe this reflects a number of factors:

- The modelled data sources tending to under-estimate the extent of geographical diversity benefit to a certain degree, as demonstrated by the comparison with real-world generation in Appendix A.
- The observed GWAP/TWAP values also taking into account the real-world effects of transmission constraints
- The asymmetry in prices between periods of significant surplus versus significant scarcity. This will tend to magnify the effect of variations in generation at either end of the duration curve. In other words, what appears to be a relatively small change in generation at periods of extreme scarcity can be very valuable, and likewise (although to a lesser extent) for periods of significant surplus.

1 Introduction

The uncontrollable nature of wind and solar generation means that it may not be available when needed. This will be more of a challenge to manage as the proportion of wind and solar energy increases. This report investigates how increasing amounts of variable renewable generation[2] plant might result in prolonged periods of low generation, and the extent to which diversity – both geographical location of schemes, and diversity of different types of renewable generation – can reduce the extent of such shortage periods.

Our approach is to construct future scenarios based on our expectations of wind and solar generation and assess how supply shortages arise over different time frames. We use data from a range of sites to construct scenarios with three different levels of geographic diversity. To assess the effect of technology diversity, we consider "all solar" and "all wind" scenarios in addition to our base case technology mix.

Our analysis is broken into 3 stages:

- Investigating correlation between different locations and technology types
- Investigating generation characteristics for our build schedules
- Investigating how build schedule generation interacts with the wider New Zealand electricity market

We have used forty years of 'modelled historical' wind and solar data as the basis for this analysis. Appendix A describes this data further and reviews its accuracy by comparing its predicted wind output with actual wind output from wind farms. It shows that using this data is reasonable for reflecting the likely generation patterns of wind at various sites around the country, but it likely slightly under-estimates the geographical diversity benefit of wind.

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[2] Unless otherwise stated "renewable generation" refers to wind and solar generation.

2 Correlation/diversity Analysis for generation sites

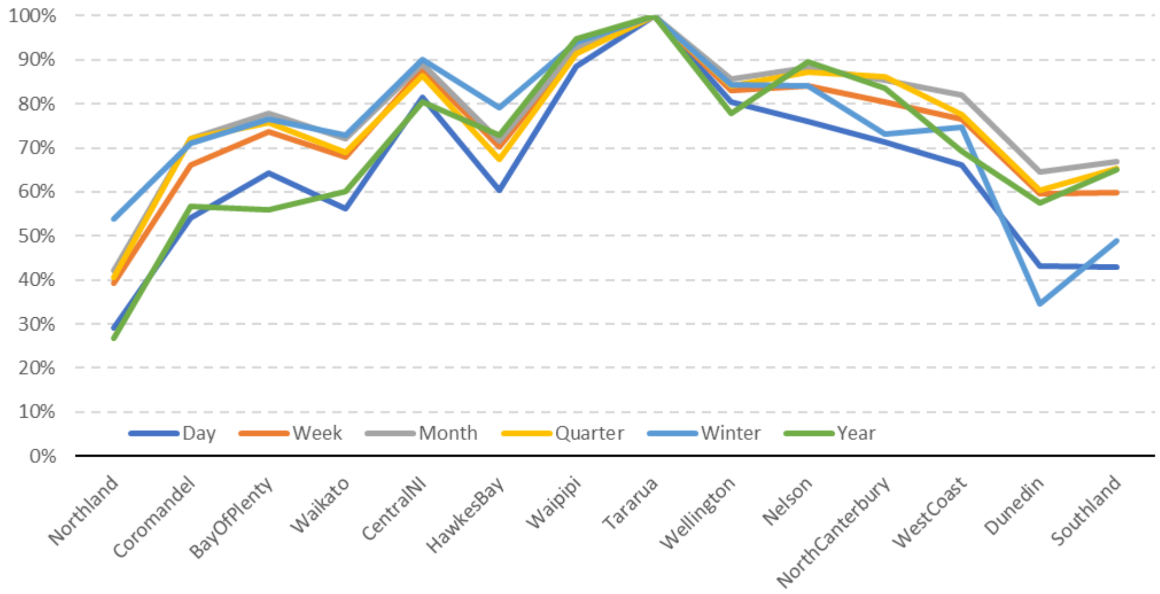
We first investigate the diversity of wind and solar generation at the sites that we use as possible build locations. This is an initial step before then combining the site data into possible build schedules.

We look at correlations between sites and generation types for range of time periods ranging from daily to yearly. As we set out in more detail later, understanding the correlations across different time frames is important because the feasibility and cost of different types of resource to 'balance' variable renewables will vary with different timeframes of requirement. For example, the type of resource to balance within-day variations is likely to be very different to that which is suitable to manage seasonal variations.

2.1 Wind vs Wind

We list locations in roughly North to South order, and show their correlations relative to Tararua. Tararua has been chosen as the reference point as it is roughly central within New Zealand, and it is currently the location of the majority of New Zealand's wind generation.

Figure 1 - Correlation relative to Tararua for wind sites



Correlation relative to Tararua drops off with geographic distance.

Northland is the least correlated for most measures, although Dunedin and Southland also have lower correlation with Tararua, particularly for winter and day-to-day measures.

Also of note is that the "winter" series[3] is the most highly correlated series for most North Island sites, suggesting that a winter with low wind generation will not be greatly improved by more diversity in the North Island unless the majority of the additional generation is located in Northland.

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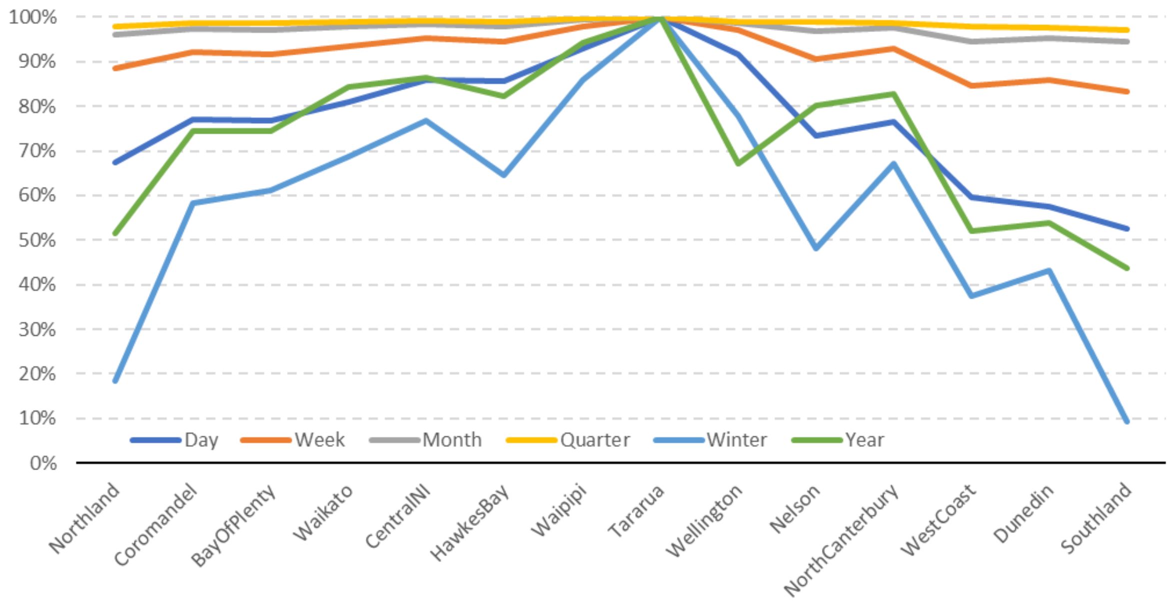
[3] For our purposes, winter is defined as the four months from June to September.

2.2 Solar vs Solar

Figure 2 - Correlation relative to Tararua for solar sites



Corelation between solar sites is very different. There is very strong correlation between all sites at a monthly and quarterly level. This is because seasonal effects (i.e. winter vs summer) dominate any locational differences.

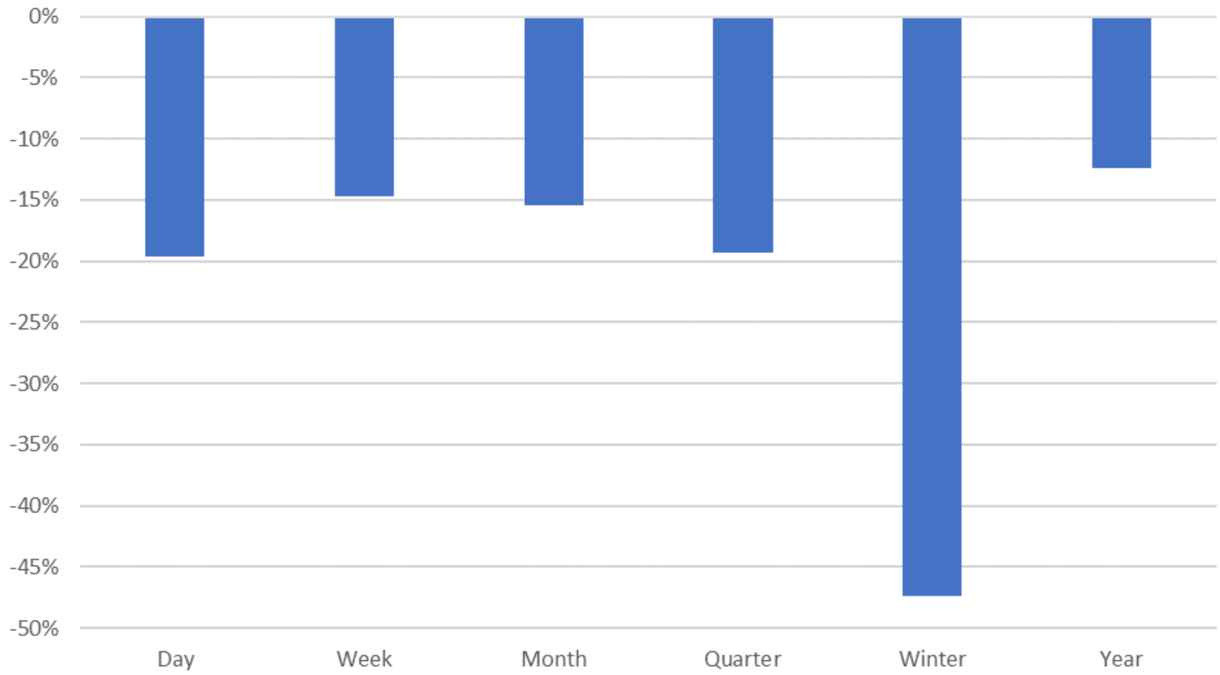
Over both longer and shorter time frames there are differences between sites. On a daily basis, there is only weak correlation between Northland and the South of the South Island, with intermediate sites somewhere in between. For the crucial winter months, there is negligible correlation between Tararua and both lower South Island and Northland sites, suggesting that diversity would be useful in providing steady (although not high) generation during winter.

Appendix B shows the cross-correlations between each of the 14 sites for the different timeframes for solar and wind. Unsurprisingly, they show that the further away two sites are, the lower the degree of correlation for both wind and solar, with the least-correlated sites being Northland and Southland.

2.3 Solar vs Wind

Solar vs wind is more difficult to summarize across all sites, so we have looked at an average for solar evenly weighted across all sites compared to a similar wind average. The results are shown in Figure 3. Across all time periods, wind is anti-correlated with solar. Intuitively, this may not be surprising, since storms produce both more wind, and less sun. This effect is particularly pronounced for winters, but this may be less useful than it first appears, since solar generation produces much less generation in winter.

Figure 3 - Solar vs wind correlation



3 Build schedules

We considered three dimensions when making our build schedules.

- There are two levels of renewable investment, corresponding to possible future years 2035 and 2050.
- There are three scenarios for relative quantity of solar and wind.
  - The base 'balanced' case is taken from Concept's in house modelling of the future. In MW capacity terms, this has 3,650 MW of wind and 1,200 MW of solar in 2035, rising to 5,650 MW and 4,200 MW, respectively, by 2050. In GWh terms, this results in a wind:solar share of approximately 84%:16% in 2035 and 70%:30% in 2050. The higher proportion of wind is due to our modelling of the relative economics of the two technologies, being a combination of the LCOE of the technologies coupled with analysis of the extent to which the generation-weighted average price (GWAP) of the technologies will increasingly be at a discount to the time-weighted average price (TWAP) of the market as the proportion of wind or solar on the system increases.[4]
  - "Solar Only" only builds solar generation to produce as much energy as combined wind and solar in our base case (7,530 MW in 2035 and 14,000 MW in 2050); and
  - "Wind Only" only builds wind generation to produce as much energy as our base case (4,340 MW in 2035, and 8,070 MW in 2050).

    (These latter two scenarios are not intended to be realistic build schedules, but instead isolate the impact of each type of generation.)
- The final dimension relates to the geographical diversity of renewable build. We have three scenarios.
  - A "concentrated" case
    - For wind this replicates the level of diversity for wind from current, committed and highly likely generation projects.
    - For solar, we use an even distribution of solar across 4 sites that are highly likely to have generation projects, based on reported announcements.
  - We also consider a "more diverse" and "very diverse" scenario, in which progressively higher levels of generation are added evenly to other sites. In the very diverse scenario, 90% of build is evenly distributed amongst all sites, with only 10% matching existing locations. The "more diverse" scenario is half-way between the concentrated and very diverse scenarios. We consider all these scenarios to be plausible outcomes.

Convolving these dimensions give 18 possible build schedules. Each of these is named with a three-part reference indicating which value is used for each of the three dimensions above. For example, the "2035_Balanced_Concentrated" scenario corresponds to a balanced mix of solar and wind generation, built with a concentrated level of diversity, for 2035.

The distribution of generation for the different levels of concentration is shown below.

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[4] Put simply, this increasing GWAP/TWAP discount is due to spot prices being relatively lower when it is very windy/sunny and there is a relative surplus of energy on the system, and spot prices being relatively higher when it is very calm/dark and there is a relative deficit of energy on the system.

Table 1 - Renewable generation build locations

	Concentrated		Diverse		Very Diverse	
	Wind	Solar	Wind	Solar	Wind	Solar
Northland	0.0%	25.0%	3.6%	16.1%	6.4%	8.9%
Coromandel	0.0%	0.0%	3.6%	3.6%	6.4%	6.4%
BayOfPlenty	0.0%	25.0%	3.6%	16.1%	6.4%	8.9%
Waikato	5.4%	0.0%	6.3%	3.6%	7.0%	6.4%
CentralNI	14.8%	25.0%	10.9%	16.1%	7.9%	8.9%
HawkesBay	0.0%	0.0%	3.6%	3.6%	6.4%	6.4%
Waipipi	11.1%	0.0%	9.1%	3.6%	7.5%	6.4%
Tararua	43.8%	0.0%	25.5%	3.6%	10.8%	6.4%
Wellington	17.0%	0.0%	12.1%	3.6%	8.1%	6.4%
Nelson	0.0%	25.0%	3.6%	16.1%	6.4%	8.9%
NorthCanterbury	0.0%	0.0%	3.6%	3.6%	6.4%	6.4%
WestCoast	0.0%	0.0%	3.6%	3.6%	6.4%	6.4%
Dunedin	0.0%	0.0%	3.6%	3.6%	6.4%	6.4%
Southland	7.9%	0.0%	7.5%	3.6%	7.2%	6.4%

Figure 4 - Wind sites for different levels of diversity

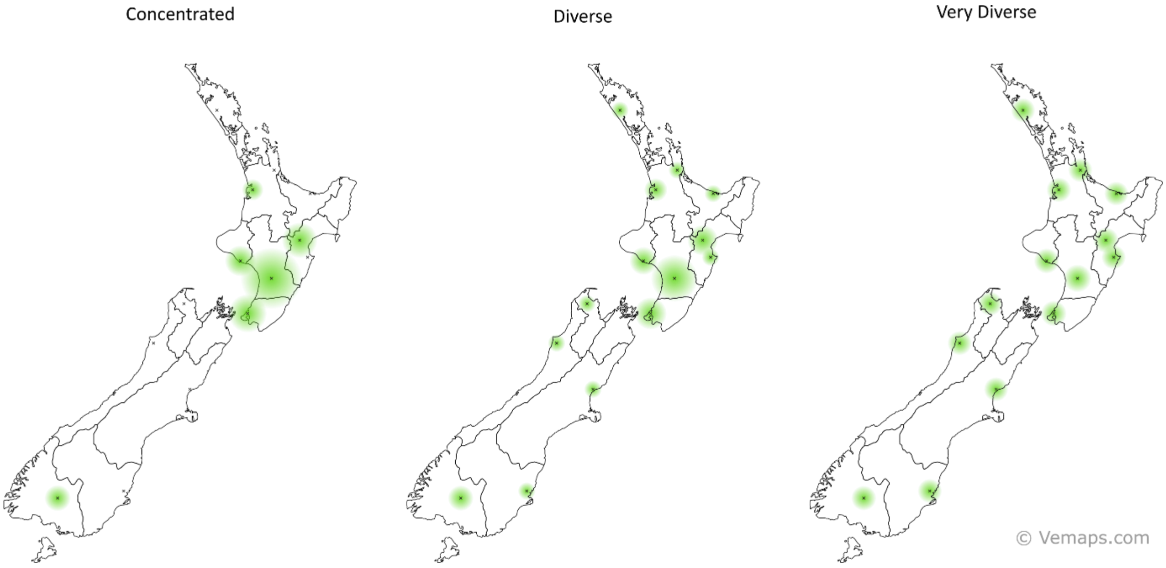


Figure 5 - Solar sites for different levels of diversity

3.1 Levels and shape of demand

We have modelled both 2035 and 2050 scenarios. These have levels of supply that we estimate would occur in these future years. Some of our analysis also considers the interaction of variable supply with demand, and for this we have used the demand profile from 2019. Although total demand is forecast to increase significantly through to 2050 (and beyond), the total level of demand is not relevant. Instead, it is the within-day and within-year profile of demand relative to that from renewable generation, and possible changes in this demand profile that matter, and it is not clear how that will change in the future. Most of the increase in demand is expected to come from the electrification of process heat and transport, so will have a different shape to existing residential demand. Additionally, flexible electric vehicle charging and batteries will further distort demand shape. Given this uncertainty, we have used current demand shape as a proxy for future demand shape, but recognize that it could be materially different than assumed.

4 Build schedule output

4.1 Average generation output

Wind and solar generation is mostly uncontrollable, which can be difficult to manage in an electricity system. One of the additional challenges of solar is that its output varies drastically depending on the time of day and time of year. Wind also exhibits these characteristics, but to a much lesser extent.

Figure 6 - Within day generation profile for scenarios (2035)

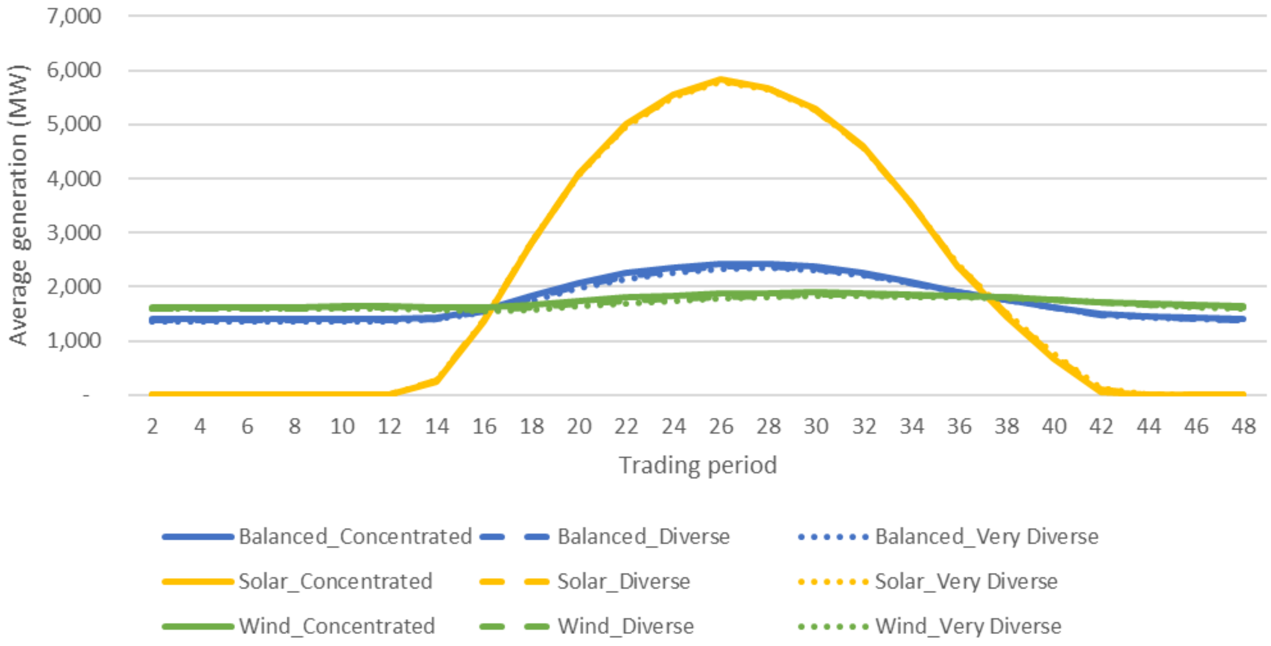


Figure 7 - Within day generation profile for scenarios (2050)

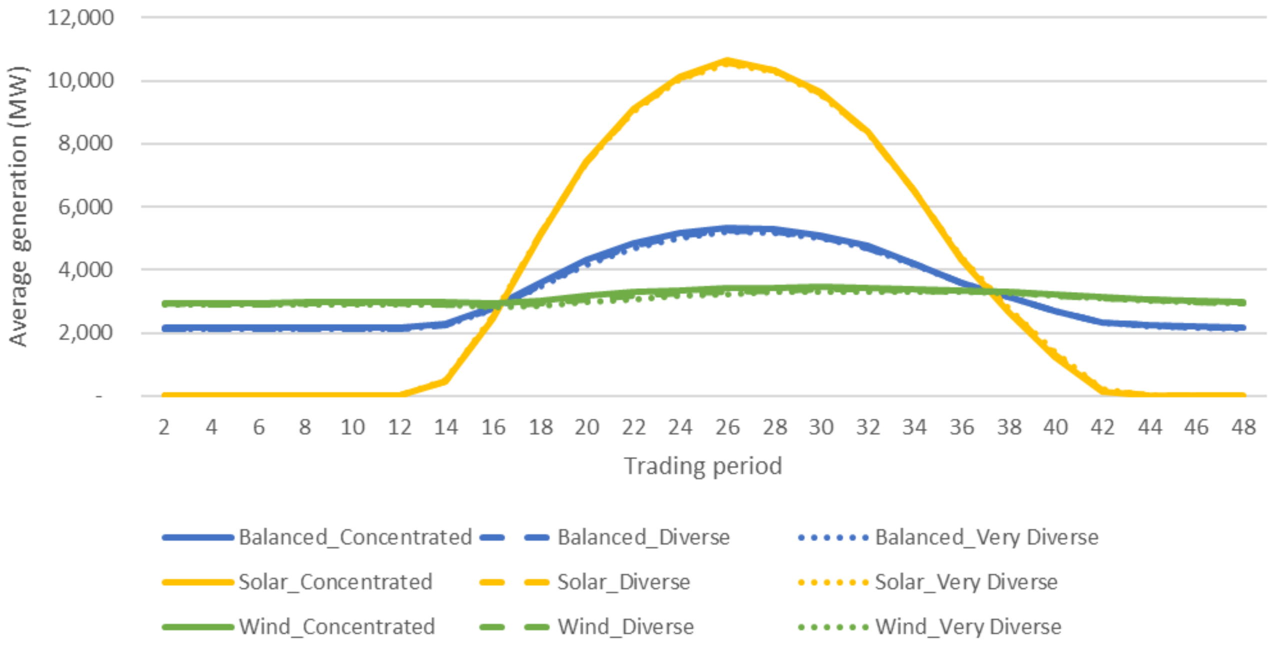


Figure 6~~Figure 6~~ and Figure 7 show the within day generation profiles for our build scenarios. Solar-only ones have the expected diurnal shape with no overnight generation. Location diversity has such a small effect that it is hard to distinguish between the different series.

Wind generation also has more generation during the day, but to a much lesser degree than solar generation. Location diversity reduces this very slightly, because Tararua has a stronger diurnal shape than most other sites.

The balanced scenario is somewhere between the two.

Note that the area under the curve is equal for each line on their respective graphs.

Figure 8 - Within year generation profile for scenarios (2035)

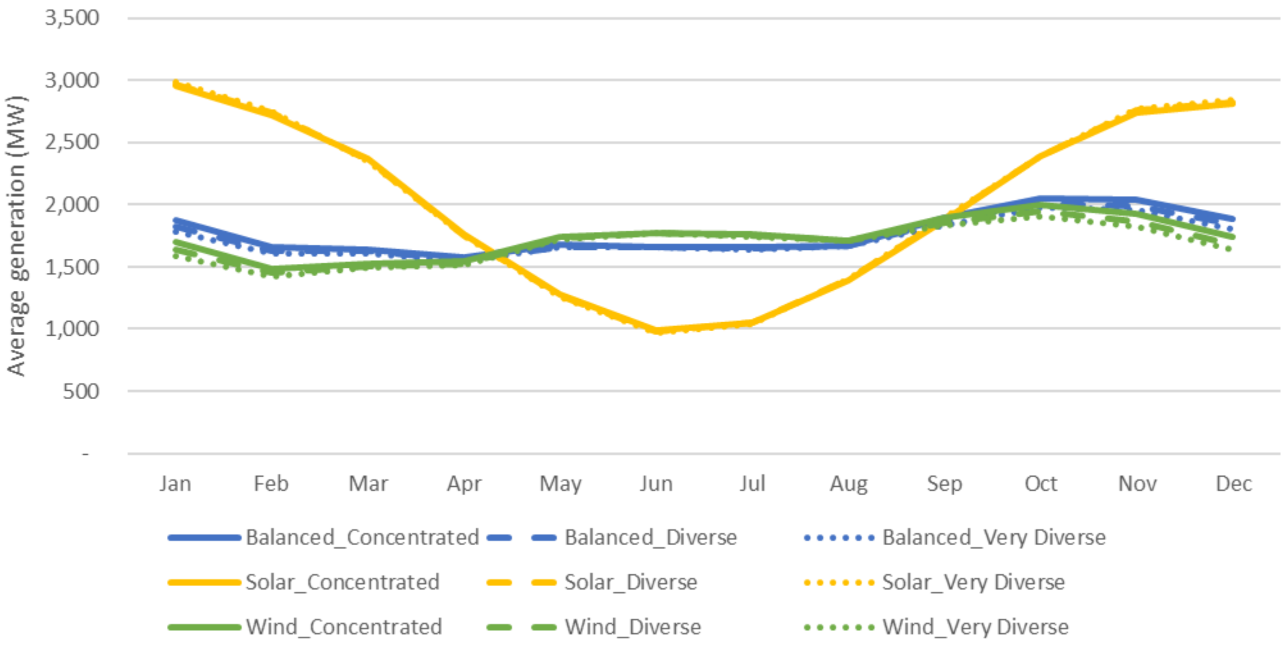


Figure 9 - Within year generation profile for scenarios (2050)

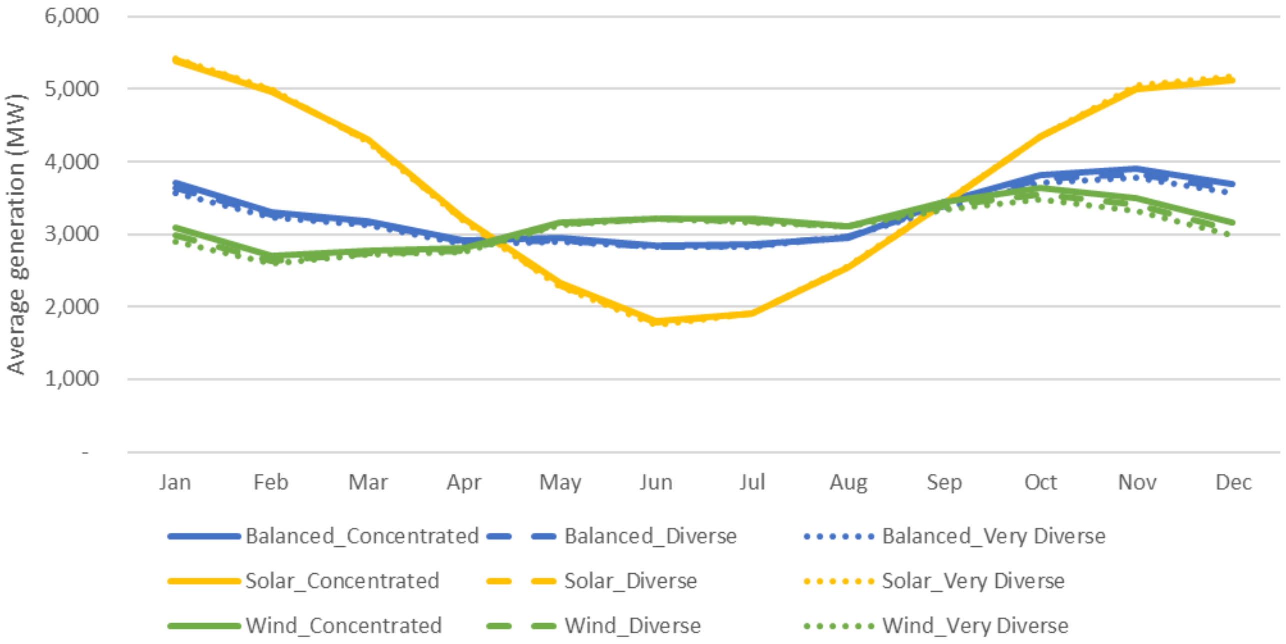


Figure 8~~Figure 8~~ and Figure 9 show similar data but for months within a year rather than hours within a day. Solar generation is drastically lower during winter months, as expected. Wind generation has a more peculiar shape, being highest in spring, although the differences between months is minor compared to solar.

Solar generation can reduce some of this within day and within year shape by oversizing panels relative to the inverter capacity, altering tilt of the solar panels and/or tracking the sun during the day. We have assumed the panels are oversized by 20% relative to inverters, that the tilt of the panels is equal to latitude and that panels have 1-axis tracking.

4.2 Generation duration curves

Another useful way to look at the highly variable generation data is to sort all values from highest to lowest, ignoring when each hour occurred within the 40-year data series. This approach is called making a generation duration curve (GDC).

4.2.1 Hourly generation

The finest time step that we consider is hourly. Hourly generation is important for meeting peak demand.

Figure 10 - Hourly generation duration curve (2035)

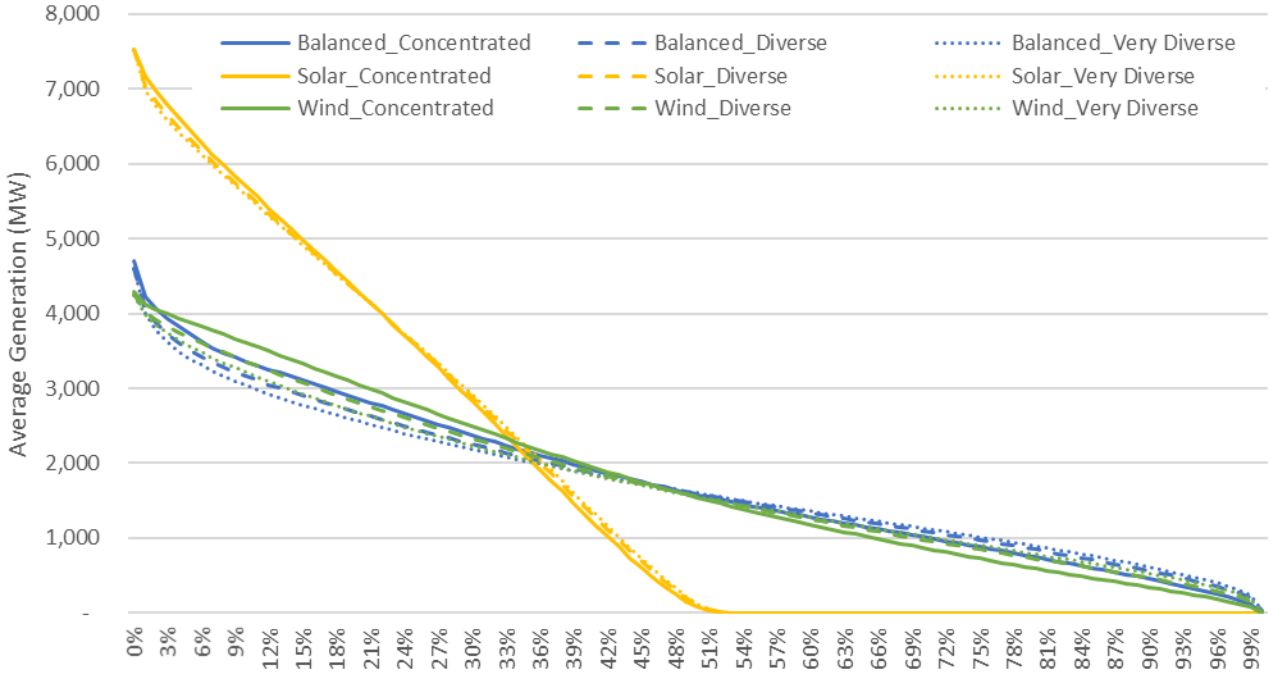
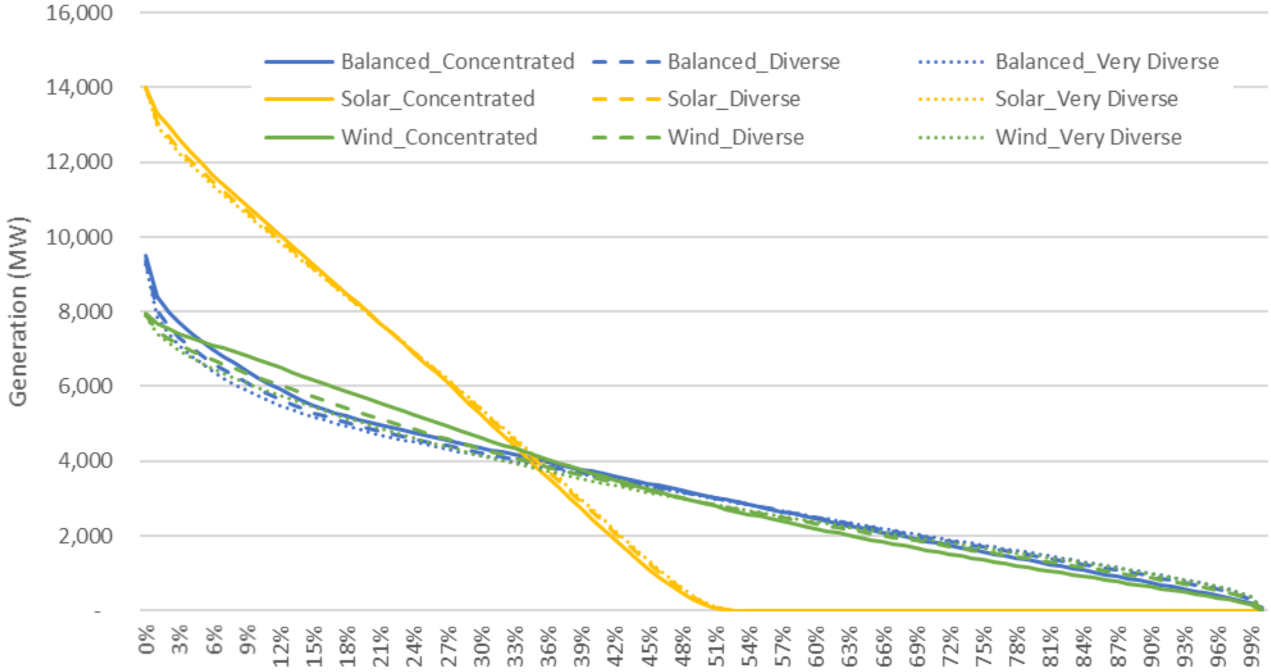


Figure 11 - Hourly generation duration curve (2050)



Different levels of geographic diversity in Figure 10~~Figure 10~~ are shown by solid (Concentrated), dashed (diverse) and dotted (very diverse) lines. Different focuses of new generation (solar-only, wind-only, balanced) are shown by different colours.

Because each scenario has been sized to produce the same amount of GWh generation, the area under each curve is the same

Solar generation has a distinctive shape whereby it doesn't generate anything for about 50% of the time (i.e. during the night).

Wind is quite different, with a roughly linear curve from no output to nearly maximum output, and far less variation than solar.

Diversity has a noticeable impact on all types of generation here, reducing the extremes of peak levels of generation, and also reducing the extent of periods of low generation. This flattens the curve, making generation more consistent compared to the concentrated scenarios.

4.2.2 Daily generation

As shown by the following two figures, at a daily level, the GDC looks very different. The within day shape of solar is no longer apparent, and instead it has less day-to-day change than wind.

Locational diversity has a much higher impact here for wind resulting in very noticeable differences from the concentrated cases.

There is relatively little geographical diversity benefit for solar.

Having a mix of wind and solar provides even greater levels of diversity, flattening the duration curve such that the system doesn't suffer the same extent of extremes of low generation, nor experience the same extent of extremes of high generation.

Figure 12 - Daily generation duration curve (2035)

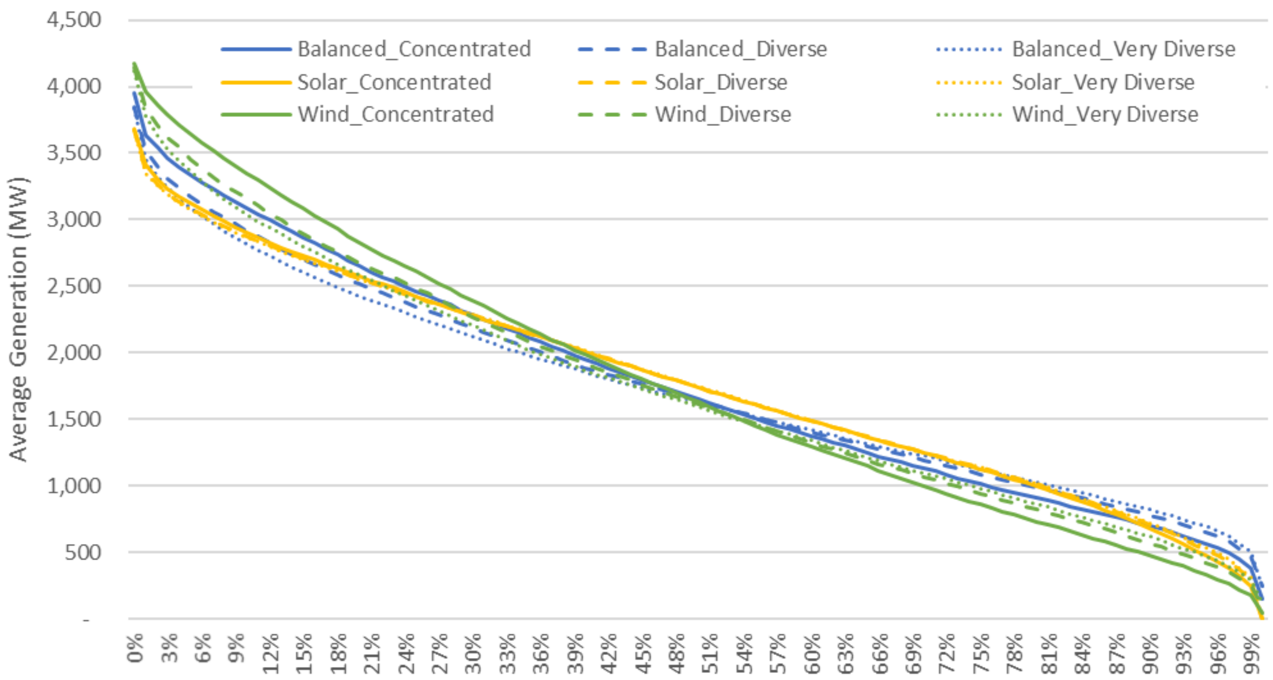
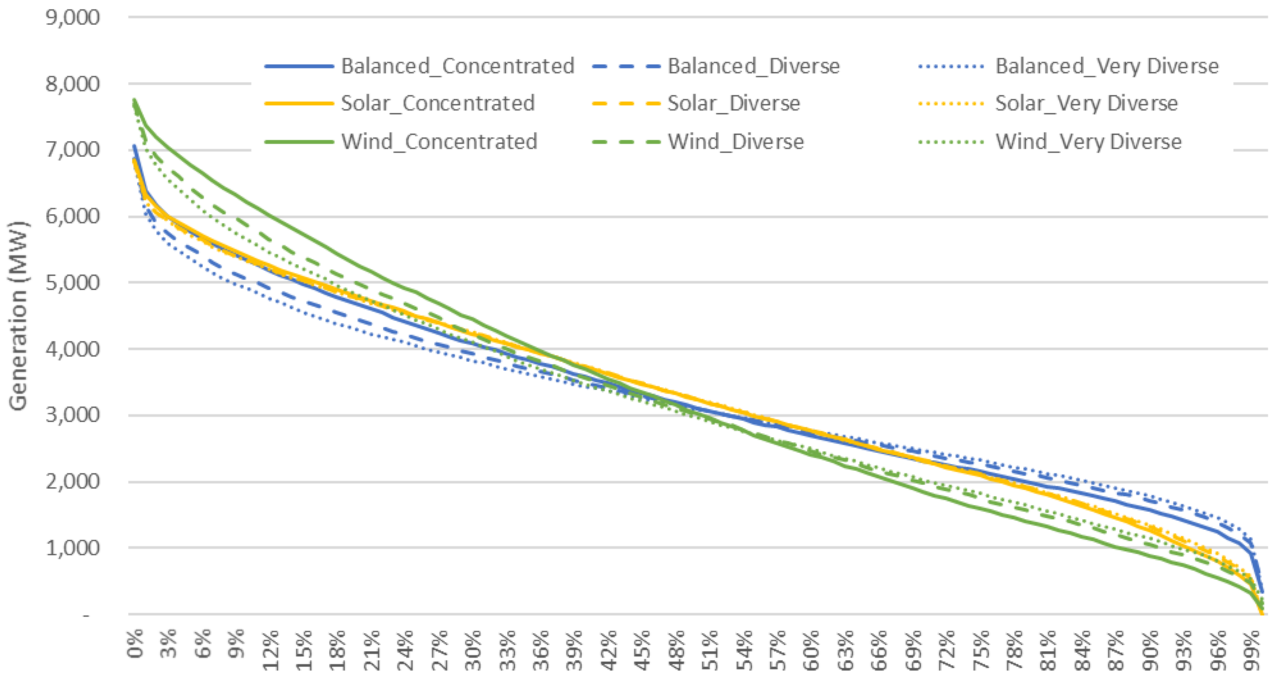


Figure 13 - Daily generation duration curve (2050)



4.2.3 Weekly generation

Figure 14 - Weekly generation duration curves (2035)

As shown in the following figures, the weekly GDC is similar to the daily one in many respects. One notable difference is that locational diversity has slightly less impact on the wind and balanced curves.

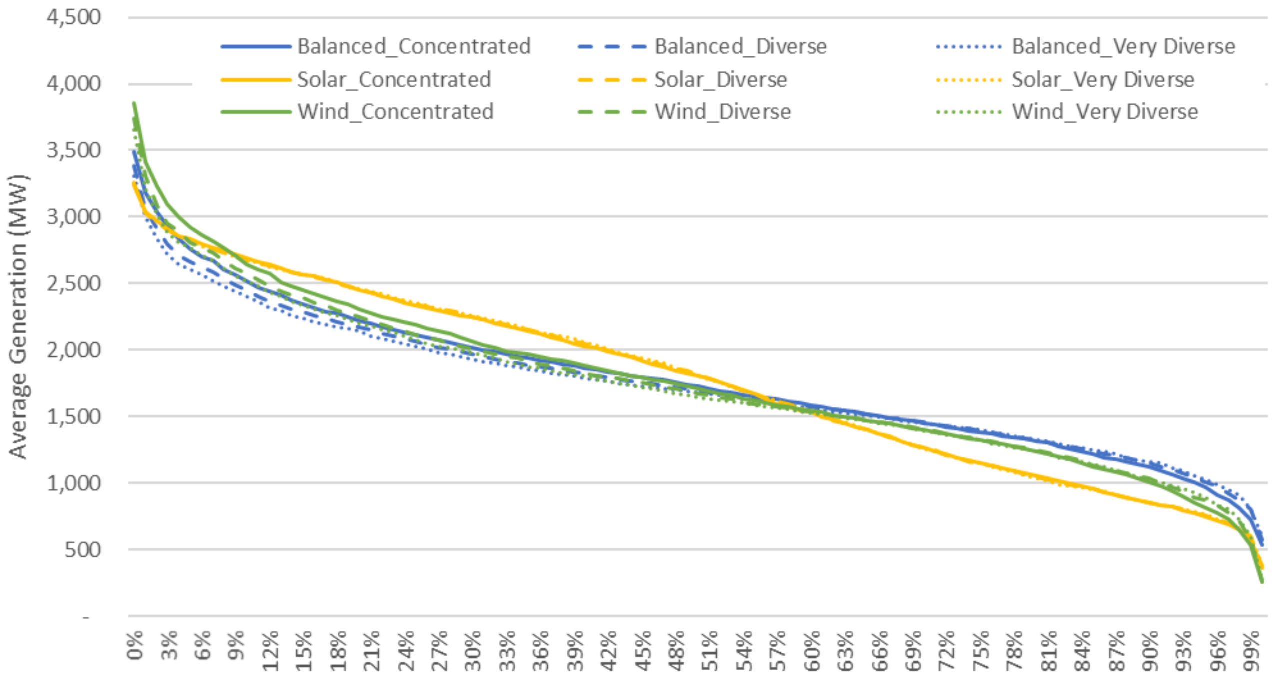
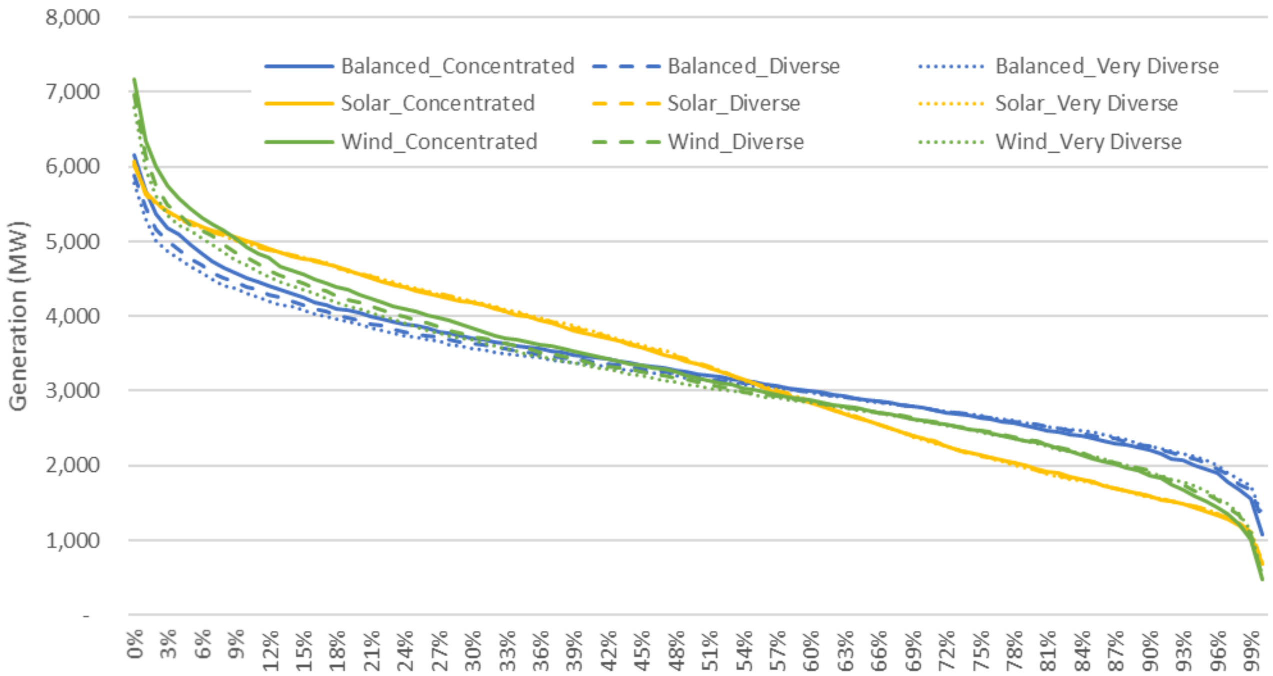


Figure 15 - Weekly generation duration curves (2050)



4.2.4 Monthly generation

As shown in the following two figures, the summer/winter split is evident in monthly generation for solar. Locational diversity has less effect compared to weekly or daily.

Figure 16 - Monthly generation duration curves (2035)

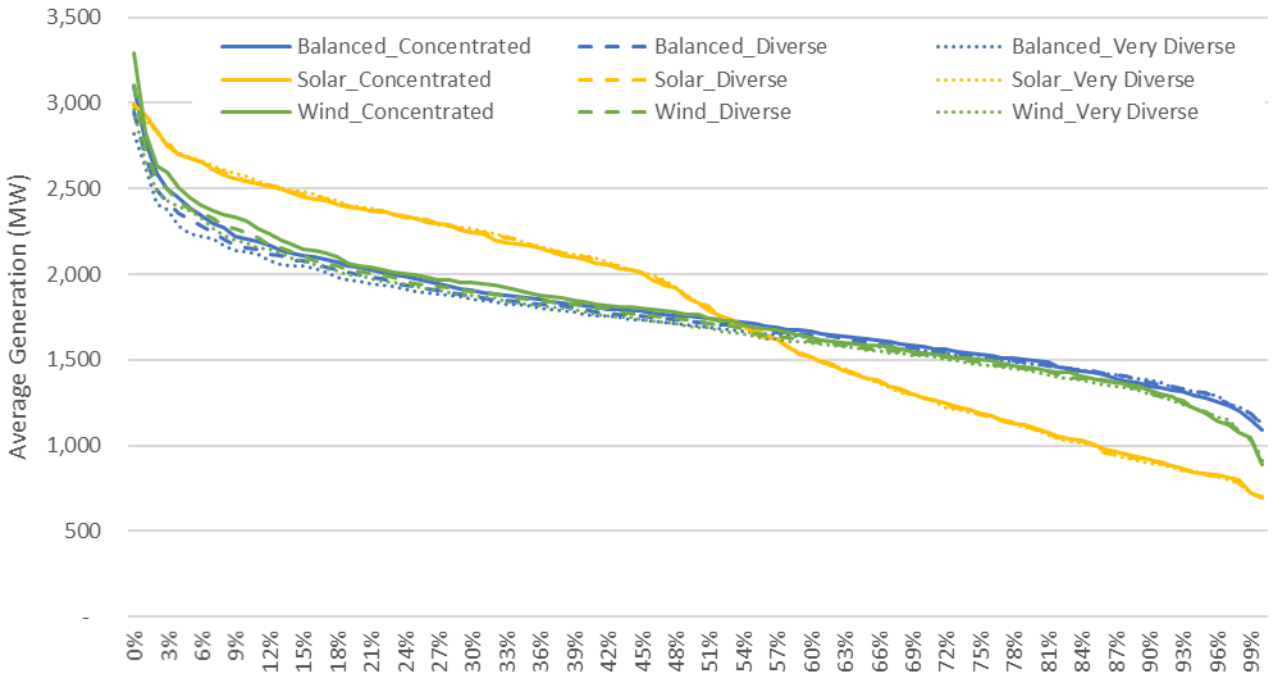
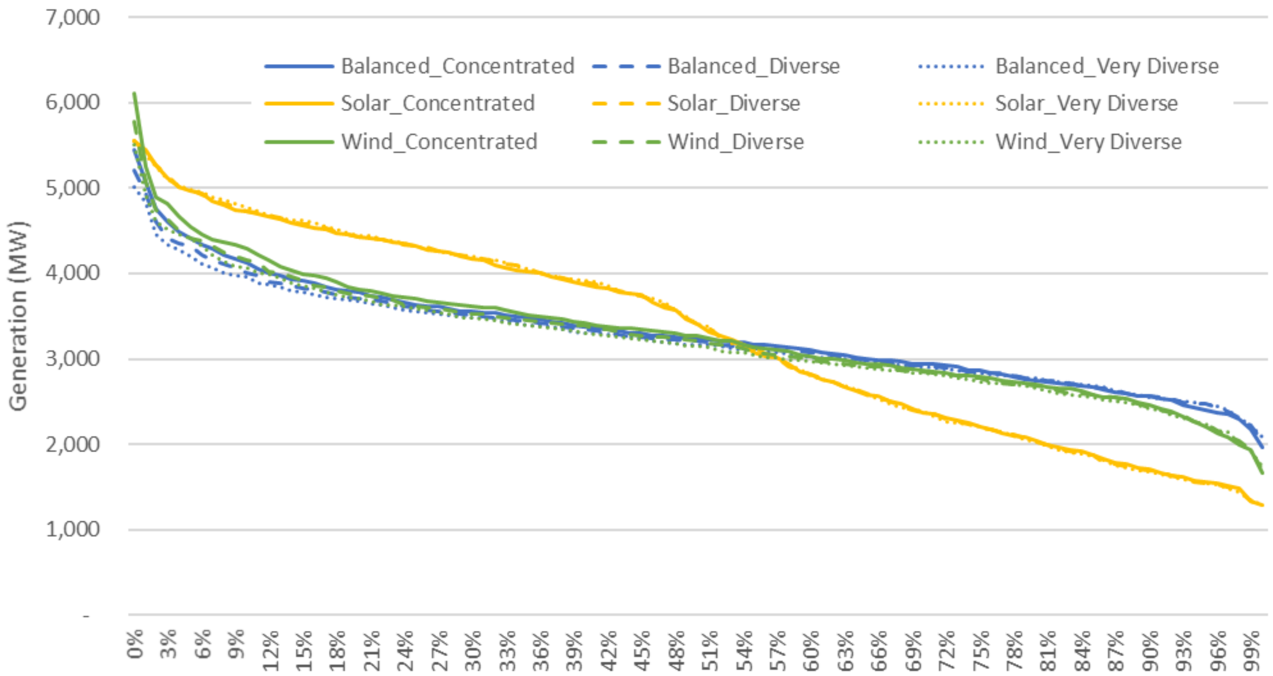


Figure 17 - Monthly generation duration curves (2050)



5 How generation interacts with the New Zealand system

The preceding sections looked at raw generation data for sites and build scenarios. The following sections look at how that generation would interact with the wider New Zealand electricity system.

Supply must meet demand at all times, but three timeframes are of particular interest in the New Zealand system:

- Peak supply
- Seasonal swing
- "Dry years"

Additionally, we have also considered the week-to-week situation, as with high levels of renewable generation that may become a fourth important timeframe.

5.1 Peak supply issues

One of the key challenges for the New Zealand electricity system is meeting demand at all times. This is particularly difficult when demand is highest, and increasing levels of renewable generation may make this even more difficult if that generation does not coincide with periods of high demand.

To investigate this challenge more closely, we considered the peak "residual demand" requirement. In this context, residual demand is total demand minus generation from wind and solar.[5]

Figure 18 - Residual peak demand requirement - 2035[6]

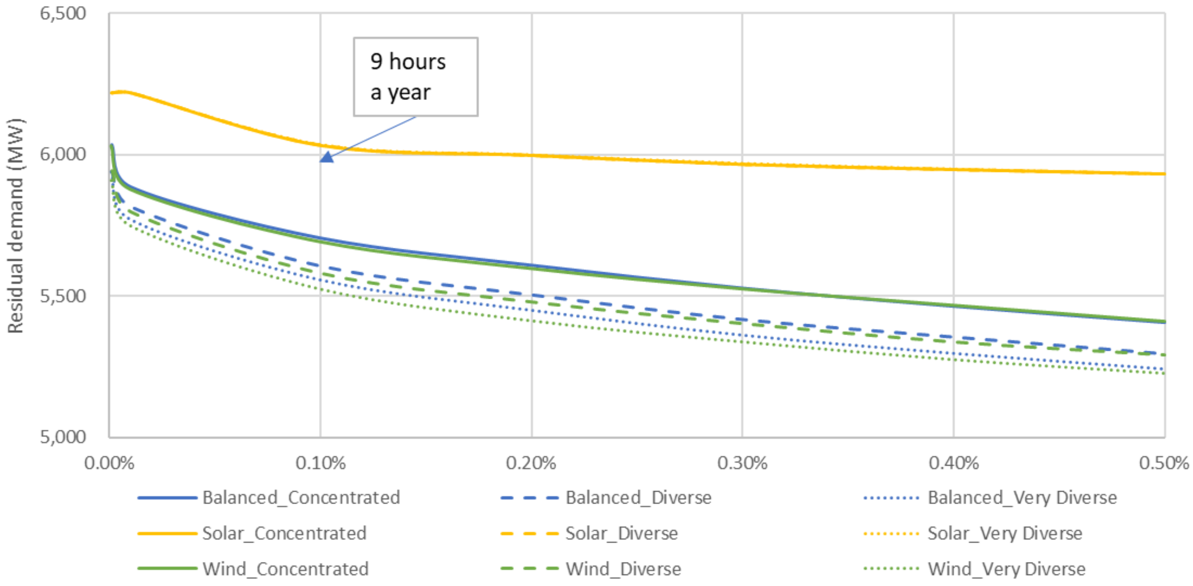


Figure 18 shows the top 0.5% of the residual demand duration curve, which corresponds to about 45 hours per year (8,760*0.5%).

Most apparent is that solar heavy builds have significantly higher residual demand, giving rise to increased need for other forms of 'supply' at such times – e.g. other types of generation, batteries, or demand response. This is unsurprising, because peak demand typically occurs during winter

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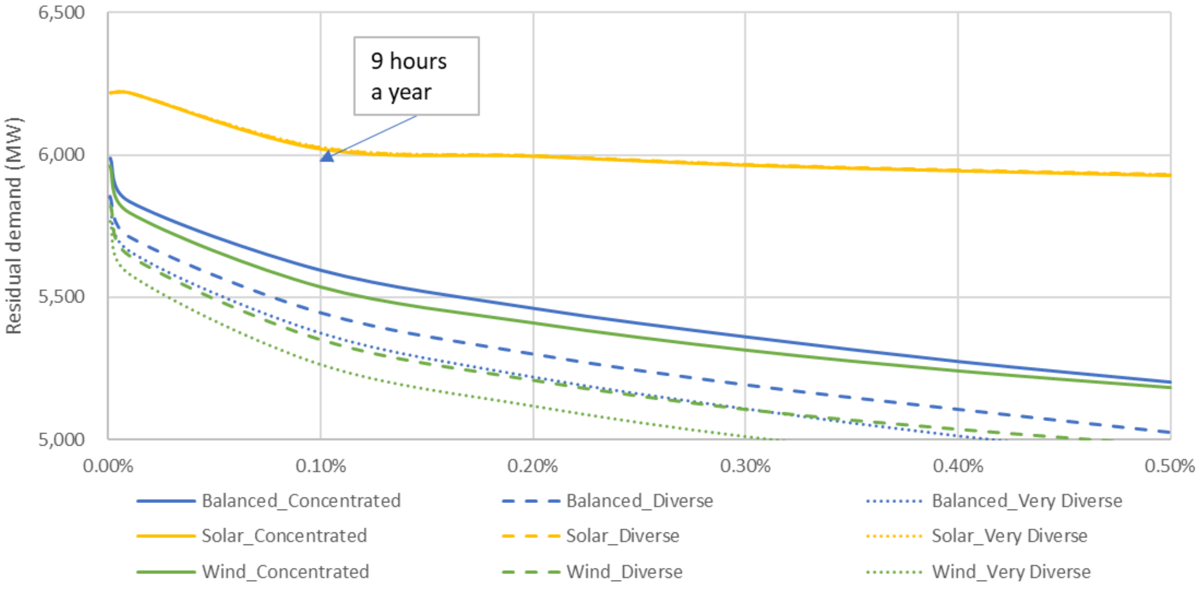
[5] We do not consider how hydro might contribute to this residual demand requirement, except to note that this ability would be very similar across all build schedules.

[6] The "kink" at the leftmost point of the solar curves is because the very top of the curve is flat. There is no output from solar, and the demand is repeated because we loop a single year's demand across all renewable generation output years. This isn't the case for other generation types because the output is non-zero.

evening peaks where there is minimal solar generation. This also means that diversity has no effect on the solar curves, because zero is still zero.

For the balanced scenarios, at the “9 hours a year” 0.1% line, the “diverse” scenario reduces the peak relative to the “concentrated” by about 70 MW, while the “very diverse” reduces it by about 120 MW. The wind scenario is similar, although slightly more pronounced. Using the carrying costs of an OCGT peaker as a rough proxy for the cost of the resources to meet any shortfall in capacity, a “concentrated” scenario would result in an extra $18m in cost per year relative to the “very diverse” scenario.

Figure 19 - Peak residual demand requirement - 2050



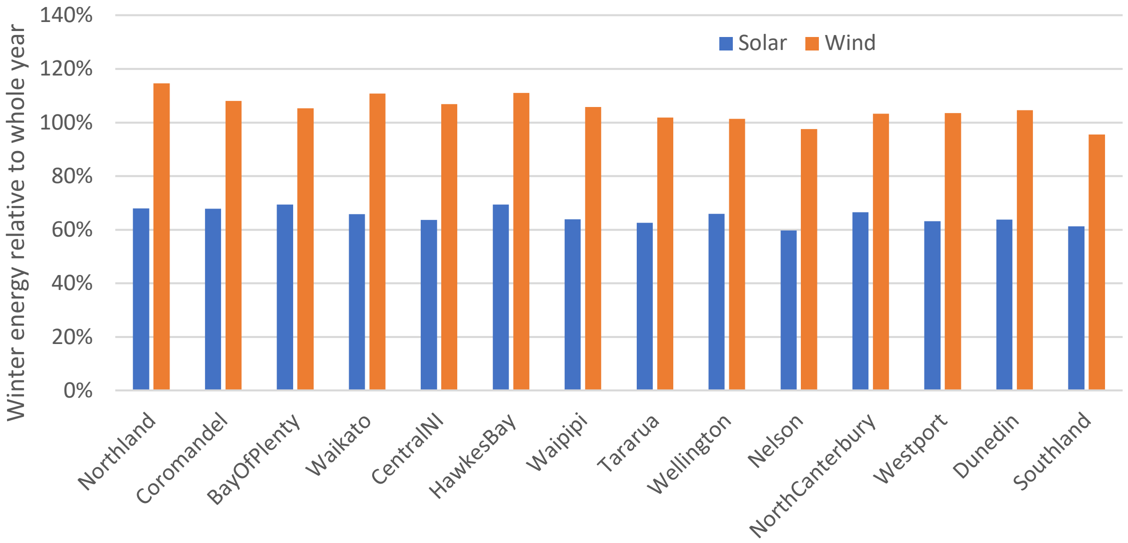
For 2050, the difference between solar and other build priorities is more pronounced. The impact of diversity is increased in the wind and balanced scenarios, meaning that at the “9 hours a year” level, there is about 125 MW and 175 MW less residual demand in the “diverse” and “very diverse” scenarios – worth approximately $25m per year. The solar scenarios are identical to 2035, because zero is still zero.

5.2 Winter energy support

The New Zealand electricity system also needs to supply more energy over winter to meet increased heating demand. If renewable energy generates more over winter compared to summer, then this would assist with this requirement.

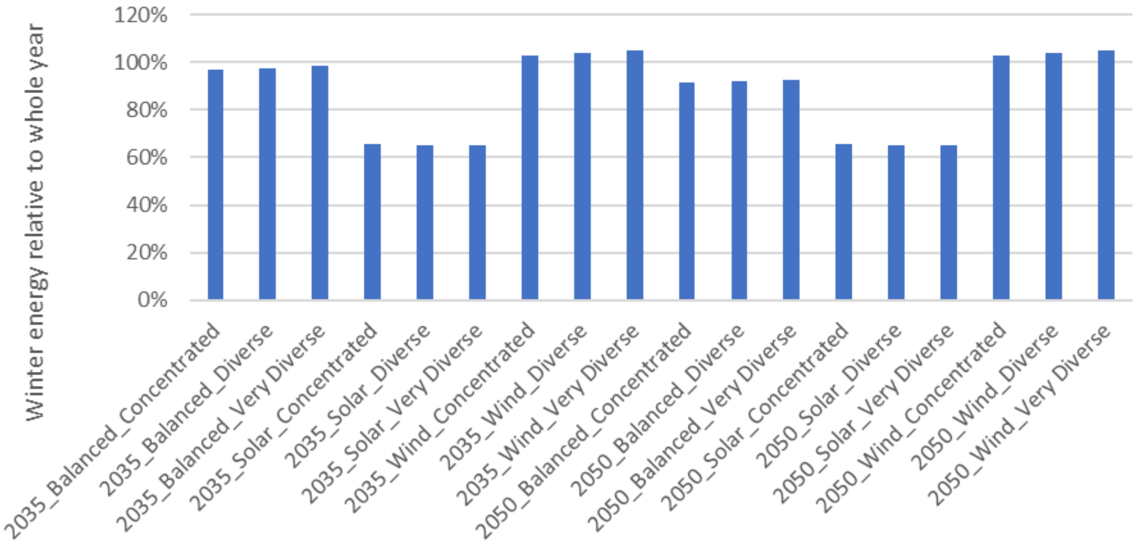
We calculated the average capacity factor during winter (June to September), and compared it to the average capacity factor from the entire year. We have shown data for sites and generation type, because the difference between generation types is stark. For all solar sites, this value is much less than 100%, because there is less sunlight in winter. For wind, most sites are greater than 100% indicating that there is more generation.

Figure 20 - Winter energy compared to rest-of-year for sites



When converted into build schedules, the lower output from solar generation results in lower output during winter in all scenarios except the wind-only ones. This suggests that increased amounts of solar generation will exacerbate the need for other forms of winter energy relative to summer.

Figure 21 - Winter energy compared to rest-of-year for build schedules



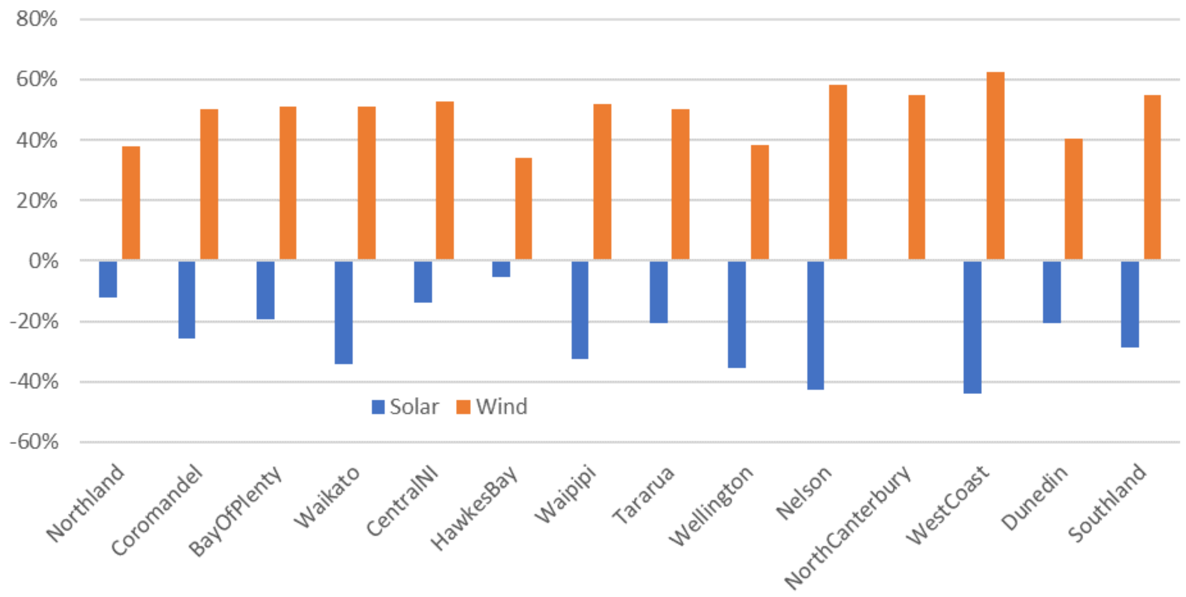
The reduced winter output from solar in the 2050_Balanced_Concentrated scenario means this scenario produces about 800 GWh less energy during winter than it would if wind and solar's generation was flat through the year. This is of a similar magnitude to the increase in *demand* over winter months relative to average annual demand. To assess the cost implications of this would require detailed system modelling, including the interaction with dry-years (see next section below), all of which is out of scope for this study. However, diversity helps this slightly as in the 2050_Balanced_VeryDiverse scenario there is only 700 GWh less energy during winter.

5.3 Dry winter support

The energy challenge over winter is not just due to increased demand. Inflows to hydro storage lakes also decrease – partly due to precipitation occurring as snow which isn't released into the lakes until the spring/summer melt. If inflows are significantly lower than normal, this leads to a "dry winter", in which energy requirements can be more difficult to meet than normal.

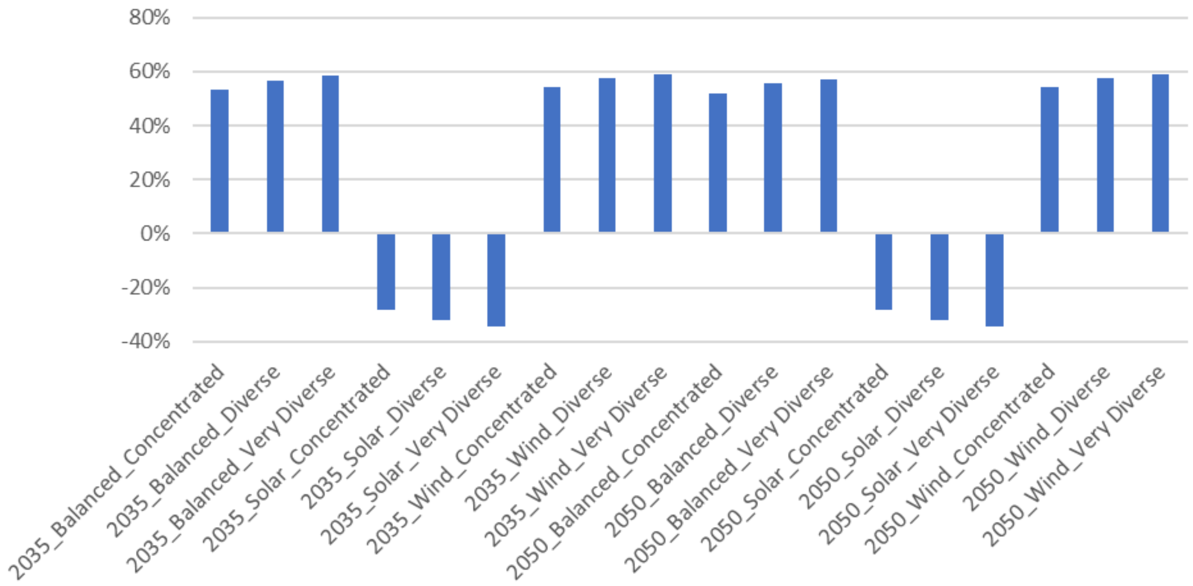
This means that it is not only important how much less energy renewable generation normally generates during winter, but also whether the output is correlated with the incidence of dry winters. To investigate this, we compared renewable generation output during winters with inflows to storage lakes.

Figure 22 - Correlation between hydro inflows and renewable generation sites



All wind sites are positively correlated with winter hydro inflows, and all solar sites are negatively correlated, except North Canterbury which has a correlation coefficient very close to zero. This means that wind will tend to exacerbate dry-year generation – when it is dry, it is relatively less windy. Solar appears to counteract dry-year outcomes – when it is dry, it is relatively sunnier. However, this effect is outweighed by the less generation from solar on average during winter.

Figure 23 - Correlation between hydro inflows and renewable generation build schedules



Unsurprisingly, combined build schedules are somewhat positively correlated with hydro inflows (due to being relatively wind-heavy), which would lead to more severe “dry winter” situations – all other things being equal.[7] Similarly, balanced schedules are also positively correlated. Solar build schedules are negatively correlated.

However, the correlation coefficient does not give any information on how much one variable (i.e. inflows) changes with respect to the other (i.e. renewable generation).[8] It’s possible to have a very high correlation with a negligible size of effect.

Figure 24 – Winter renewable generation and inflows (2035_Balanced_Diverse)

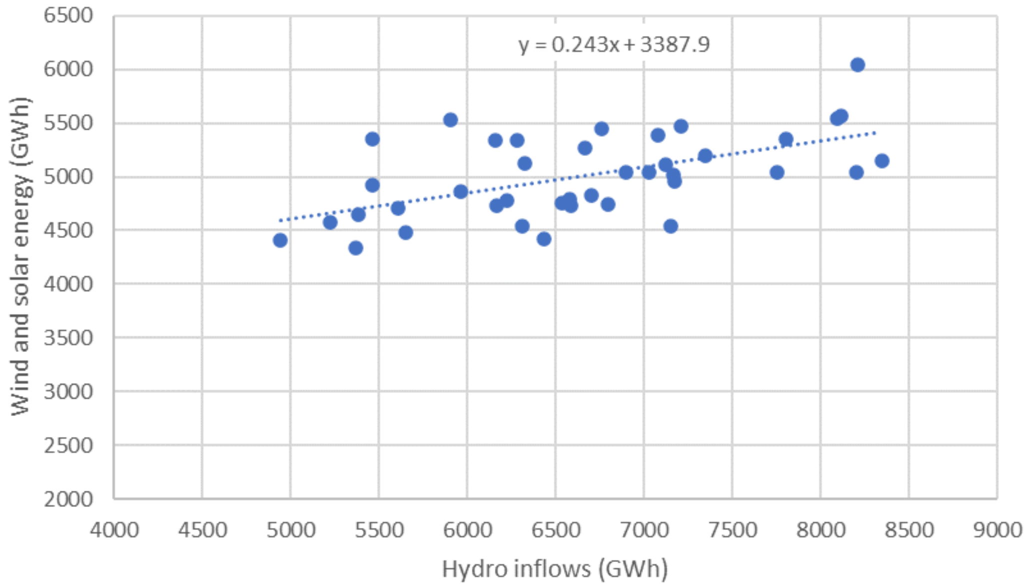


Figure 24 shows winter renewable generation and hydro inflows. There is a positive correlation, and the slope of the relationship indicates that when hydro inflows are 1,000 GWh lower than normal, renewable generation would be about 240 GWh lower. An alternative way to look at it is that the correlation between renewable generation and hydro inflows would make dry winter years ~24% more “dry” on average. With a typical “dry winter” having about 1,500 GWh less energy, we’d expect about 400 GWh less generation from wind and solar. However, note that this is *on average*, and each dry year may have more or less than this average.

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[7] However, this does not necessarily mean that the system would be less able to deal with these dry years situations because a change in the generation mix would change how the electricity system is managed, including the seasonal storage and release of the hydro lakes. Modelling this effect is outside the scope of our investigation.

[8] The correlation coefficient indicates how closely the relationship between the two series is to a perfect straight line, but does not give any indication of the steepness of that line. Another way to think about this is that a relatively scattered plot but with a steep best-fit gradient will have lower correlation but, on average, a greater effect on dry-year generation than a plot which was tightly fitted around a line (i.e. high correlation) but with a very shallow gradient.

Figure 25 - Slope of dry winter correlation

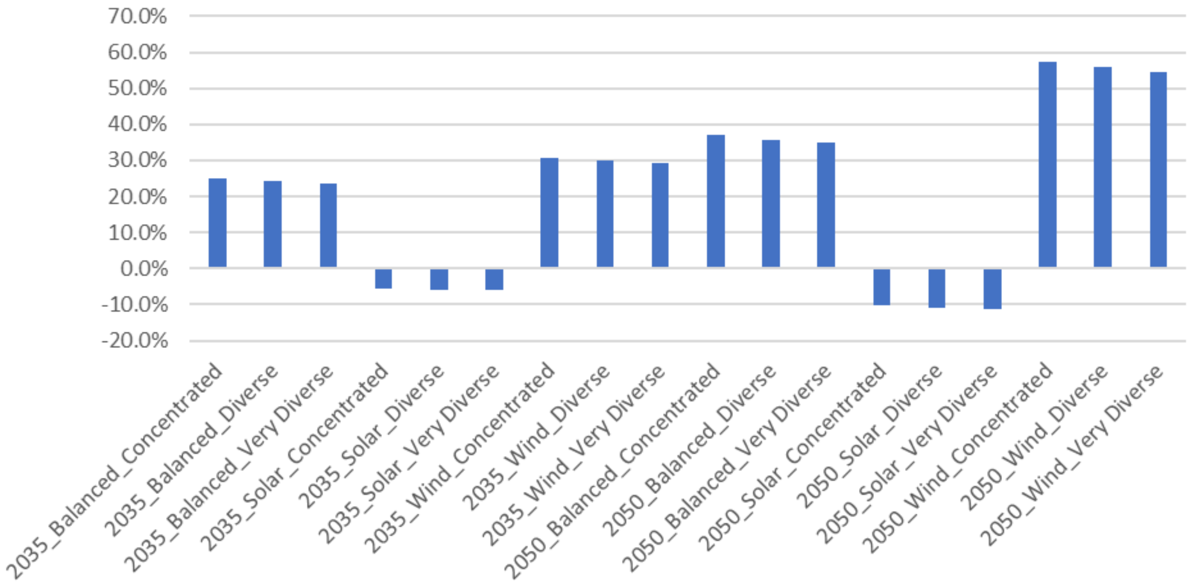


Figure 25 shows the slope (shown for 2035_balanced_diverse above) for each scenario. While diversity does reduce the slope of this relationship, its effect is minimal. The slope for 2035 balanced build schedules changes from 25% to 23.7% with increasing diversity. The type of generation built has a much larger effect since solar heavy build schedules have a negative relationship.

The results should be considered as indicative only, since the strength of this relationship (i.e. correlation) is not particularly strong.

To assess the cost implications of this would require detailed system modelling which is out of scope for this study.

5.4 Week to week variability

A potentially important time period to look at is week-to-week. Batteries and time shifting of EV charging may be able to deal with hourly peaks, but it is less feasible to store energy for an entire week.

Figure 26 - Low generation weeks (2035)

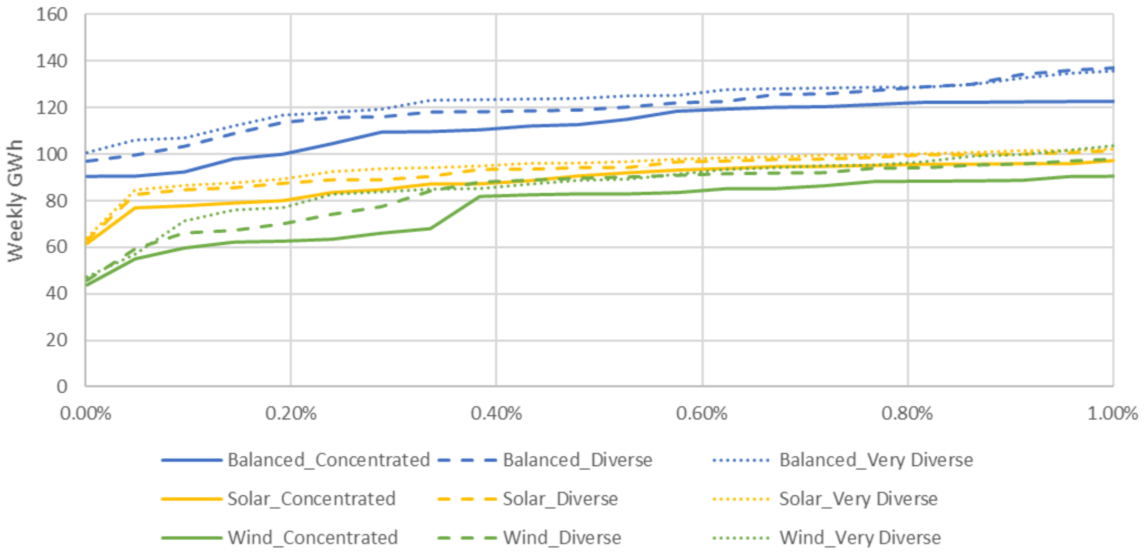


Figure 26 shows output from the lowest 1% of weeks. The wind heavy scenarios have the lowest output weeks, followed by solar ones, and the balanced scenario has the highest. Diversity between generation types has a very large effect for increasing renewable generation during the lowest weeks.

The effect of locational diversity is lower, but still noticeable. For the balanced generation type case, the more diverse scenarios result in approximately 15 GWh more generation during low weeks.

Figure 27 – Low generation weeks (2050)

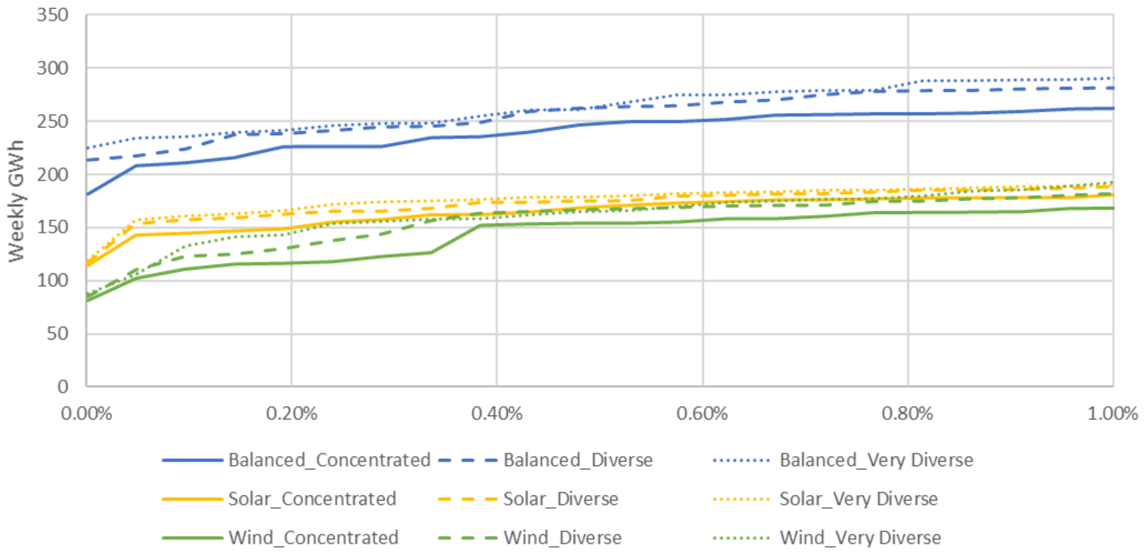


Figure 27 shows the same data for 2050, and it draws similar conclusions. Generation type diversity increases output significantly during the lowest weeks, while location diversity has a smaller effect.

6 Conclusions

The variability of most renewable generation (i.e. wind, solar, and hydro, but not geothermal) will create some significant challenges as New Zealand transitions to an electricity system with very high levels of renewables. It will need to manage periods of low generation, particularly if they coincide with periods of high demand. Similarly, periods of high generation could result in uneconomic wasted 'spill' if these periods coincide with periods of low demand.

Our analysis has demonstrated that having a diverse portfolio of renewable generation is – all other things being equal – likely to enable New Zealand to meet this challenge at lowest cost:

- Having a diversity between different *types* of variable renewables (i.e. having a mix of wind and solar) materially reduces the extremes of low and high generation that would occur if additional renewable development was only wind or only solar. This is because of a general anti-correlation between the two technologies.

  Further, wind and solar have different strengths and weaknesses in terms of their correlations with demand and hydro, and thus their suitability at meeting the need for generation (or at least, not giving rise to the need for balancing generation) at different times:

  - Solar's relative lack of generation in winter and early mornings & evenings make it poorly suited for meeting the need for seasonal and peaking generation. However, on the positive side, it has less variability than wind over week-to-week timeframes, which is a timeframe that is difficult to address with lithium-ion batteries.
  - Wind's average output is well matched to daily and yearly demand shapes, meaning that, on average, there will be reduced need for additional balancing energy over these timeframes in a wind-heavy future. However, wind's positive correlation with winter hydro inflows means it will tend to exacerbate the need for dry-year firming energy.

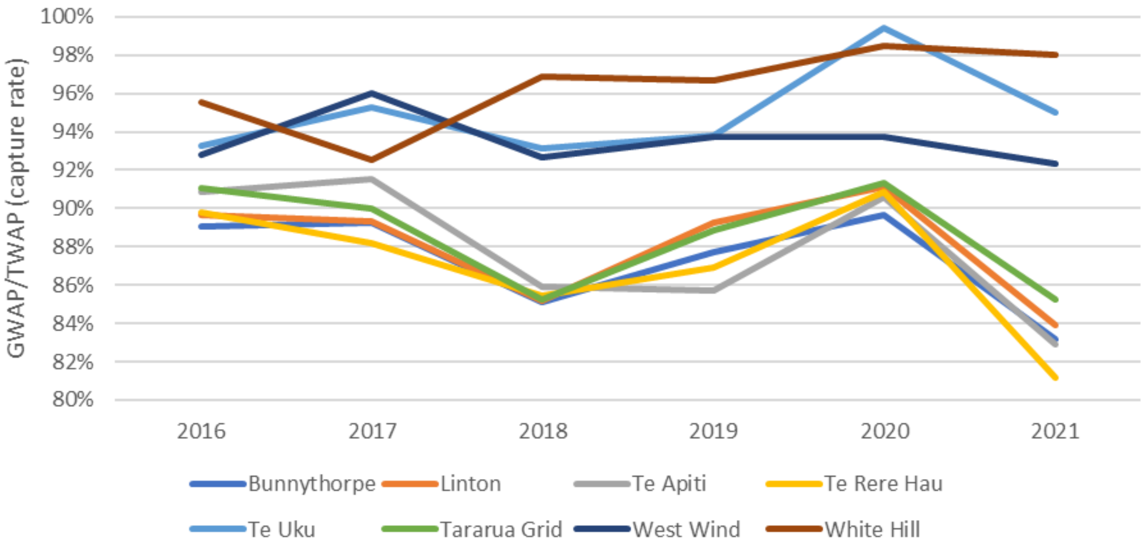
- Having a diversity in the *geographical spread* of renewables will further reduce the extent of extremes of both low and high generation.

  This geographical diversity benefit appears greatest for wind, relative to solar, with the extent of benefit varying with different time-frames. It appears to deliver greatest benefit for seasonal and dry-year requirements, with the top of the North Island in particular appearing to have significantly different wind patterns relative to much of the rest of the country.

  The geographical diversity benefit for shorter time periods (e.g. over a day or week) is less than for the seasonal benefits.

That said, we note that the apparent scale of geographical diversity benefit for wind (as indicated by the extent of reduction of extremes of both low and high generation) is less than might be expected when looking at the observed price benefit of smaller wind schemes located distant from the main Tararua concentration of wind generation.

Figure 28 - GWAP/TWAP for existing wind farms



As can be seen, the GWAP/TWAP ratio for the Tararua schemes is materially worse than for the much smaller (in generation terms) and more distant sites such as White Hill. This seems to imply greater geographical diversity benefits than that implied by the generation duration curves comparing concentrated and very diverse scenarios.

We believe this reflects a number of factors:

- The simulated data tending to under-estimate the extent of geographical diversity benefit to a certain degree, as demonstrated by the comparison with real-world generation in Appendix A.
- The observed GWAP/TWAP values also taking into account the real-world effects of transmission constraints
- The asymmetry in prices between periods of significant surplus versus significant scarcity. This will tend to magnify the effect of variations in generation at either end of the duration curve. In other words, what appears to be a relatively small change in generation at periods of extreme scarcity can be very valuable and likewise (although to a lesser extent) for periods of significant surplus.

It is beyond the scope of this analysis to try and decompose these factors further.

Appendix A. Basis of analysis

Our analysis uses 40 years of simulated wind and solar generation data. In this appendix we compare the simulated generation data to historical generation data to verify the validity of using the simulated data for our analysis.

Correlation

We compared historical wind farm output to the simulated generation data.

Figure 29 - Correlation between simulated data and real station data

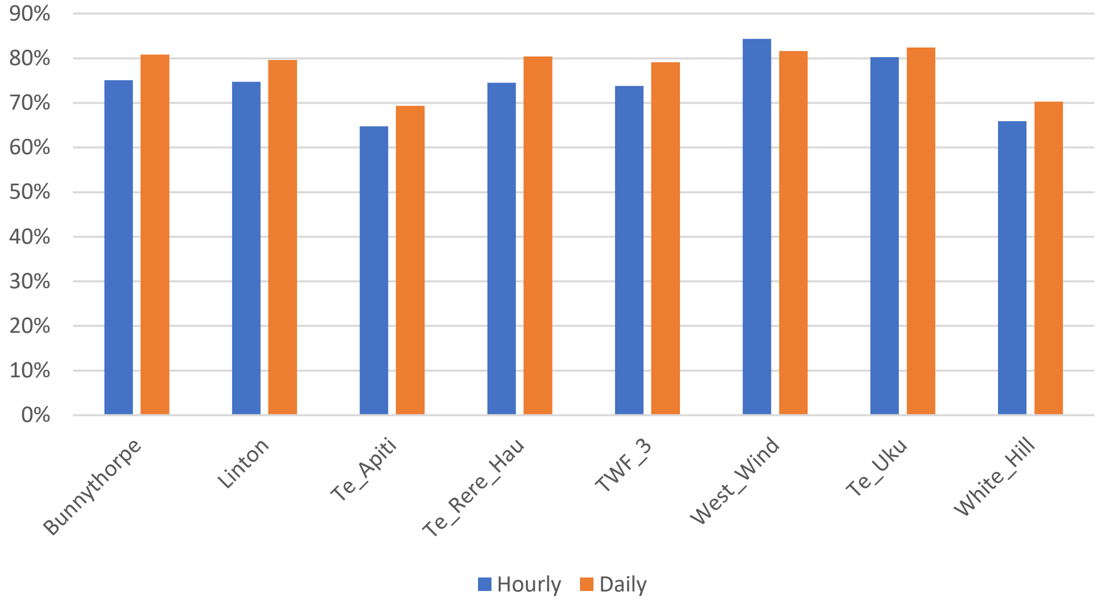


Figure 29 shows the correlation for each site. At the hourly level, most correlations are between 70 and 80%, with Whitehill and Te Apiti being noticeably worse. Most correlations improve when looking at a daily level, suggesting that even if the hour-by-hour prediction may be a little off, the daily data is better.

Figure 30 - Comparison of Simulated and real Tararua hourly generation[9]

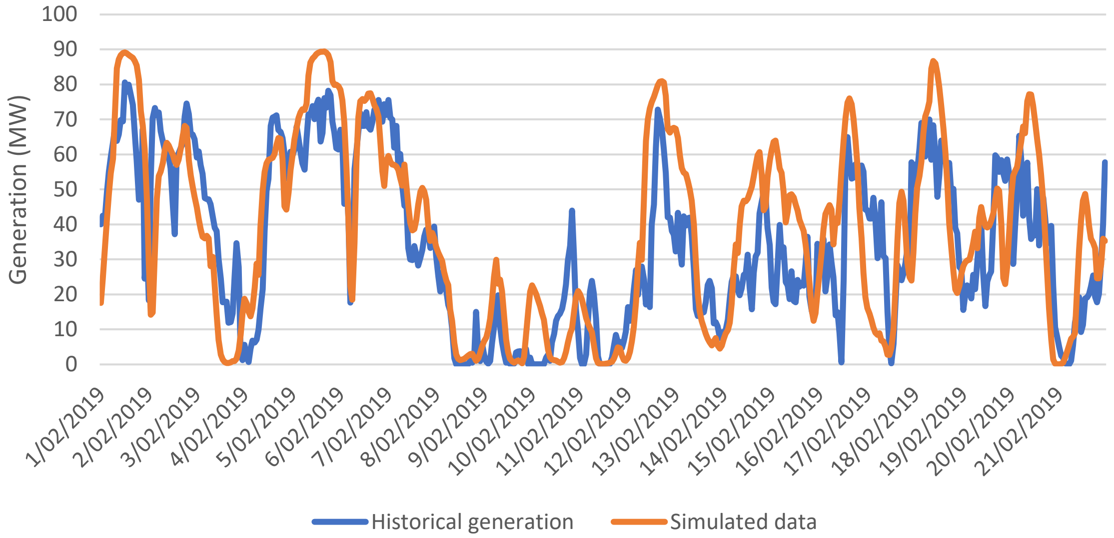


Figure 30 shows a three-week snapshot of the two different series. The two largely move in sync, although there are obvious differences.

Figure 31 – Comparison of simulated data with real station data

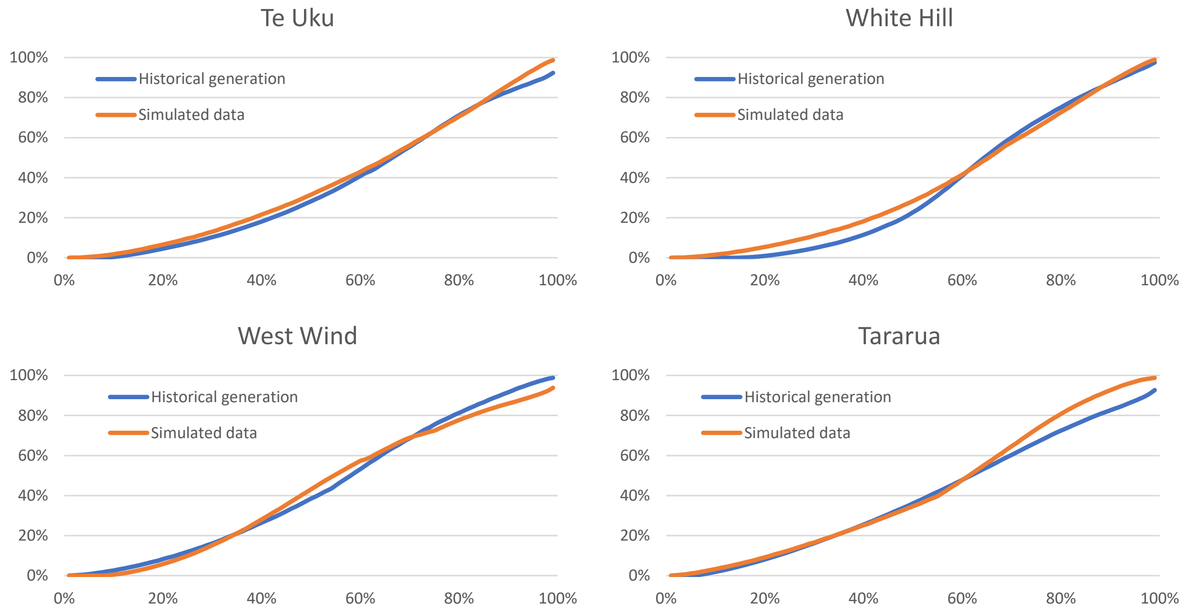


Figure 31 shows an hourly duration curve for data from 2011 to 2019 for the four sites that we have real generation data to compare to.

These match each other quite well, apart from a couple of exceptions. Whitehill real generation is significantly lower at the lower end of the curve. This is because of an unusually high number of zero generation periods, which may be because of maintenance or outages. Tararua simulated data is higher at the top of the curve. It is not clear why this is, but is unlikely to materially affect periods of *low* generation, which are our primary concern.

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[9] The correlation factor for this snapshot is 78%, which is similar to the overall level of 74%.

Figure 32 – Hourly comparison of simulated data with real composite data

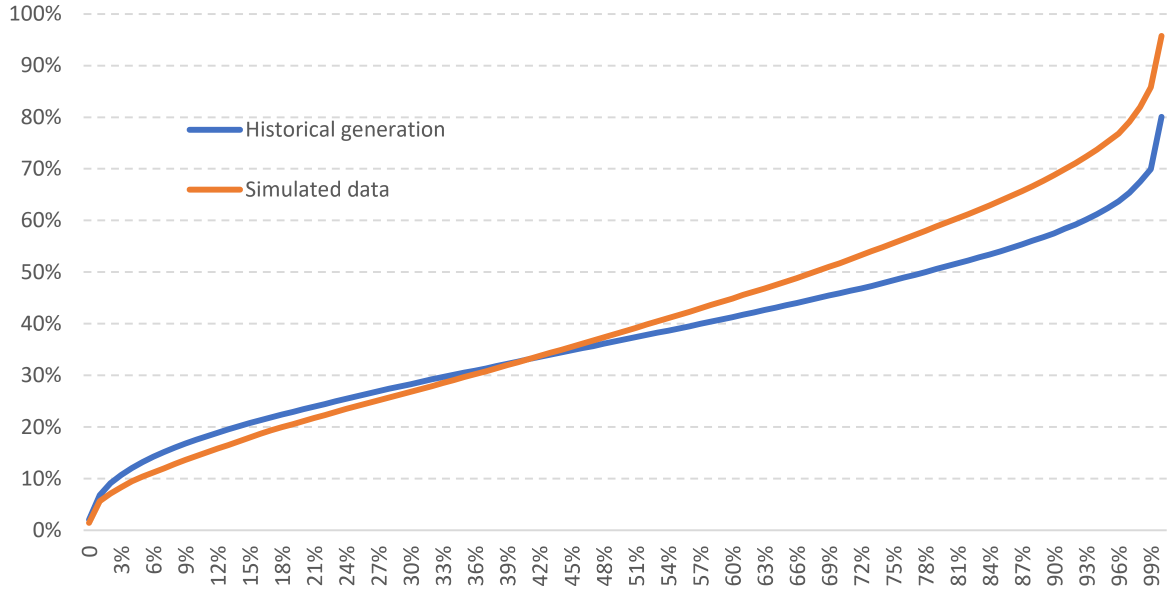


Figure 32 shows something slightly different. We have created a hypothetical build schedule with equal weighting among the four sites listed above. The hourly duration curve for this build schedule appears to show a greater difference between simulated data and generation data than the individual sites. The actual generation data is higher at low levels of output, and lower at high levels of output. This implies that simulated data is under-estimating the effect of diversity. This may be due to a mix of factors, including the effect of sites having maintenance outages at different times.

Figure 33 Daily, Weekly and Monthly comparison of simulated data with real composite data


Daily

Weekly

Monthly

Figure 34 shows the GDC for aggregate daily, weekly and monthly totals. It suggests that simulated data continues to underestimate the effect of diversity on these timeframes, although to a lesser extent for weekly and monthly data.

Capacity factor adjustment

The simulated wind data can have unusually low capacity factors. We have made an adjustment to modify overall capacity factors for all sites closer to 40-45%. This is a reasonable step because it appears that the simulated data does not take into account local topography at a high resolution meaning that higher capacity factors could be achieved by siting wind turbines on ridgelines and hill tops.

Additionally, the site we have chosen for the simulated data for a region may not be the optimal ones for that region. It is likely that a site with higher average wind speeds would be available that would still have a similar overall wind resource.

Maintenance and actual generation vs potential generation

Note that real-world generation data is affected by outages and maintenance, while the simulated data is not. This may explain some of the difference between the series. Concept is aware that Te Apiti, in particular, has operated at reduced capacity from time to time recently.

Overall, our real composite data series has a capacity factor of 39%, while the comparable simulated data series has a capacity factor of 41%. We expect that most of this difference is due to real-world maintenance reducing output from generation sites from time to time.

Scaling the simulated data to deliver a 39% capacity factor would lower the blue, "simulated" curve in the above graphs by about 5%. This will tend to increase the relative diversity benefit of Real-world generation at times of low output, and reduce it at times of high output.

Appendix B. Correlations for different renewable sites

Figure 34 - Daily wind correlation

	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	77%	66%	79%	55%	53%	44%	29%	23%	33%	21%	40%	24%	1%
Coromandel		100%	88%	94%	73%	70%	63%	54%	32%	59%	38%	54%	39%	19%
BayOfPlenty			100%	84%	86%	77%	72%	64%	46%	58%	40%	56%	34%	17%
Waikato				100%	77%	74%	70%	56%	39%	61%	41%	61%	40%	19%
CentralNI					100%	84%	85%	82%	66%	62%	55%	63%	41%	26%
HawkesBay						100%	66%	60%	49%	45%	43%	49%	40%	13%
Waipipi							100%	88%	77%	76%	62%	74%	41%	34%
Tararua								100%	80%	76%	71%	66%	43%	43%
Wellington									100%	56%	72%	63%	30%	34%
Nelson										100%	66%	83%	53%	54%
NorthCanterbury											100%	71%	62%	64%
WestCoast												100%	54%	48%
Dunedin													100%	65%
Southland														100%

Figure 35 - Daily solar correlation

	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	84%	75%	83%	69%	65%	70%	67%	64%	58%	57%	50%	50%	51%
Coromandel		100%	92%	95%	82%	75%	79%	77%	72%	64%	62%	54%	52%	51%
BayOfPlenty			100%	84%	87%	81%	76%	77%	72%	60%	61%	48%	50%	47%
Waikato				100%	80%	73%	86%	81%	75%	69%	65%	60%	55%	54%
CentralNI					100%	95%	80%	86%	78%	60%	66%	44%	48%	44%
HawkesBay						100%	76%	86%	78%	55%	65%	39%	46%	41%
Waipipi							100%	93%	89%	79%	75%	67%	60%	56%
Tararua								100%	92%	73%	76%	60%	58%	53%
Wellington									100%	78%	84%	64%	62%	54%
Nelson										100%	75%	88%	65%	60%
NorthCanterbury											100%	68%	71%	59%
WestCoast												100%	69%	66%
Dunedin													100%	87%
Southland														100%

Figure 36 - Weekly wind correlation

	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	82%	74%	82%	62%	64%	54%	39%	32%	39%	31%	48%	29%	7%
Coromandel		100%	92%	96%	80%	79%	74%	66%	46%	69%	53%	67%	50%	32%
BayOfPlenty			100%	90%	90%	83%	82%	74%	58%	68%	55%	70%	47%	30%
Waikato				100%	84%	82%	80%	68%	52%	70%	57%	73%	53%	33%
CentralNI					100%	88%	91%	88%	75%	73%	71%	77%	57%	44%
HawkesBay						100%	77%	70%	62%	57%	60%	63%	54%	29%
Waipipi							100%	92%	81%	82%	73%	81%	56%	50%
Tararua								100%	83%	84%	80%	76%	60%	60%
Wellington									100%	64%	76%	70%	43%	46%
Nelson										100%	76%	88%	67%	68%
NorthCanterbury											100%	80%	76%	78%
WestCoast												100%	66%	60%
Dunedin													100%	77%
Southland														100%

Figure 37 - Weekly solar correlation

	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	95%	91%	94%	89%	87%	90%	88%	87%	84%	84%	79%	81%	82%
Coromandel		100%	97%	98%	93%	90%	93%	92%	90%	88%	87%	82%	82%	82%
BayOfPlenty			100%	94%	95%	92%	91%	92%	90%	85%	87%	78%	80%	78%
Waikato				100%	92%	88%	95%	93%	91%	90%	87%	86%	84%	84%
CentralNI					100%	98%	93%	95%	92%	84%	89%	76%	80%	78%
HawkesBay						100%	91%	94%	92%	81%	89%	73%	79%	76%
Waipipi							100%	98%	96%	93%	92%	88%	87%	85%
Tararua								100%	97%	91%	93%	85%	86%	83%
Wellington									100%	91%	95%	85%	87%	83%
Nelson										100%	90%	95%	87%	85%
NorthCanterbury											100%	86%	90%	85%
WestCoast												100%	88%	88%
Dunedin													100%	95%
Southland														100%

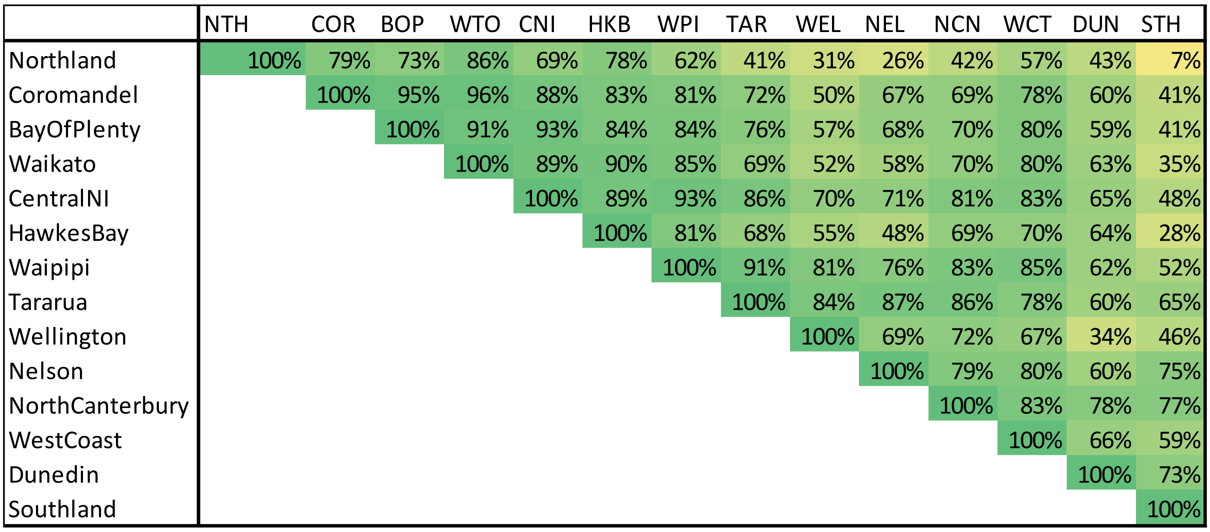
Figure 38 - Monthly wind correlation

	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	82%	74%	84%	66%	72%	59%	42%	32%	36%	36%	51%	38%	9%
Coromandel		100%	94%	96%	85%	83%	80%	72%	51%	71%	61%	74%	59%	39%
BayOfPlenty			100%	92%	92%	85%	85%	78%	62%	72%	65%	78%	57%	41%
Waikato				100%	88%	88%	85%	72%	56%	68%	64%	78%	61%	37%
CentralNI					100%	89%	94%	89%	76%	76%	79%	84%	66%	52%
HawkesBay						100%	82%	72%	62%	58%	67%	71%	64%	34%
Waipipi							100%	93%	82%	82%	80%	87%	64%	56%
Tararua								100%	86%	88%	86%	82%	65%	67%
Wellington									100%	70%	79%	73%	44%	52%
Nelson										100%	79%	86%	67%	73%
NorthCanterbury											100%	84%	78%	78%
WestCoast												100%	69%	64%
Dunedin													100%	76%
Southland														100%

Figure 39 - Monthly solar correlation

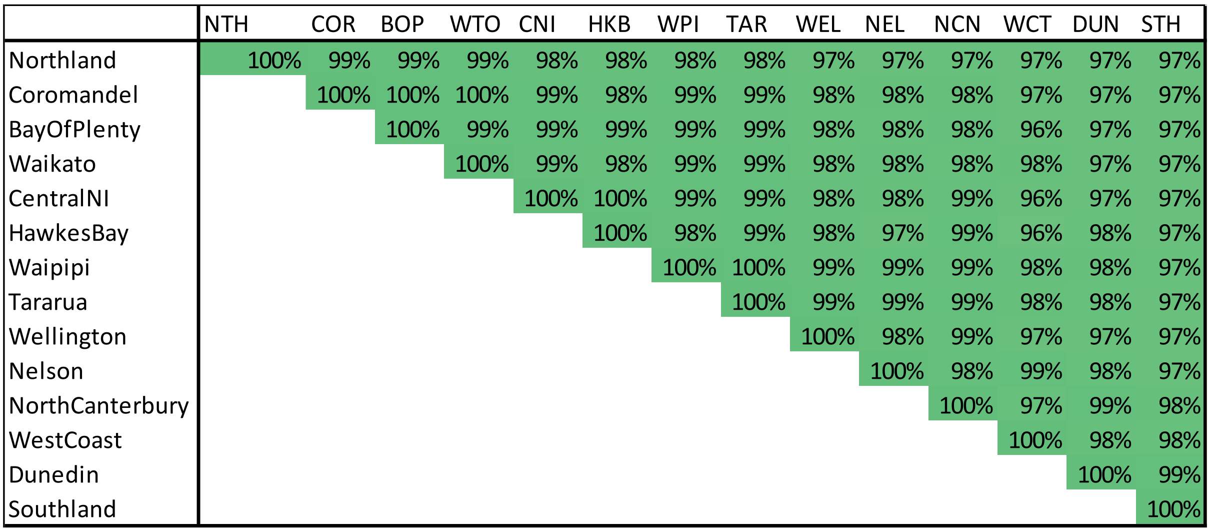
	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	98%	97%	98%	96%	96%	96%	96%	95%	94%	95%	92%	94%	94%
Coromandel		100%	99%	99%	98%	97%	98%	97%	96%	96%	96%	93%	94%	94%
BayOfPlenty			100%	98%	98%	97%	97%	97%	96%	95%	96%	92%	94%	93%
Waikato				100%	97%	96%	98%	98%	96%	96%	96%	95%	95%	95%
CentralNI					100%	99%	97%	98%	97%	95%	97%	91%	94%	93%
HawkesBay						100%	97%	98%	97%	93%	97%	90%	93%	93%
Waipipi							100%	99%	98%	98%	97%	96%	96%	95%
Tararua								100%	99%	97%	98%	95%	95%	95%
Wellington									100%	96%	98%	94%	95%	94%
Nelson										100%	96%	98%	96%	95%
NorthCanterbury											100%	94%	97%	95%
WestCoast												100%	96%	96%
Dunedin													100%	99%
Southland														100%

Figure 40 - Quarterly wind correlation



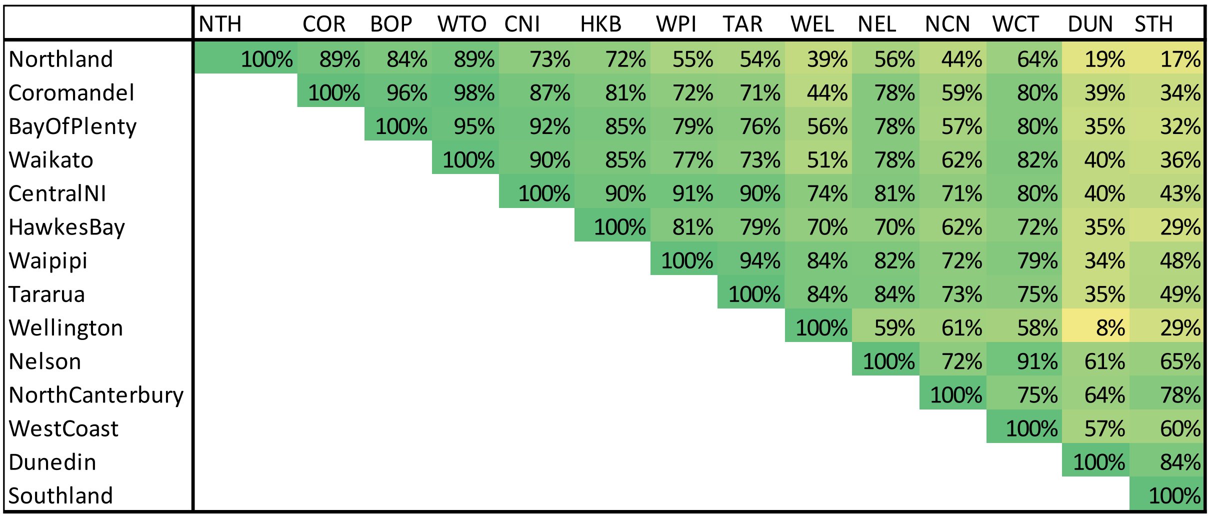
	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	79%	73%	86%	69%	78%	62%	41%	31%	26%	42%	57%	43%	7%
Coromandel		100%	95%	96%	88%	83%	81%	72%	50%	67%	69%	78%	60%	41%
BayOfPlenty			100%	91%	93%	84%	84%	76%	57%	68%	70%	80%	59%	41%
Waikato				100%	89%	90%	85%	69%	52%	58%	70%	80%	63%	35%
CentralNI					100%	89%	93%	86%	70%	71%	81%	83%	65%	48%
HawkesBay						100%	81%	68%	55%	48%	69%	70%	64%	28%
Waipipi							100%	91%	81%	76%	83%	85%	62%	52%
Tararua								100%	84%	87%	86%	78%	60%	65%
Wellington									100%	69%	72%	67%	34%	46%
Nelson										100%	79%	80%	60%	75%
NorthCanterbury											100%	83%	78%	77%
WestCoast												100%	66%	59%
Dunedin													100%	73%
Southland														100%

Figure 41 - Quarterly solar correlation



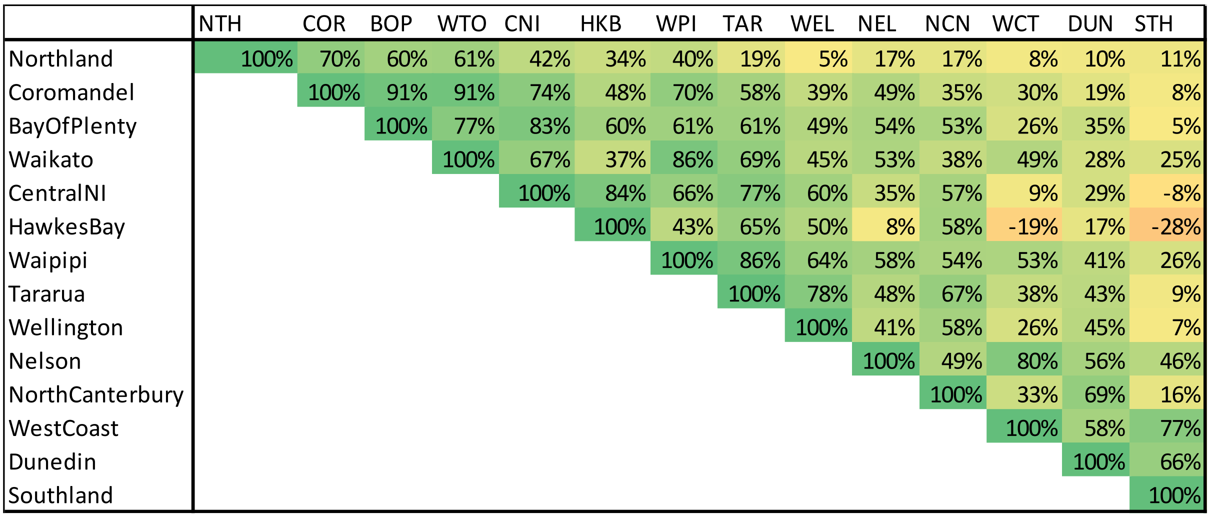
	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	99%	99%	99%	98%	98%	98%	98%	97%	97%	97%	97%	97%	97%
Coromandel		100%	100%	100%	99%	98%	99%	99%	98%	98%	98%	97%	97%	97%
BayOfPlenty			100%	99%	99%	99%	99%	99%	98%	98%	98%	96%	97%	97%
Waikato				100%	99%	98%	99%	99%	98%	98%	98%	98%	97%	97%
CentralNI					100%	100%	99%	99%	98%	98%	99%	96%	97%	97%
HawkesBay						100%	98%	99%	98%	97%	99%	96%	98%	97%
Waipipi							100%	100%	99%	99%	99%	98%	98%	97%
Tararua								100%	99%	99%	99%	98%	98%	97%
Wellington									100%	98%	99%	97%	97%	97%
Nelson										100%	98%	99%	98%	97%
NorthCanterbury											100%	97%	99%	98%
WestCoast												100%	98%	98%
Dunedin													100%	99%
Southland														100%

Figure 42 - Winter wind correlation



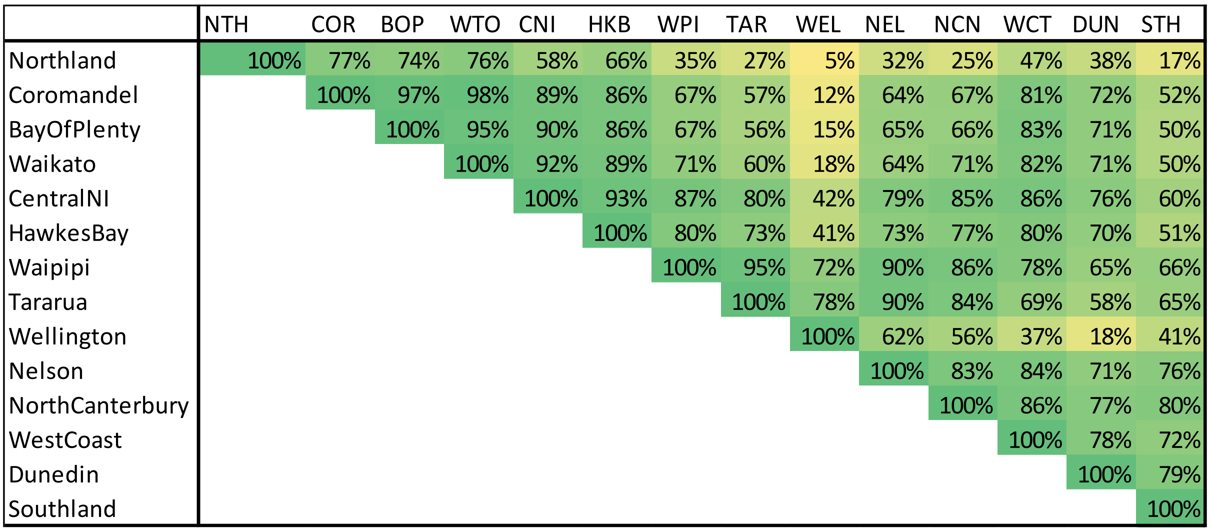
	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	89%	84%	89%	73%	72%	55%	54%	39%	56%	44%	64%	19%	17%
Coromandel		100%	96%	98%	87%	81%	72%	71%	44%	78%	59%	80%	39%	34%
BayOfPlenty			100%	95%	92%	85%	79%	76%	56%	78%	57%	80%	35%	32%
Waikato				100%	90%	85%	77%	73%	51%	78%	62%	82%	40%	36%
CentralNI					100%	90%	91%	90%	74%	81%	71%	80%	40%	43%
HawkesBay						100%	81%	79%	70%	70%	62%	72%	35%	29%
Waipipi							100%	94%	84%	82%	72%	79%	34%	48%
Tararua								100%	84%	84%	73%	75%	35%	49%
Wellington									100%	59%	61%	58%	8%	29%
Nelson										100%	72%	91%	61%	65%
NorthCanterbury											100%	75%	64%	78%
WestCoast												100%	57%	60%
Dunedin													100%	84%
Southland														100%

Figure 43 - Winter solar correlation



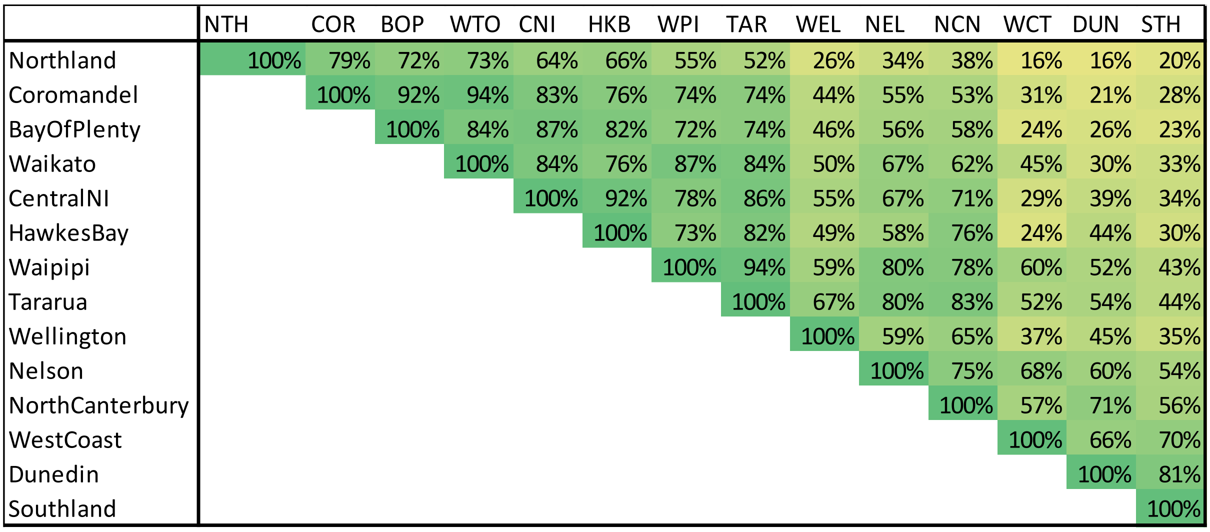
	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	70%	60%	61%	42%	34%	40%	19%	5%	17%	17%	8%	10%	11%
Coromandel		100%	91%	91%	74%	48%	70%	58%	39%	49%	35%	30%	19%	8%
BayOfPlenty			100%	77%	83%	60%	61%	61%	49%	54%	53%	26%	35%	5%
Waikato				100%	67%	37%	86%	69%	45%	53%	38%	49%	28%	25%
CentralNI					100%	84%	66%	77%	60%	35%	57%	9%	29%	-8%
HawkesBay						100%	43%	65%	50%	8%	58%	-19%	17%	-28%
Waipipi							100%	86%	64%	58%	54%	53%	41%	26%
Tararua								100%	78%	48%	67%	38%	43%	9%
Wellington									100%	41%	58%	26%	45%	7%
Nelson										100%	49%	80%	56%	46%
NorthCanterbury											100%	33%	69%	16%
WestCoast												100%	58%	77%
Dunedin													100%	66%
Southland														100%

Figure 44 - Yearly wind correlation



	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	77%	74%	76%	58%	66%	35%	27%	5%	32%	25%	47%	38%	17%
Coromandel		100%	97%	98%	89%	86%	67%	57%	12%	64%	67%	81%	72%	52%
BayOfPlenty			100%	95%	90%	86%	67%	56%	15%	65%	66%	83%	71%	50%
Waikato				100%	92%	89%	71%	60%	18%	64%	71%	82%	71%	50%
CentralNI					100%	93%	87%	80%	42%	79%	85%	86%	76%	60%
HawkesBay						100%	80%	73%	41%	73%	77%	80%	70%	51%
Waipipi							100%	95%	72%	90%	86%	78%	65%	66%
Tararua								100%	78%	90%	84%	69%	58%	65%
Wellington									100%	62%	56%	37%	18%	41%
Nelson										100%	83%	84%	71%	76%
NorthCanterbury											100%	86%	77%	80%
WestCoast												100%	78%	72%
Dunedin													100%	79%
Southland														100%

Figure 45 - Yearly solar correlation



	NTH	COR	BOP	WTO	CNI	HKB	WPI	TAR	WEL	NEL	NCN	WCT	DUN	STH
Northland	100%	79%	72%	73%	64%	66%	55%	52%	26%	34%	38%	16%	16%	20%
Coromandel		100%	92%	94%	83%	76%	74%	74%	44%	55%	53%	31%	21%	28%
BayOfPlenty			100%	84%	87%	82%	72%	74%	46%	56%	58%	24%	26%	23%
Waikato				100%	84%	76%	87%	84%	50%	67%	62%	45%	30%	33%
CentralNI					100%	92%	78%	86%	55%	67%	71%	29%	39%	34%
HawkesBay						100%	73%	82%	49%	58%	76%	24%	44%	30%
Waipipi							100%	94%	59%	80%	78%	60%	52%	43%
Tararua								100%	67%	80%	83%	52%	54%	44%
Wellington									100%	59%	65%	37%	45%	35%
Nelson										100%	75%	68%	60%	54%
NorthCanterbury											100%	57%	71%	56%
WestCoast												100%	66%	70%
Dunedin													100%	81%
Southland														100%

Appendix C. Offshore wind

We extended our initial scope to briefly investigate how offshore wind might affect our results.

The New Zealand generation stack updates published by MBIE identified three regions that could be suitable for offshore wind farms:

- Off the west coast of Auckland
- Off the Waikato west coast
- Off the South Taranaki coast

To determine the distance from the coast, we used the furthest point offshore that was 50 metres deep, as this is roughly the maximum depth for offshore seafloor wind turbines.

We created an offshore wind scenario based on our very diverse scenario, but also including the three offshore wind sites with a weighting three times higher than other sites. For example, the West Coast site has 4.5% of all wind built, while each offshore wind site has 13.5%. This higher weighting for offshore wind is due to the very large economies of scale for this technology, thereby likely resulting in very large-scale developments at each offshore wind location.

Overall, the results were not materially different, and indeed diversity was reduced somewhat by some measures. This is because the South Taranaki site is highly correlated to existing Tararua wind farms, and because of the larger size of offshore wind farms (each wind farm is perfectly correlated with itself).

We reproduce the key graphs from preceding sections below.

Figure 46 – Correlation factors for different sites

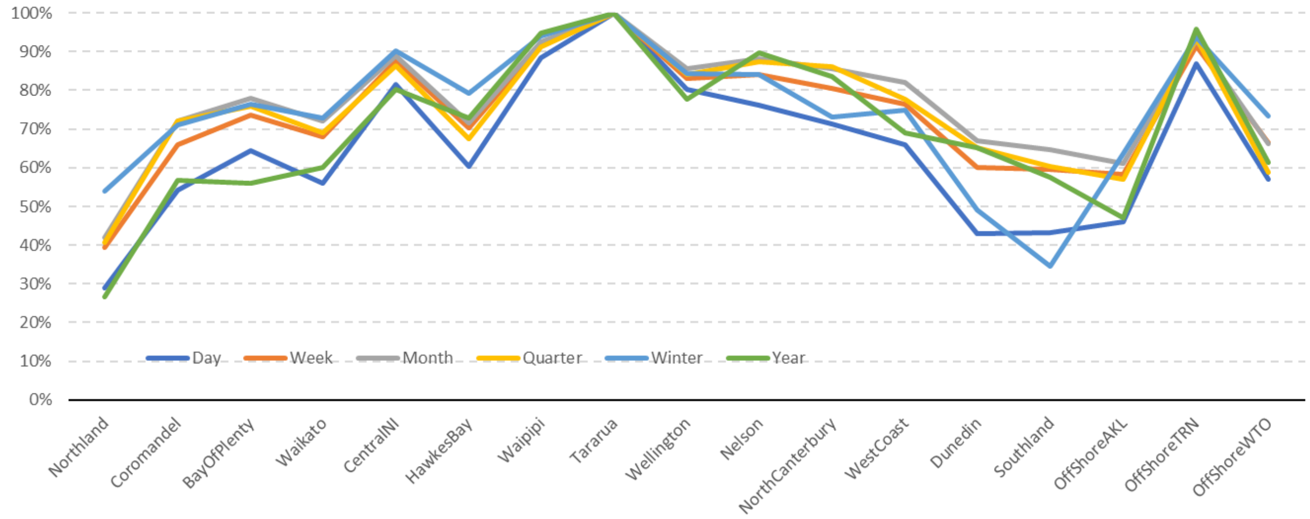


Figure 46 shows that Offshore Taranaki (OffshoreTRN) is highly correlated with Tararua across all time frames, Offshore Waikato (OffshoreWTO) is moderately correlated and Offshore Auckland (OffshoreAKL) is weakly correlated.

This hints that our build schedules involving offshore wind might not materially improve the diversity measures.

Figure 47 - Peak residual demand (2035)

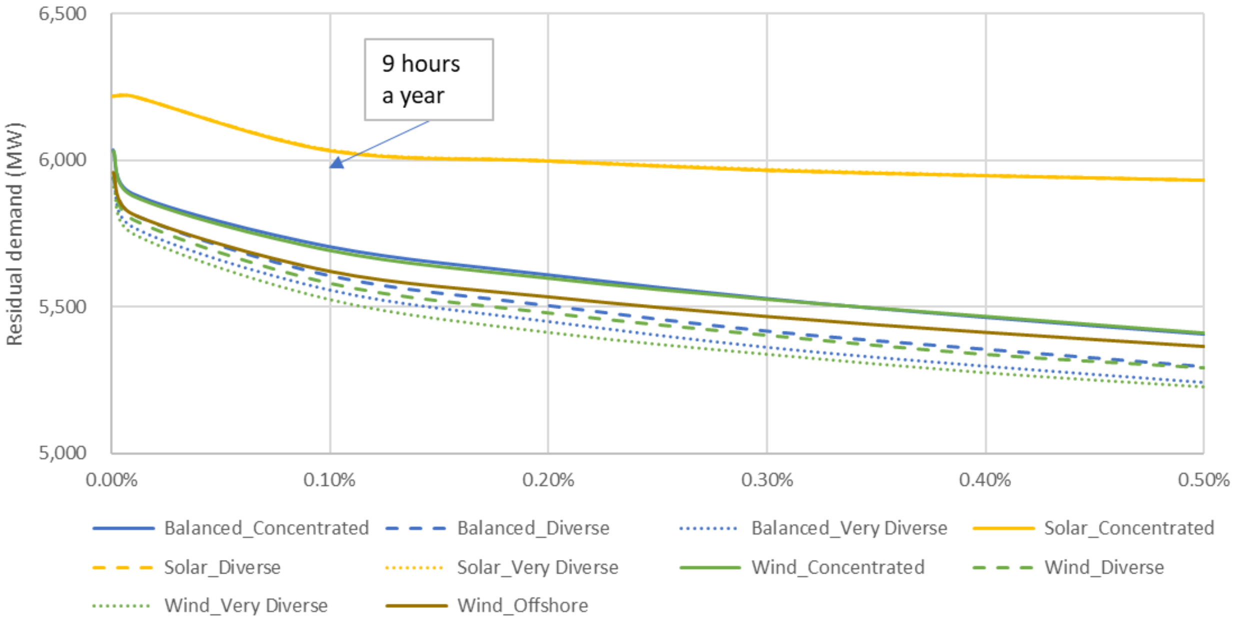
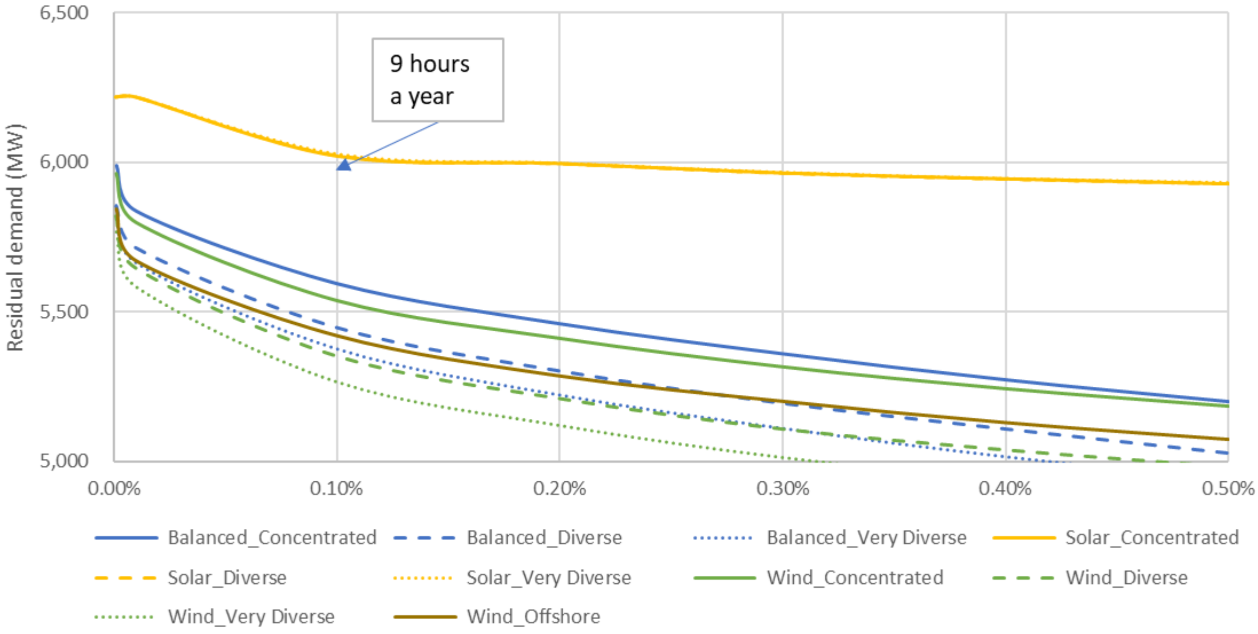


Figure 48 - Peak residual demand (2050)



The offshore wind build scenario has lower demand at peak than the concentrated wind scenario, but more than the diverse and very diverse scenarios.

Figure 49 - Winter energy compared to rest-of-year for sites

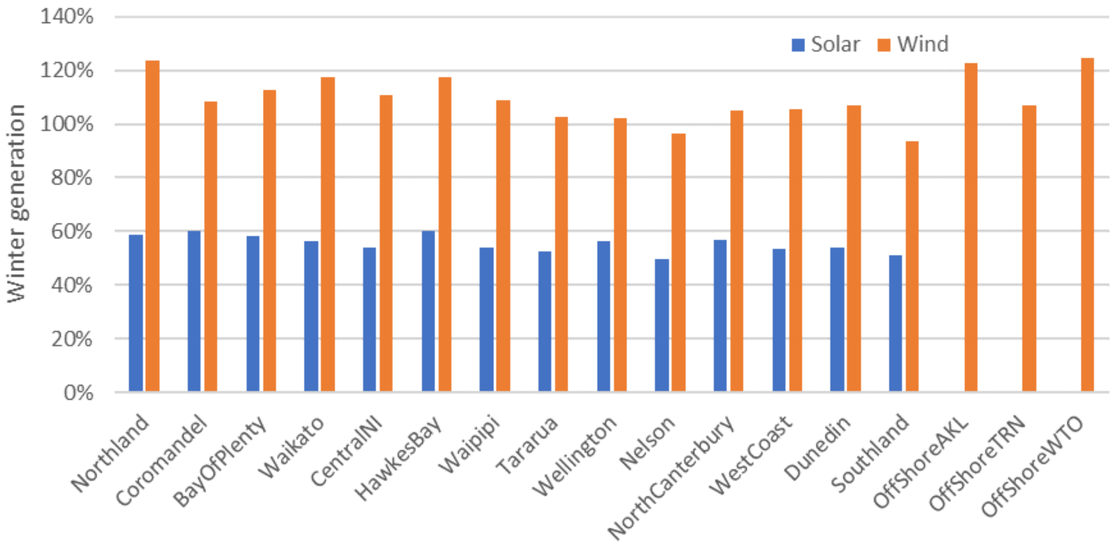
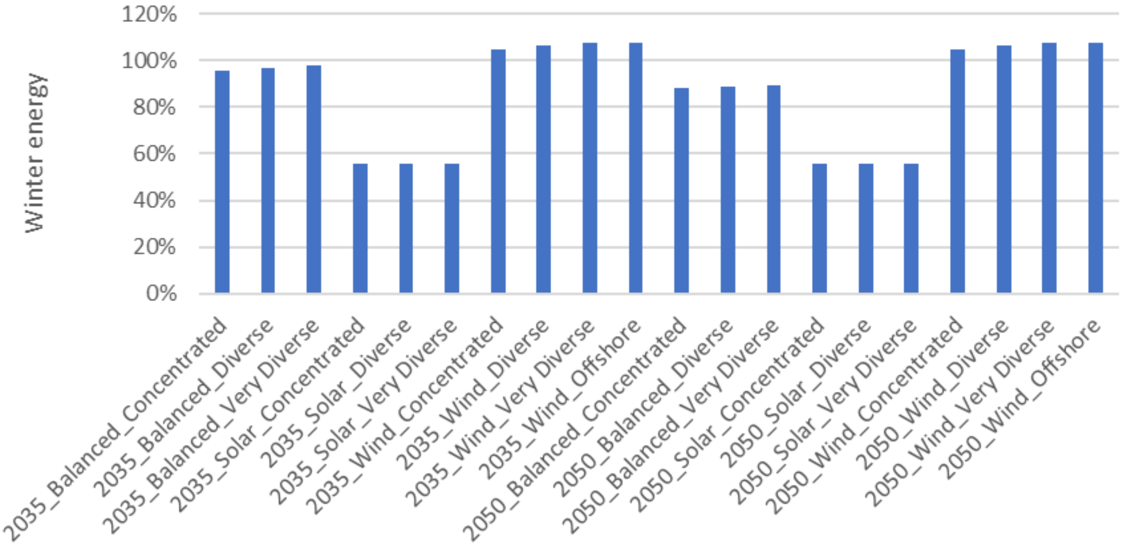


Figure 50 - Winter energy compared to rest-of-year for build schedules



The offshore wind sites have favourable winter/summer energy profiles, with more energy in winter for all three sites. The offshore wind build schedule has the highest winter/summer split out of all scenarios, but is minimally different from the very diverse wind scenario.

Figure 51 - Correlation between hydro inflows and renewable generation

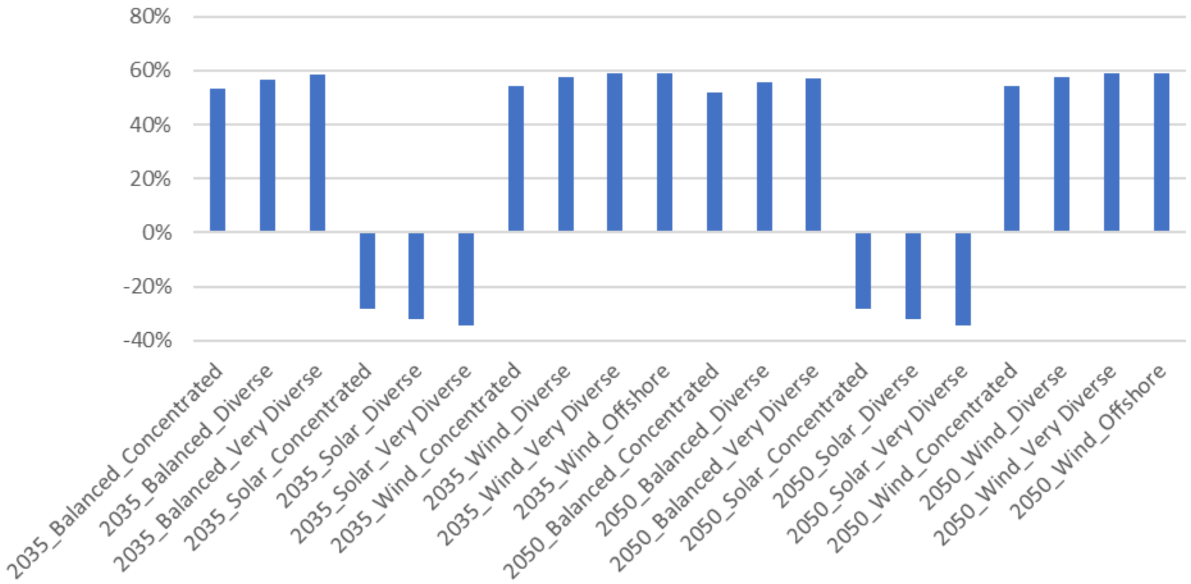
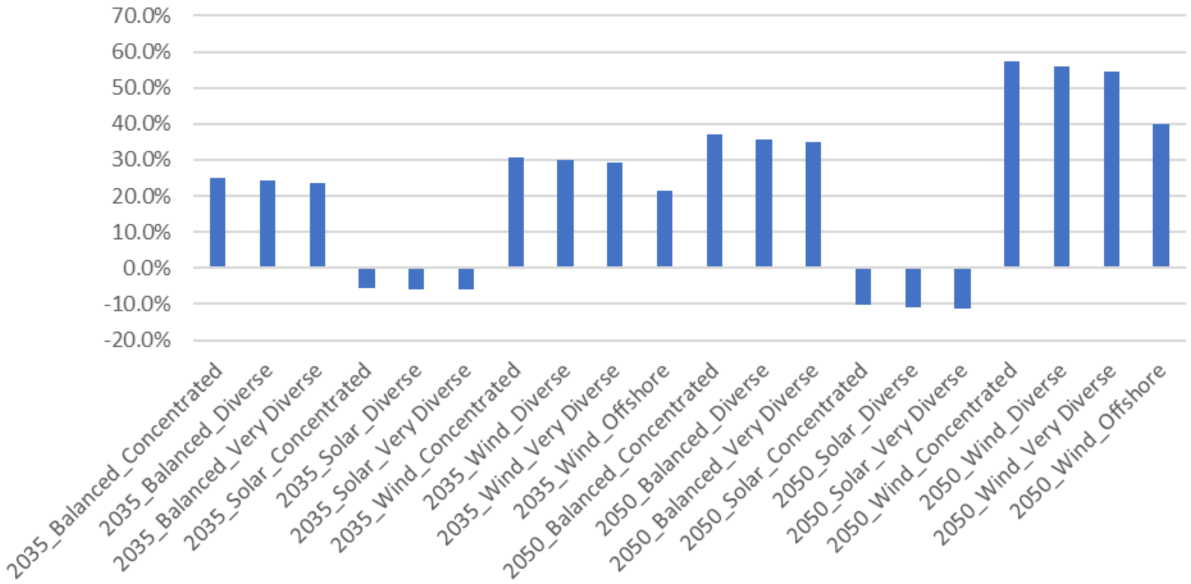


Figure 52 - Slope of dry winter correlation



Offshore wind appears more beneficial for dry winter effects. Although the correlation between inflows and renewable generation is similar for the offshore scenarios, the slope of the relationship is notably lower.

Figure 53 - Low generation weeks (2035)

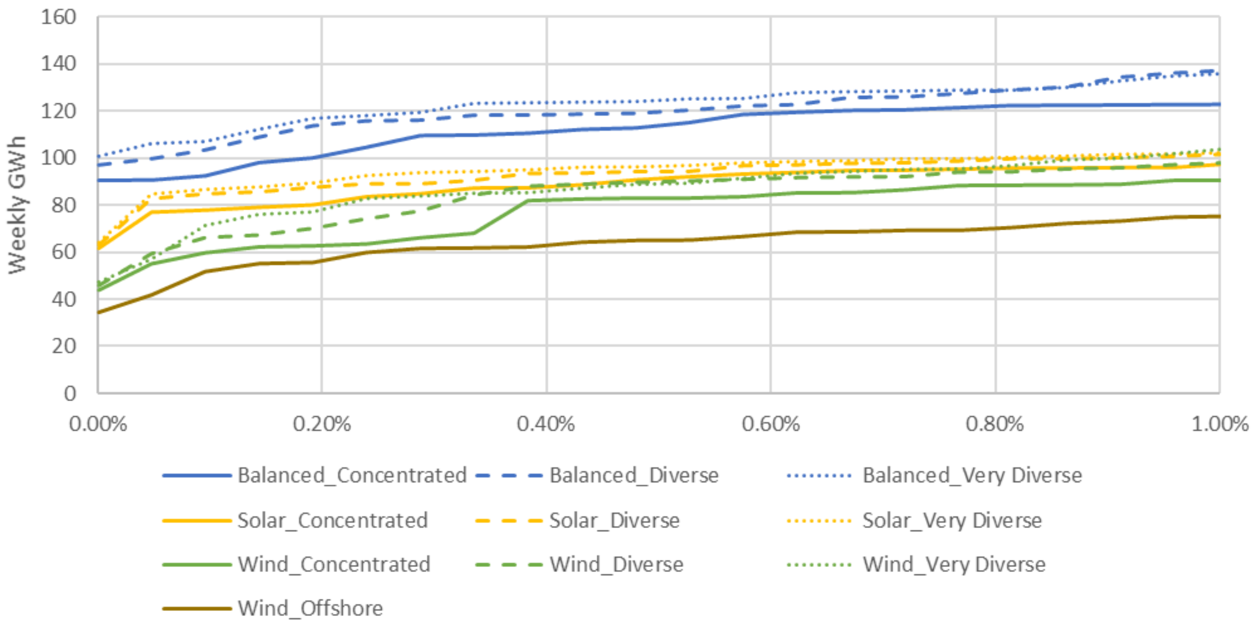
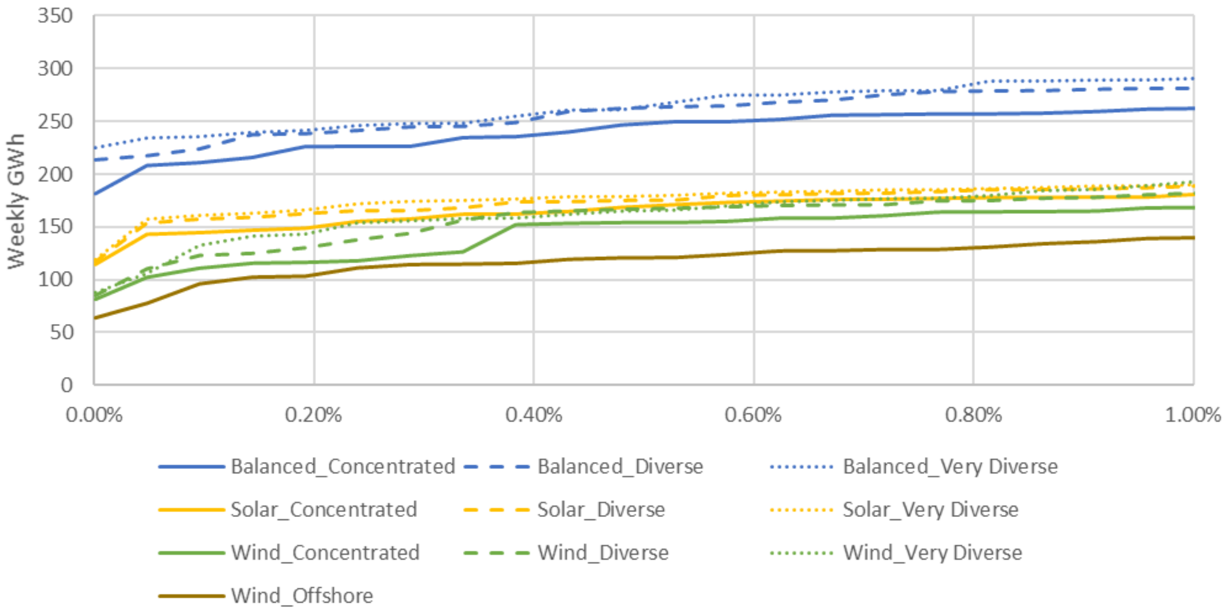


Figure 54 - Low generation weeks (2050)



The offshore wind scenarios perform poorly when looking at low weeks. The schedules have the lowest generation of all scenarios considered. This may reflect all offshore wind being on the West Coast of the North Island, meaning that less wind generation is located in Northland or the South Island.