Elemental
Group

The Ability of Offshore Wind to Improve New Zealand’s Electricity Security of Supply

Final Report

This page has been left intentionally blank

Preface

Elemental Group is an international energy developer and consultancy dedicated to providing better energy outcomes for our clients.

We deliver world class solutions for a world in energy transition, ranging from remote Pacific Island communities to megacities. We aim to create enduring benefits for people and places.

We are diverse, smart, hard-working, and innovative, with services across science, engineering, environment, project management and finance.

Client: Elemental Group Ltd

Client Project Code: 286

Elemental Project Code: 286

Rev	Date	Revision Details	Author(s)	EGL Check	Client
0	17 May 2023	First Issue	Hannah Konings	Will Thorp, Ngaio Fulton	Elemental Group Ltd

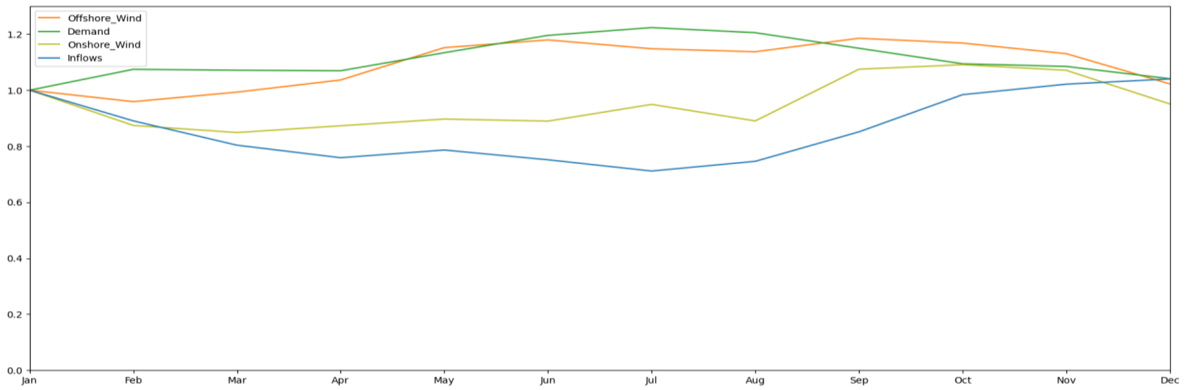
Executive Summary

Offshore wind is a growing technology, with successful projects throughout Europe. As New Zealand aims to reach 100% renewable electricity generation by 2035, diversification of the generation fleet is vital. Previous work has identified areas around New Zealand with an excellent wind resource and suitable coastal shelfs. Wind generation is variable and only generates when there is sufficient wind. Electricity generation in New Zealand is predominantly hydro-powered, which enables some flexibility and ability to match demand. However, this resource can also become depleted in what is known as “dry years”.

Comparisons on a temporal basis of offshore wind generation with demand, other renewables, and hydro inflows, particularly during dry periods, provide useful information and context on how offshore wind could be suitably integrated into New Zealand’s generation. This report aims to identify and quantify the benefits of offshore wind for New Zealand. More specifically, how it matches electricity demand, how it works alongside other renewables, whether it could form part of a solution to the dry-year problem, and how offshore wind will contribute to the security of electricity supply in New Zealand.

Data was predominantly sourced from Electricity Authority, which provides electricity generation by type, and half-hourly electricity demand data, for the period 1999-2020. This was resampled to hourly for better comparison with offshore wind ERA5 hindcast data, provided by BlueFloat Energy. Resampling to a daily basis allowed comparisons with hydro inflows also. This was done using Python through Jupyter notebooks.

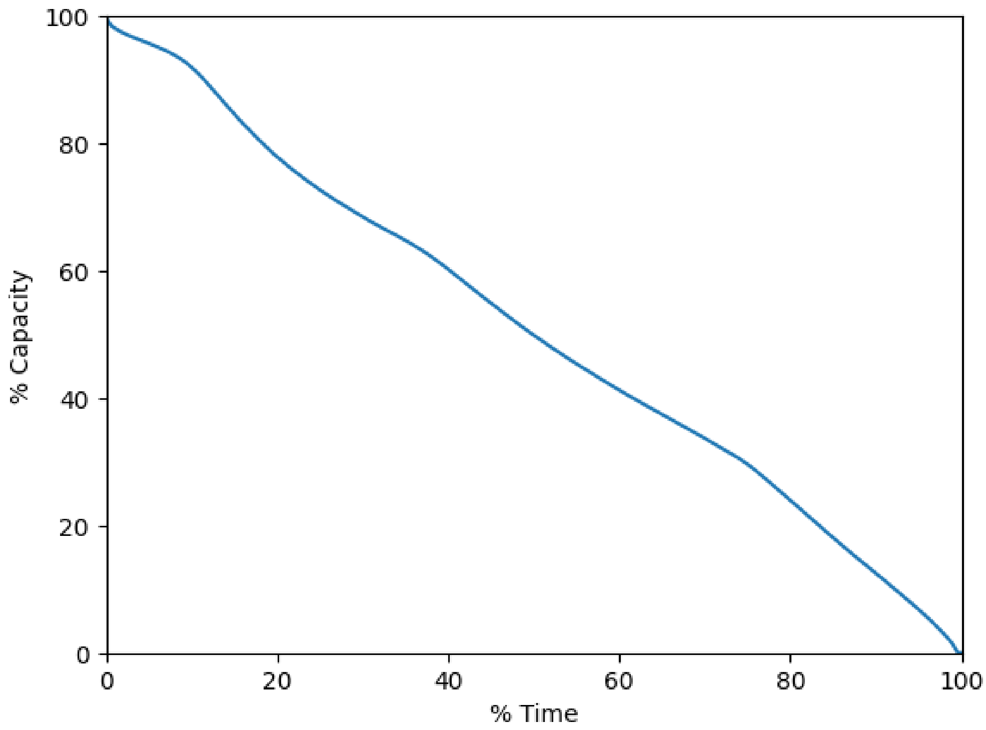
Variables were compared on multiple temporal bases; averages being calculated both over the full set of data (20-year average) or over the dry years only. This was also done visually, comparing the average annual and daily profile using monthly and hourly values. The average monthly inflow energy and offshore wind generation during dry years were also individually presented, to highlight the difference with ‘normal’ years.



Average yearly profile of variables, normalised by January average

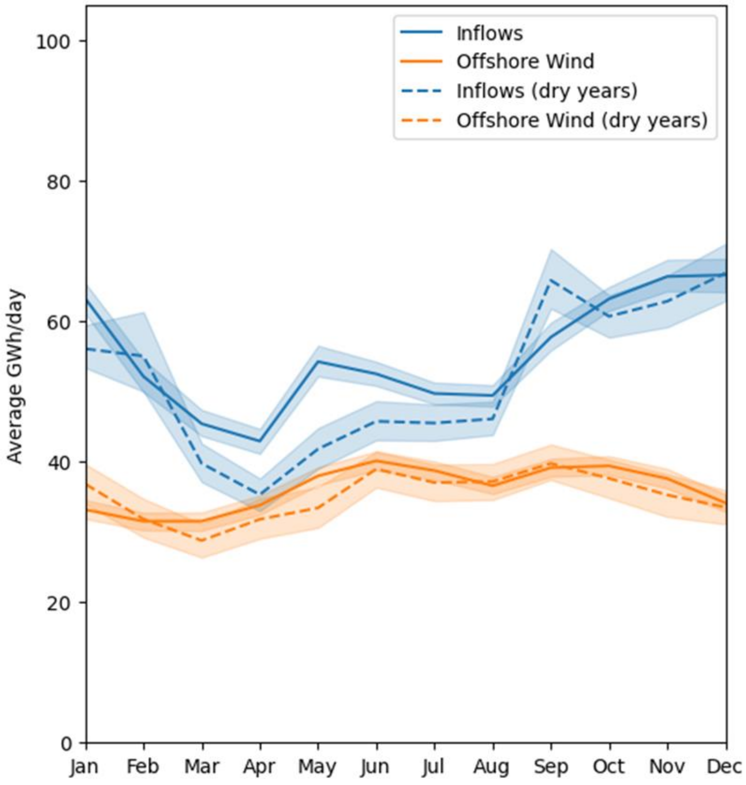
The diurnal profiles of both onshore and offshore wind were relatively flat compared to electricity demand, but the monthly offshore wind production was found to be closer correlated with electricity demand than other renewables. Both offshore wind generation and electricity demand increase over the middle of the year. This is a promising result as other renewables, including offshore wind, tend to have generation lower than the respective January average over Autumn and Winter. It also shows an inverse correlation between hydro inflows and offshore wind.

The capacity factors for the modelled offshore wind sites across New Zealand were 53.4% in Taranaki, 39.9% in Waikato, and 54.3% in Southland. For comparison, the average capacity factor over all onshore wind sites in New Zealand is approximately 40%, and for solar generation around 15%. The combined duration curve across the three sites also showcases the benefits of multiple locations of generation, with minimal time of zero generation, and at least 50% of the capacity being produced approximately 50% of the time.



Duration curve of combined generation

It was identified that the dry years assessed all included decreased hydro inflows over the Autumn months, March, April, and May (MAM). To identify how offshore wind performs during dry years, these months during the identified years were assessed. It was found that during these months, offshore wind produced less than the monthly average over all months and all years. However, compared to the hydro inflows over the same dry periods, offshore wind produced around 88.2% of the all-time-average, while hydro inflows produced 76.4% of the all-time-average. This shows that while offshore wind does decrease during dry periods, it is not to the same extent as hydro inflows. Offshore wind was not included for this as the data covers periods of changing capacities, and is very limited for the earlier identified dry years.



Annual profile of daily inflow and offshore wind energy

The offshore wind production models revealed relatively high capacity factors and generation profiles compared to onshore renewables, particularly for Taranaki and Southland. The combination of three sites across the country also showed high reliability with minimal times where there is no generation, suggesting suitability to provide some baseload electricity. A strong correlation with monthly demand further suggests that offshore wind has good potential to aid in renewable generation for New Zealand and furthering the security of supply over the higher demand winter months. While offshore wind does not ideally compensate for low inflows during a dry year, the decrease in generation from offshore wind appears to be less than that of the inflows.

This report has shown how offshore wind would benefit New Zealand due to the added renewable generation capacity, well matched annual generation to demand, and relatively high capacity factors. Geographic diversity in generation locations is also shown to increase the reliability, aiding in the security of supply for New Zealand electricity.

Table of Contents

List of Figures

1. Introduction

In 2016 New Zealand was one of 194 parties that committed to the Paris Agreement that aims to limit the global rise in temperature below 2°C above pre-industrial levels [1]. To achieve this, New Zealand plans for 100% renewable electricity by 2035 and net zero emissions by 2050 [2]. While approximately 80% of New Zealand's electricity currently comes from renewable sources, reaching 100% renewable is made difficult by the limited storage capacity of hydro catchments and variable generators that are out of sync with daily and seasonal demand peaks. Furthermore, net zero emissions will require a large increase in electricity demand as high emission sectors are decarbonised and electrified. One scenario in a 2020 paper estimates an 68% increase in electricity demand between 2020-2050, primarily due to population growth and the electrification of process heat and transport [2].

Onshore variable renewables such as solar and wind are largely dependent on the weather and tend to have generation profiles that do not match demand profiles. Currently, this mismatch is largely made up by controllable generation sources, such as hydro or fossil fuelled 'peakers'. Hydro power makes up approximately 60% of New Zealand's current electricity supply, however, is highly dependent on regular inflows into hydro catchments due to the limited storage capacity of the lakes. When inflows are consistently low, and variable renewable generators cannot meet the demand, the reliance on fossil fuels increases. This has implications such as increased wholesale electricity, increased emissions, and eventually the public may be asked to reduce their energy use. Alongside an increasingly variable system, these dry periods challenge all aspects of the energy trilemma: environmental sustainability, accessible and affordable energy, and security of supply.

Variable renewables in particular make ensuring security of supply more challenging. One way to mitigate this issue is ensuring the generation networks are diverse in both generation type and location. It is also valuable for the generation types to have high-capacity factors and if the generation profiles can match those of demand. Wind generation technologies, both onshore and offshore, are variable generators and tend not to have the consistent general daily profile that solar generation for example has. This could be a strength, as wind generation while not necessarily matching demand profiles, doesn't consistently oppose demand either. Comparisons of wind generation profiles to demand profiles both daily and seasonally will provide further context on future challenges of variable generation.

Currently there are 20 wind farms operating in New Zealand with a combined installed capacity of 1045 MW [3], of which 355 MW was installed in 2021, with a further 219 MW currently being built. The total onshore wind capacity has grown significantly throughout the last twenty years, but often faces consent issues. The visual and auditory impact of wind turbines tends to be negatively received by the public, and areas identified as suitable for wind farms often overlap with significant sites to Māori [1]. Additionally, the energy yield of onshore windfarms is very location dependent as altitude, topography, and land structures all have significant effects on wind speeds.

Offshore wind is a well-developed, renewable generation technology, which exploits the natural wind energy in the same way as onshore turbines. They often have less visual and auditory impacts on humans, can be larger in both size and number, and don't occupy valuable land space [4]. The offshore sites are more exposed and tend to have more consistent and stronger winds. Offshore wind is a proven technology, with 21.1 GW of offshore wind farms installed globally in 2021, increasing the global total capacity to 56 GW [5]. Many countries have set targets to increase their respective offshore wind capacity, for example Australia, who aim to install 9 GW by 2030.

A study assessing the potential of offshore wind in NZ identified an offshore area in Taranaki to have an "*exceptional wind resource*", with suitable bathymetry for both fixed and floating wind turbines [6]. Venture Taranaki and Elemental Group further explored this, developing 200 MW and 800 MW offshore wind turbine capacity scenarios [4]. Largely, there has been significant interest in offshore wind in New Zealand, with most developers focusing on the South Taranaki Bight.

BlueFloat Energy, an experienced European offshore wind energy developer, formed a partnership with Elemental group in 2021, which has proposed to develop a 900 MW offshore wind site in South Taranaki, followed by projects off Waikato and Southland. [7].

2. Aim

The aim of this report is to assess the impact offshore wind could have on New Zealand's electricity supply. Specifically, whether this new form of generation could better match demand peaks, or generate at times uncorrelated to other renewables, therefore aiding in ensuring security of supply.

As New Zealand aims for 100% renewable energy, diversification in both the location and technology of electricity generation is vital. Past research has quantified the need for diverse generation within onshore wind [8] and solar [9], to manage the effects of the intrinsic variability of renewable generation methods.

This research aims to address the following questions:

- Does offshore wind match demand in a way that other renewables can't?
- Would offshore wind generate at different times to other variable renewables?
- Can offshore wind form part of a solution to the dry-year problem?
- How is offshore wind able to contribute to the security of supply?

By exploring the trends and correlations between onshore renewables, hydro inflows, electricity demand, and offshore wind, over multiple temporal resolutions, a quantitative analysis will be produced that identifies the impact offshore wind will add to the New Zealand electricity sector. Daily and seasonal variations are particularly of interest, which will be analysed using hourly and monthly averages and totals.

3. Methodology

This section covers the way in which data was obtained, assessed, and analysed. As this research involved multiple large datasets, this section has been broken down into seven sections where each variable is detailed, starting with general methods, and finishing with general correlation methodologies used.

3.1. Data Sources

First, variables surrounding energy production and use in NZ were gathered and assessed, to further contextualise the future for offshore wind. The period and frequency covered by the data were important as both instantaneous and seasonal trends were of interest. Often conversions were required, to allow for capacity factors to be calculated or the energy potential of hydrological inflows. These calculations, the data source and other attributes are detailed in Table 1.

The selected period of interest covers 1999-2020, as this is covered by each variable and includes decadal cycles and seasonal trends, without going too far back. The past two decades also include several dry periods which can be used to analyse the relationship between these events and offshore wind generation. Data before 1999 includes generation that is no longer active (gas & oil, coal), as well as becoming less relevant as the climate, population, and industry changes, alongside increasing electrification. Onshore wind generation from EMI datasets only starts from 2004, and the available capacity changes often. Data before 1999 may be used to show these changes.

Table 1 – Attributes of each variable

Variable	Source	Timescale	Sorted by	File frequency	Available period	Calculations
Electricity Generation	EMI Wholesale [10]	TP – half hourly	Grid point of connection (POC) and fuel	Monthly	1997/08 - 2022	Convert to GWh, sum for hourly
Hydro Inflows	EMI Environment [11]	Daily	Two primary inflows for major catchments	One per inflow	1932-2020	Convert from inflows to energy potential
Electricity Demand	EMI Wholesale [12]	TP – half hourly	Grid point of connection (POC)	Monthly	1996/10 - 2022	Convert to GWh, sum for hourly
Offshore wind	BlueFloat	Hourly	Region where projects are proposed	One file; location per sheet	1979 - 2021	Calculate capacity factor
Onshore wind	EMI Wholesale [13]	TP – half hourly	Network node: Identified non-grid wind gen.	Monthly	1998/10 - 2022	Calculate capacity factor

3.2. Hydro Inflows and storage

As New Zealand has little storage capacity relative to demand, the availability of hydro generation depends strongly on the immediate inflows into the catchments [10]. Additionally, hydro generation and thus storage and lake levels are subject to dispatch decision. Daily hydro inflows were sourced from the EMI hydrological modelling dataset. These inflow values are converted from flow rates (m^3/s) to potential energy (GWh/day) using specific energy values unique to each catchment.

Smaller schemes and inflows have less storage capability and thus have less ability to provide security of supply. Four major catchment areas were identified each with two components selected to represent most of the hydro storage potential throughout New Zealand. The schemes, their inflow components, and the specific energy can be seen in Table 2, where the scheme names has been chosen to avoid confusion between the catchment, lake, river, power station, and inflow names.

The inflow components for each scheme were decided using the inflow descriptions as in Table 1.4 in the EMI HMD report [11]. The values used to convert the data from inflow flow rates to the specific energy that could be generated were found in the 2020 hydrological modelling dataset, specifically the derived series for storage capacity and specific energy [12].

Table 2 - Hydro inflows for each scheme with conversion values (* indicating an averaged value)

Scheme	Flow	Site number	Description	Mean flow [m^3/s]	Specific energy [kW/m^3]
Waikato	Karapiro	92714 (1)	Waikato tributary flow between Taupo and Karapiro PS	91.08	0.3998*
	Taupo	92790 (1)	Sub catchment inflows nonlinear functions of Taupo inflows to create Taupo inflows including TPD diversions using 1995-2004 consent conditions	155.45	0.6865
Clutha	Hawea	9170 (1)	Hawea inflows	64.47	0.2555
	Roxburgh	99110 (1)	Roxburgh tributary flows – but excluding Hawea outflows	446.64	0.2555
Aoraki	Waitaki	98714 (2)	Waitaki tributary flows between Lakes Pukaki & Tekapo and Waitaki Lake relative to Waitaki Power Station	149.60	0.3706*
	Pukaki	98614 (2)	Pukaki inflows including Tekapo outflows, removing the Tekapo B station discharges from 1977 to avoid duplication	195.59	0.7299
Southland	Manapouri	99551 (1)	Manapouri local inflows allowing for Mararoa dirty water spill	137.07	0.4254
	Te Anau	9570 (1)	Te Anau Inflows	284.48	0.4254

The average annual profile of daily hydro inflows is shown in Figure 1, for both all 80 years of data (green) and the selected timeframe, the past two decades (blue). While these are generally very similar, the average daily inflow during the first four months for each scheme are consistently lower for the last two decades versus the last 80 years. This suggests a general trend towards lower summer and autumn inflows. Each scheme appears to have its own trend, the majority decreasing during winter, with the Southland and Clutha catchments including notable May and September increases. Waikato unsurprisingly has quite a different profile, as it is the only selected catchment in the North Island. This catchment tends to decrease leading into winter before steadily increasing from April onwards. It should be noted that the scale on the left and right columns of the figure differ, ranging 0-45 GWh/day and 0-25 GWh/day, respectively. This reflects the relative size of each scheme.

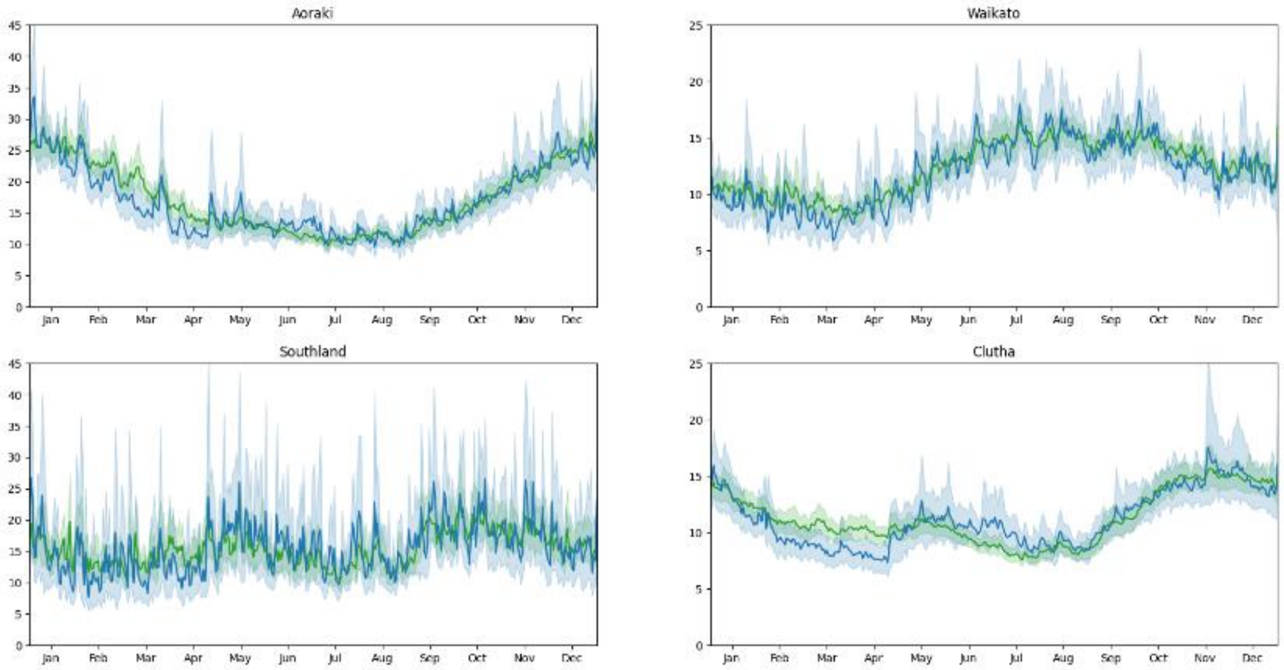


Figure 1 - Average annual profile of daily GWh of hydro inflows; Green - 1932-2021; Blue - 1999-2020

3.3. Demand

Demand data was sourced from EMI grid export data, mapped by node to the North and South Island, converted to GWh and resampled to an hourly time series covering 1996-2022. This can be used to analyse correlations with offshore wind generation on an hourly, daily, and seasonal basis, as well as comparisons with other onshore renewables.

3.4. Generation

Metered generation data was organised by fuel type and Island, converted to GWh, and resampled to an hourly timeseries covering late 1997 to 2022. The available grid-connected generation data from the South Island was hydro only. Hydro generation for both islands was excluded as this is subject to dispatch decisions and demand, thus isn't always representative of the available hydro supply. This is instead represented by hydro inflows. The remaining fuel types were classified as one of coal, diesel, gas, Gas & Oil, geothermal, wind, and wood.

Most nodes were summed together once sorted into Island and fuel type, except for wind, which was kept with its identifying node point so the capacity factor could be calculated. For this, wind farms missing from the metered data were included via the embedded data.

3.5. Embedded generation

Some generating plants do not export to the national grid. For analysis of past generation, particularly wind, we import embedded generation data also, as many wind farms in New Zealand export totally or partially into local electricity distribution networks. The windfarms not included in the metered grid data and imported from the embedded data were Hau Nui (GYT0331) and Mill Creek (WIL0331). Southbridge windfarm in Christchurch was neglected as the farm had a minimal capacity of 0.1 MW and only had recorded data through 2003-2004. A small number of wind farms were included in both the metered and embedded data, with minimal differences between the two sources. For these wind farms, only the metered data was used, to simplify the processing.

Many of the wind farms only became active within the last two decades, some going through multiple stages of development. With the number of active wind turbines changing so often, the capacity factor of total wind capacity was used rather than the amount of energy generated, to portray the performance of wind generation more accurately.

Other embedded fuel sources of generation were not included as the individual fuel types were not of interest and it was determined that the metered data was indicative enough of the overall trends for these.

3.6. Determine dry periods

A standard method for identifying dry periods could not be found, so to determine occurrences during the last two decades, multiple aspects of New Zealand's hydro schemes were assessed. Daily inflows were resampled to a weekly average of GWh/day. The bottom tenth percentile of this was found, and years with twenty or more of these was taken to be a dry year. These years were 2001, 2003, 2008, 2017, and 2020. The first of these matches the years identified by official conservation campaigns: 2001, 2003, and 2008, as identified in a 2019 report which may not include the more recent occurrences [1].

The identified low years were grouped, and the yearly profile averaged to provide an idea of how a low year differs from an average year. Figure 2 shows the typical yearly profile when averaging all 80 years of data, the past two decades, and the dry years. This not only characterises the profile of dry years, but also shows possible shifts in hydro inflows as climate change effects increase, such as higher winter inflows as precipitation falls as rain rather than snow.

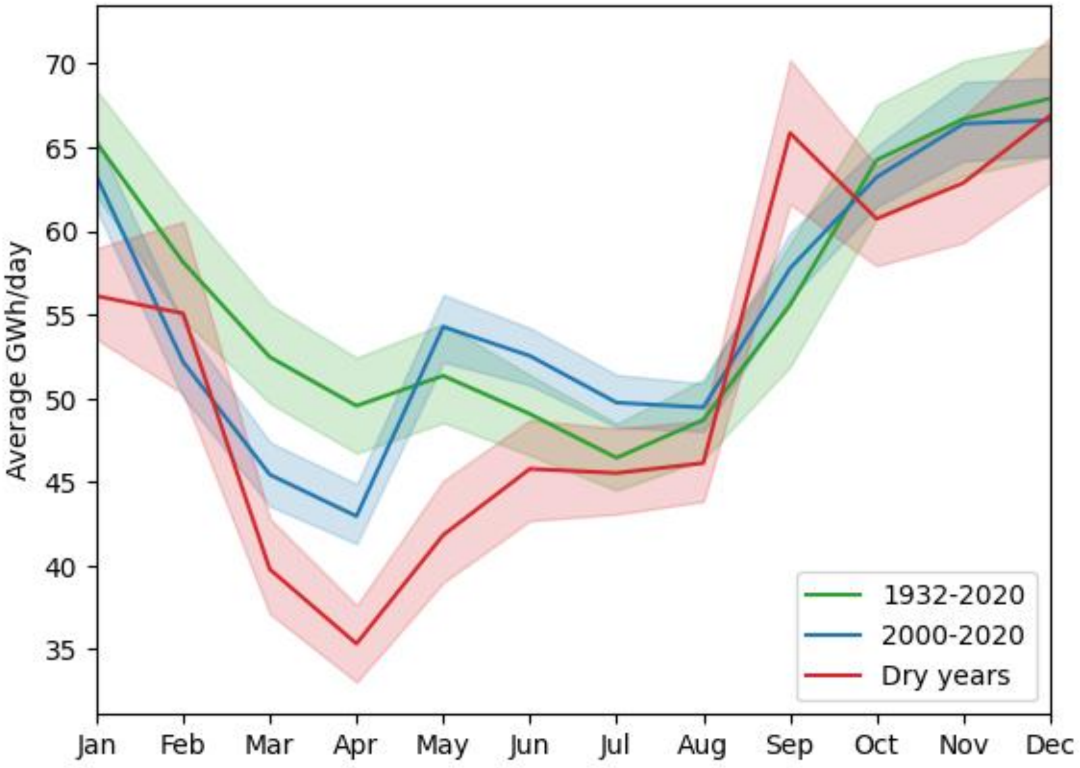


Figure 2 - Average daily inflow for each month, sampled from specified years

In dry years, the average inflow isn't always the lowest, as seen by the huge spike in the dry year's inflow seen from August to September. This is likely representative of increased spring showers and snow melt after these dryer periods, reinforcing that dry 'years' are caused by low inflows during certain critical periods, not just low inflows any time. Assuming the lowest dry year months identify those crucial periods, it is clear autumn inflows have a significant influence on energy security in New Zealand.

3.7. Offshore wind hindcasts

For offshore wind, hindcasts were produced by BlueFloat Energy to indicate how much energy would have been generated if the proposed offshore wind farms were installed, given past weather recordings. These hindcasts used the V236 15 MW turbine, with the power curve as shown in Figure 3, and used satellite data based on the ERA5 model. The received data covered 1979-2020 on an hourly basis with 1 GW capacity for Taranaki, Waikato, and Southland.

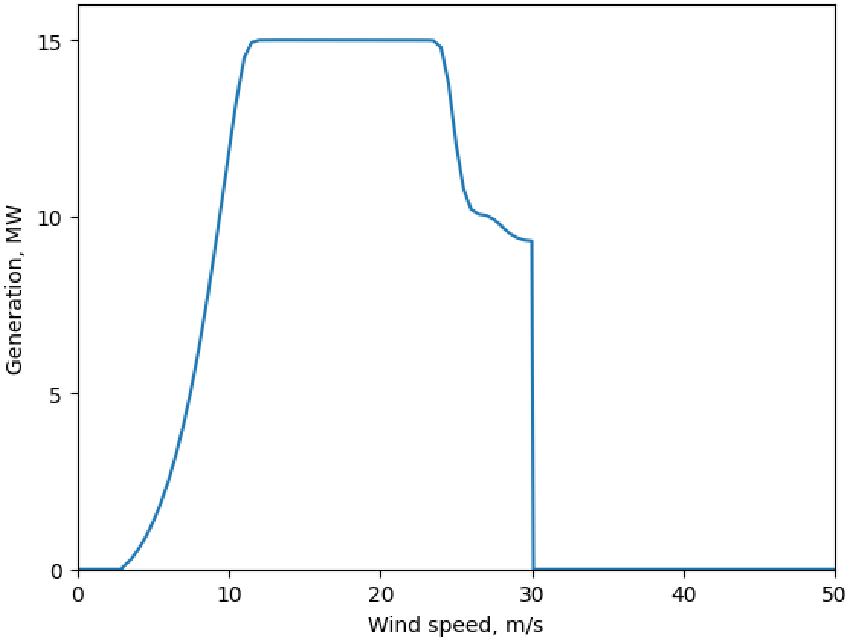


Figure 3 - Power curve for 15MW V236 wind turbine

3.8. Comparisons and correlation values

Once the data was imported and organised, results were found by creating duration curves, plotting variables against another, finding Pearson R coefficients, and comparing the daily and annual profiles of variables, all on multiple temporal bases. From this, the characteristics of offshore wind were determined, and comparisons made on a seasonal basis.

The correlation between variables was of interest rather than the fit of potential models, so it was appropriate to use the Pearson R coefficient which is a measure of linearity between two datasets (as opposed to other commonly used statistics such as the R^2 value which measures a model's quality of fit). The Pearson R value is between -1 and +1, where 0 indicates no correlation, +1 indicates a positive linear relationship while -1 represents a negative linear relationship. This is calculated as shown in Equation 1, where *x* and *y* represent the deviation scores of each variable X and Y (each value in X (Y) minus the mean of X (Y)) [13].

Equation 1:

$$\boldsymbol{r = \frac{\sum xy}{\sqrt{\sum x^2 \sum y^2}}}$$

4. Results

4.1. Characteristics of offshore wind

Load duration curves show how much of the full generation capacity is utilised, and for how long. This is found by plotting the number of generation hours against the capacity at which each hour is generating. In the following graph, this is shown as percentages.

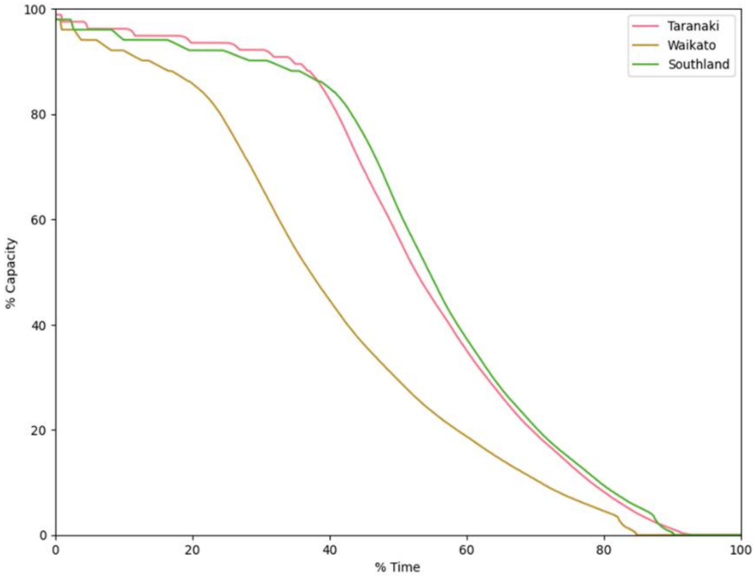


Figure 4 - Duration curve for offshore wind farms

By combining the hourly generation for each location and dividing by the combined total capacity, 3 GW, the duration curve if all sites were present

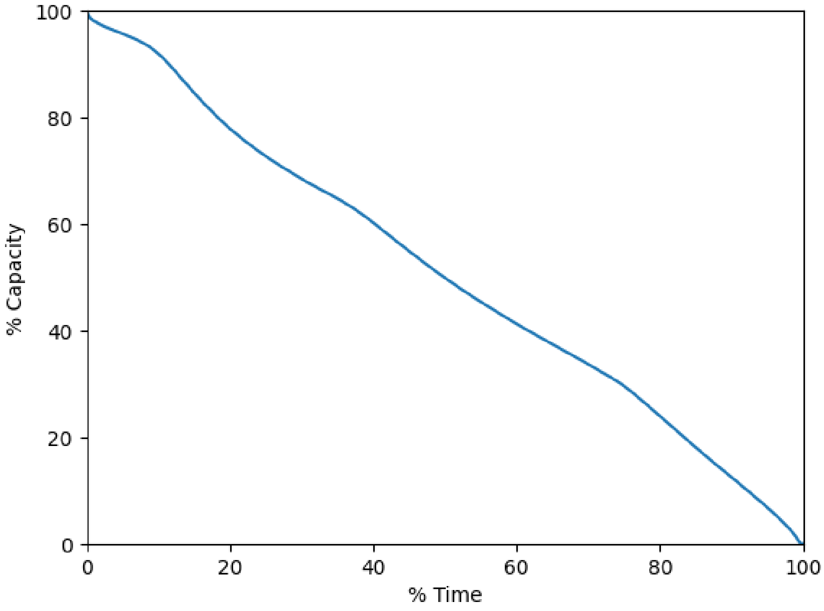


Figure 5 - Duration curve of combined generation

The capacity factor of each offshore wind location was also calculated, by dividing the mean annual generation of hindcasted generation by the theoretical maximum, if the full capacity was being generated throughout a year.

Table 3 - Capacity factors for offshore wind sites

Location	Capacity Factor
Taranaki	53.4 %
Waikato	39.9 %
Southland	54.3 %

By plotting the generation of each wind location against each other, the correlation between the two locations can be seen. If the two locations are closer, they are more likely to be highly correlated, seen by a more linear relationship and higher ***r*** value.

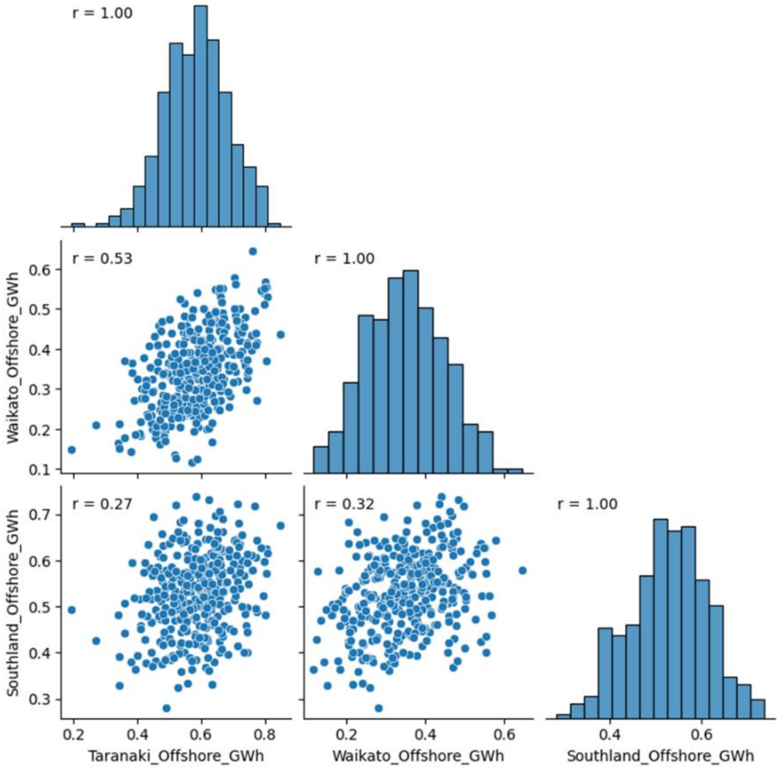


Figure 6 - Correlation between offshore wind sites with distribution plots on the diagonals

The typical annual profile of offshore wind for each location is shown by plotting the average monthly generation. This can be compared with the annual demand profile to determine how well offshore wind matches demand.

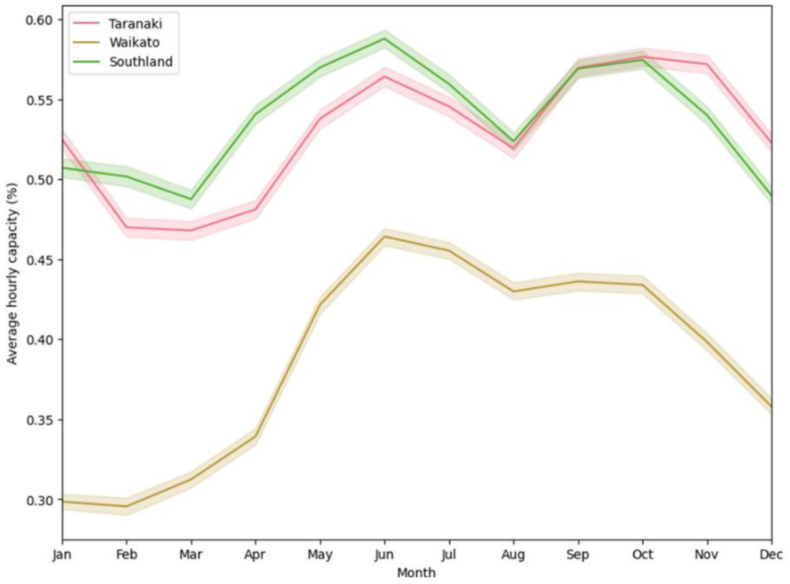


Figure 7 - Average annual profile of offshore wind locations with 95% confidence interval

The daily profile for each offshore wind site is visualised by plotting the hourly capacity factor throughout the day, averaged over all years and days of data.

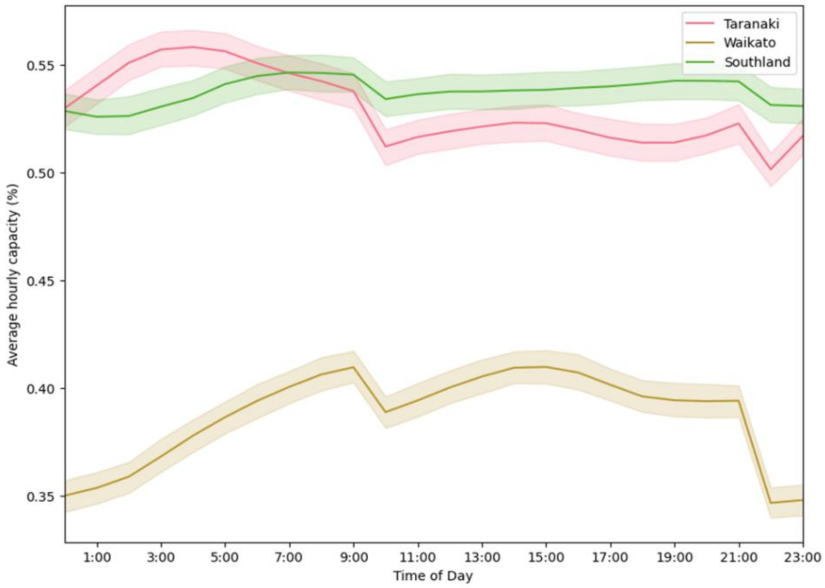


Figure 8 - Average daily profile of offshore wind locations with shaded 95% confidence interval

4.2. Annual and seasonal profiles

Comparisons on a seasonal basis can be used to analyse the performance of offshore wind during critical periods, such as the winter demand peak or low hydro inflows that may lead to a dry year.

The daily profiles of offshore and onshore wind generation, alongside the electricity demand, were examined throughout the seasons by plotting the average hourly capacity factor/demand. This provides further context of how offshore wind compares to onshore wind on an hourly basis, and the degree of correlation to electricity demand.

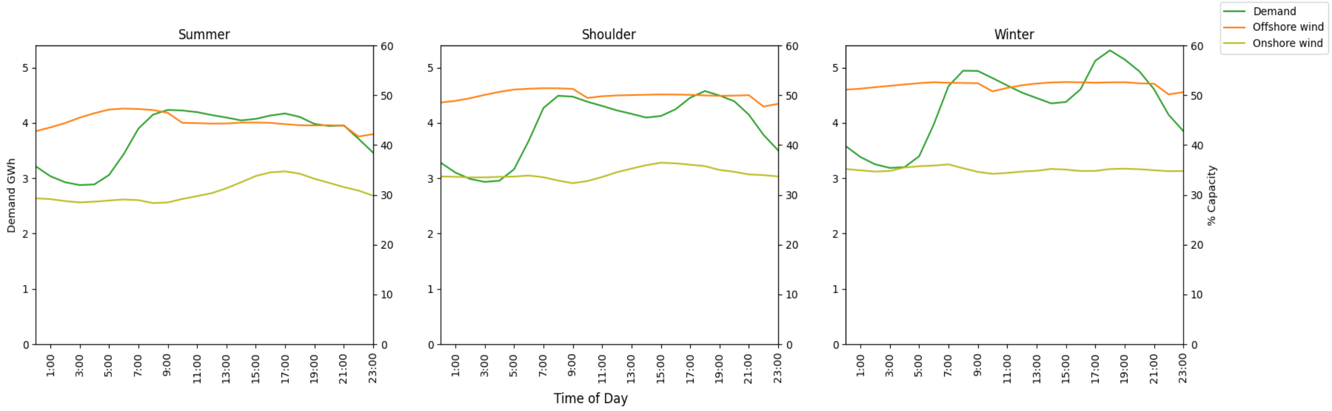


Figure 9 - Daily profile of offshore and onshore wind (right axis, capacity factor) compared to demand (left axis, GWh)

By taking the average January value as "normal" for each variable and normalising each successive month's average by this, the seasonal changes in each value can easily be seen, as a percentage of the January average. This was done to recreate exhibit 13 in the Transpower Energy Futures paper [14] with the inclusion of offshore wind generation.

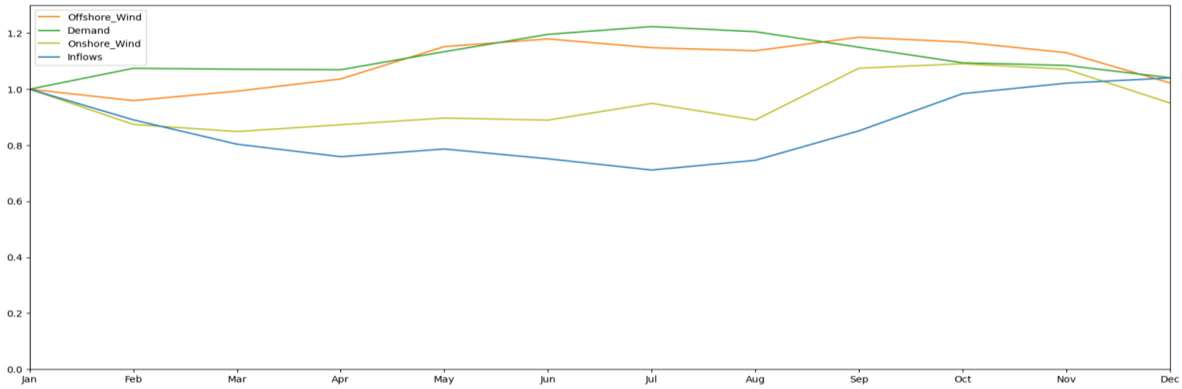


Figure 10 - Average yearly profile of variables, normalised by January average

4.3. Dry Periods

By analysing the years with identified dry periods as in Section 3.6, the possibility of offshore wind contributing part of a solution to the dry-year problem can be evaluated. The annual profiles of each variable were plotted for each dry year as in Figure 10. The average monthly capacity factor of each offshore wind location was also plotted, to further contextualise the theoretical performance of offshore wind during these low periods.

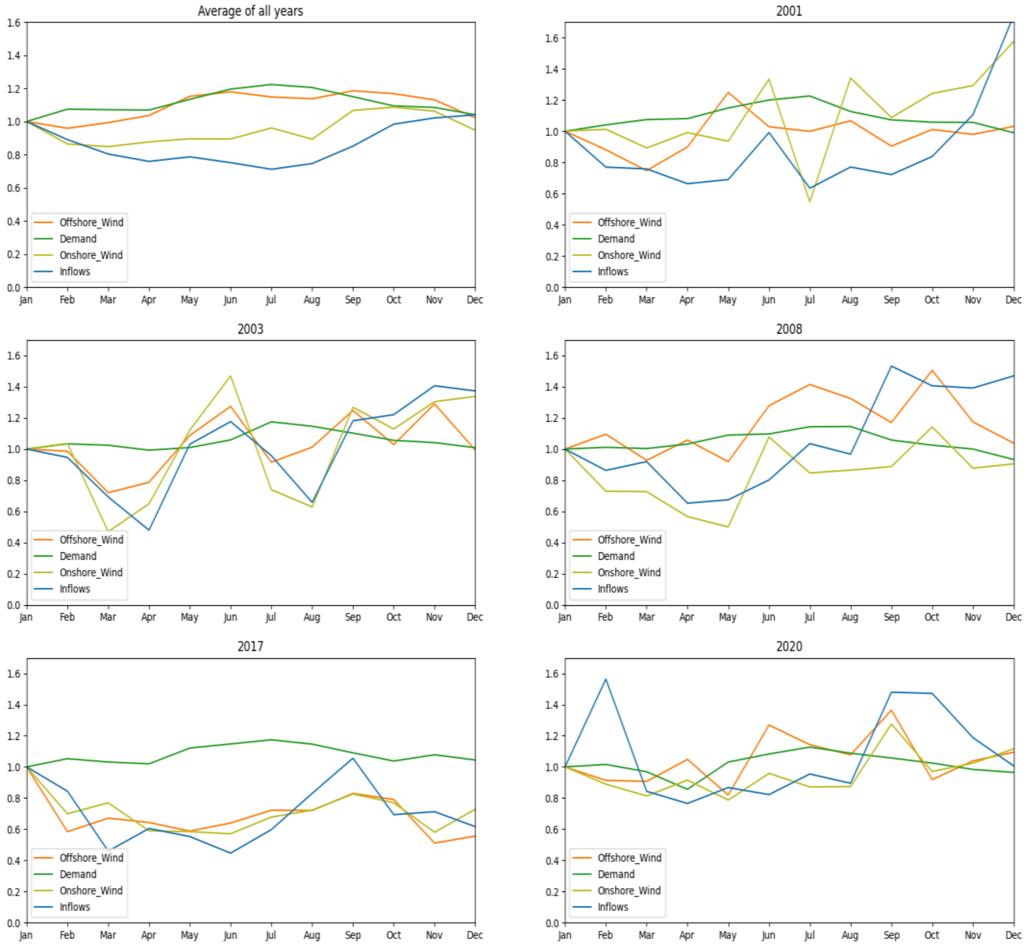


Figure 11 - Annual profile for low years, normalised by January average

The capacity factors for each location and each dry year are also given in Table 4, with the combined capacity factor in the final column, and the average over all twenty years shown in the final row (as in Table 3).

Table 4 – Offshore wind capacity factors for dry years (%)

	Taranaki	Waikato	Southland	Combined
2001	49.1	38.0	51.9	46.3
2003	52.3	38.6	54.6	48.5
2008	53.2	40.4	50.3	48.0
2017	50.1	35.9	50.2	45.4
2020	52.9	37.8	52.3	47.7
20 Year Average	53.4	39.9	54.3	49.2

The annual profile of the average daily energy in GWh/day for both hydro inflows and offshore wind were plotted, with the 20-year average shown by solid lines, and the dry year average shown by dashed lines.

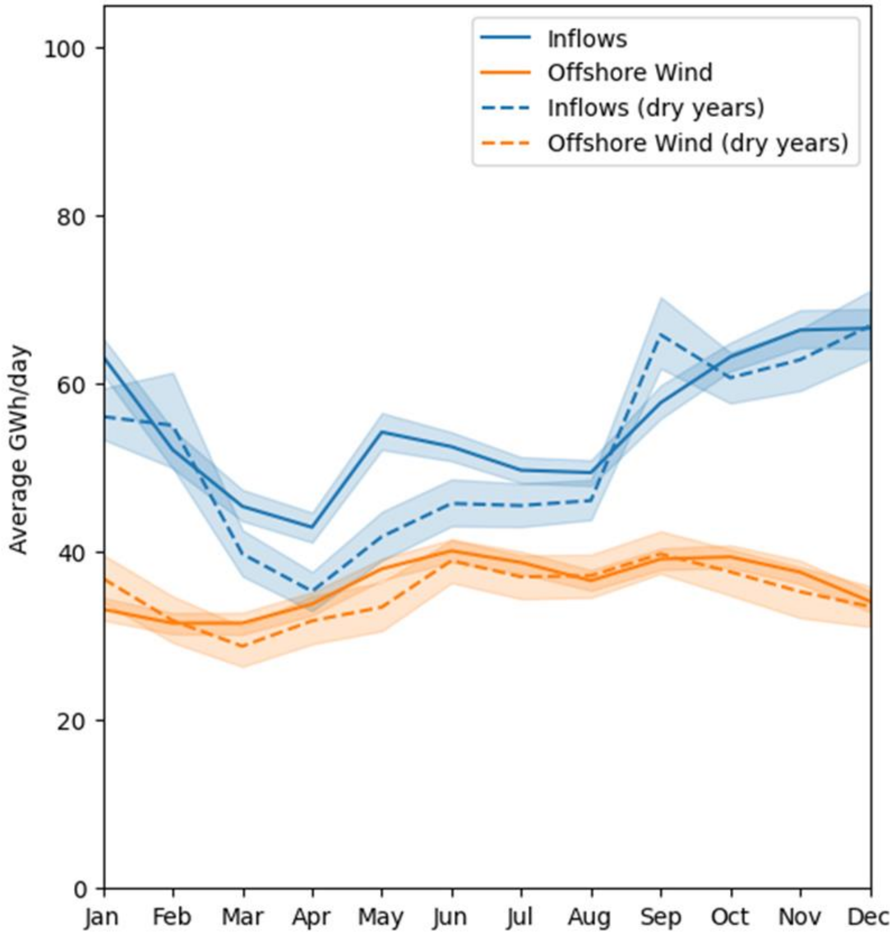


Figure 12 – Annual profile of daily inflow and offshore wind energy

The average monthly energy during the autumn months, March-April-May (MAM), from the offshore wind hindcasts and equivalent inflows, provides a more direct comparison broken down by location and catchment. Included also is the total (monthly energy) for each dry year, the values for the average of all years across 1999-2020, and the percentage of said averages during dry years.

Table 5 – Average monthly offshore wind generation for MAM by location [GWh/month]

	Taranaki	Waikato	Southland	Total	% Of Average
2001	362	275	403	**1,040**	95%
2003	339	233	364	**934**	86%
2008	366	231	320	**916**	84%
2017	355	252	349	**955**	88%
2020	354	240	367	**960**	88%
20 Year Average	410	278	404	**1,092**	100%

Table 6 – Average monthly inflow for MAM by scheme [GWh/month]

	Aoraki	Waikato	Southland	Clutha	Total	% Of Average
2001	352	297	334	182	**1,165**	74%
2003	409	239	334	197	**1,179**	75%
2008	366	272	281	207	**1,126**	72%
2017	329	562	185	171	**1,247**	80%
2020	430	192	356	288	**1,266**	81%
20 Year Average	485	301	463	319	**1,568**	100%

The *% Of Average* columns in Table 5 and Table 6 indicates the difference from the average monthly GWh for offshore wind and total inflow respectively during the critical MAM period. This quantifies the decrease in energy availability during the times most significant to dry years. While both offshore wind and hydro inflow have a less than average monthly production during the dry years, the decrease is more significant in hydro inflows than offshore wind.

5. Discussion

5.1. Offshore wind compared to other renewables

The duration curve of offshore wind generation, as in Figure 4, shows that the wind turbines in Taranaki and Southland operate for more than 90% of the time, and at above 60% capacity for more than 50% of the time. In Waikato, the turbines operate around 85% of the time, and above 60% capacity for more than 30% of the time. Contrasted with solar generation, which can only generate for 50% of the time, and is limited by cloud cover, offshore wind generates most of the time, and at high capacities for a large portion of this. The combined duration curve, as in Figure 5, shows that there is some generation across all three sites for almost all the time. Generation is under 20% of the combined 3 GW capacity for less than 20% of the time and generates at or above 50% of capacity for approximately 50% of the time. This demonstrates the benefits of geographic diversity, as it is unlikely that there is no generation at every site simultaneously.

Between locations, the duration curves are all similar in shape, despite the noticeably lower Waikato. Differences between Taranaki and Southland can be seen by their capacity factors in Table 3, 53% and 54%, respectively. Taranaki has a higher capacity for almost 40% of the time, however Southland has a larger capacity factor the rest of the time, leading to the higher overall capacity factor. For comparison, the average capacity factor over all onshore wind sites in New Zealand is 40% [15], and for solar generation around 15% [16]. This shows that investing in large offshore wind capacities is likely to generate more electricity than investing in the same capacities of onshore renewables.

Plots of each offshore wind location against another as in Figure 6 alongside the Pearson R values show that the Taranaki and Waikato locations are more closely correlated than the Southland location with either of the others. This is to be expected, as Taranaki and Waikato are geographically closer, so similar wind speeds are more likely to occur simultaneously in these locations than with Southland. Following from this, Figure 7 shows that the annual profile of Waikato is substantially lower than Taranaki and Southland. The profile of each location is relatively similar, where the generation is relatively lower at the start of the year, peaks during winter with a noticeable dip during August, peaking again during spring before lowering again during summer. The larger capacity in winter and lower capacity during summer is promising as this matches the annual trend seen in electricity demand, which is not seen in other renewables in New Zealand such as solar, onshore wind or hydro inflows.

The daily profile of generation at each site is shown in Figure 8, which shows relatively flat changes in generation, with only a 5% change in average capacity throughout the day. This means analysis of peaks is limited and unlikely to be consistent enough to determine any real generation-demand match or mismatch on a diurnal basis. This is neither good nor bad, as it suggests offshore wind generation remains relatively consistent throughout the day, potentially providing reliability. Peak demands could be managed as they are now, with controllable generation such as hydro.

Overall, offshore wind generally generates more consistently and at a higher capacity than other onshore renewables (onshore wind, solar). While offshore wind may not aid in daily demand peaks, it could provide a relatively consistent baseload of generation. Despite the lower capacity factor in Waikato than in Taranaki and Southland, the proximity to large electricity demand in the nearby cities means it should not be dismissed as a potential site, as this could minimise lines and other losses that the further sites could bring. The capacity factor of Waikato, approximately 40%, shows it is still comparable with the onshore renewables, alongside the higher consistency of offshore wind than onshore renewables.

5.2. Seasonal comparisons

Throughout all the seasons, the capacity factor, as shown in Figure 9, remains relatively constant for both onshore (yellow) and offshore (orange) wind. The demand (green) is shown in terms of average hourly GWh (left axis), with clear morning and evening peaks, intensified during winter. These graphs also demonstrate the larger capacity factor of the offshore wind production and the currently operating onshore wind farms. Both onshore and offshore wind remain relatively flat throughout the day and do not appear to closely match the demand peaks on this hourly basis, however an increase in capacity factor during winter is seen, more so in the offshore wind profile.

Figure 10 shows that offshore wind is relatively well-matched to electricity demand on an annual basis. While the inflows and onshore wind production tends to decrease over the winter period, the offshore wind generation shows an increase during this time, following the demand peak rather closely. This is promising as it indicates the ability of offshore wind to match these winter demand peaks.

As demonstrated in Figure 2, low or ‘dry’ years tend to have a large dip in inflows during the autumn months, March-April-May (MAM). This indicates the vital time for inflows that, when lower than average, may lead to a dry year. As each dry year can differ in features, each identified dry year was plotted in Figure 11, as a recreation of Figure 10. This meant the individual profile of each dry period could be seen (with the original/average in the top left). Each of these are quite different, showing that while there are some defining features of a dry year, they can differ quite substantially. The MAM dip however is present in all of these, sometimes extending through till August as in the later years of 2008, 2017, and 2020, further confirming the influence inflows during this time have the on the occurrence of dry years.

The average offshore wind production and monthly inflows during MAM months for each dry year were compared with the 20-year average in Table 5 and Table 6, respectively. In each dry year, both are less than the 20-year average, however offshore wind is in less of a deficit. This is visualised by Figure 12 which shows the annual profile of average daily inflow and offshore wind energy, for both the 20-year average, and the dry year average. The average daily inflows drops significantly during the MAM months of dry years, while the offshore wind production drops, albeit less severely. This suggests while there may be some correlation between dry years and lower offshore wind generation, it is not as extreme or to the same extent as hydro inflows. For example, in the 2001 dry year, the offshore wind generation is only at 95% of the average while the inflows fell to 74% of the average. Additionally, the overall capacity factor of offshore wind during the low years is lower than the 20-year average capacity factor, as seen in Table 4, but the individual locations are not necessarily lower. These findings show that investing in offshore wind could provide more dry-year security than the same increase in hydro capacity.

The annual profile of offshore wind is positively correlated to that of demand, while onshore renewables and inflows tend to have more of a mismatch, particularly during MAM months. Offshore wind production may decrease during low year, however not as drastically as inflows. Further analysis of this would provide more detailed and accurate descriptions of how offshore wind performs during low inflow periods.

5.3. Limitations

The existing capacity of onshore wind was inconsistent between sources, with new developments underway at time of analysis, and unclear timelines of when wind farms, or sections of these, became operational. As a result, some onshore wind generation capacity may be underrepresented, simply due to the currently active, growing, and changing nature of the wind industry. Additionally, some wind generation is embedded into the grid, so additional data was required to represent as much of the current wind generation fleet as possible. Some sites were present in both datasets, embedded and metered generation, which required careful attention to ensure farms weren't being double counted. The embedded generation data does not specify the generation source, so this was determined by matching the network code and point of connection to that of known missing wind generators, confirmed by checking the generation profile.

Solar PV was not one of the specified or analysed variables in this report, as consistent production data for this is difficult to find. Electricity generated from solar is generally used at the source and thus is not included in metered generation data. As the source is not specified in the embedded generation data and solar generation in New Zealand tends to be on a small scale, solar generation was excluded.

Another challenge during the data collection phase was choosing how to accurately represent hydro generation potential. As discussed earlier, hydro inflows were chosen as they represent the environmentally available energy rather than the amount of energy generation the controllers have historically chosen. Identifying which inflows to use to prevent double counting was again difficult here, as many hydro schemes in New Zealand are staggered, where water inflows to one lake often carry on through multiple other lakes and plants. Operators' choices may also affect when water is released from one lake to another, thus generally the first and last inflows within a scheme were used. The operational philosophy of those making these choices has huge effects on the energy trilemma, depending on where the priority lies. Often, these choices are informed by the economic benefits, but may come at a cost to the security of supply or environment, though constraints on lake levels help mitigate the latter.

Electricity grid constraints, infrastructure, costs, and losses were neglected in this report for simplicity. The installation of large capacity offshore wind farms would require additional investments to grid systems, and careful management to ensure the additional generation is integrated effectively and efficiently. Two of the locations, Taranaki and Waikato are close to large demand centres in New Zealand, meaning they would incur less lines losses than similar developments in less populated areas.

The offshore wind hindcast data is modelled from past weather, specifically using the ERA5 reanalysis datasets. This means actual production from an offshore wind farm may differ from what has been estimated here. Without detailed data gathering from the proposed sites, this method provides a useful initial analysis and indication of possible performance.

5.4. Further work

As time was limited and the scope for this report centred around offshore wind, there are aspects and topics that were either not covered or only touched on. Alongside the identified limitations, potential further work and questions that could fill these gaps have been identified.

Analysis of the effects of grid constraints such as the HVDC link would be valuable in further identifying the suitability of offshore wind for NZ, especially when considering sites further from large demand centers, such as Southland. Further understanding of how offshore wind generation could be integrated into the existing infrastructure, and the cost of this, would provide additional valuable context.

The overbuild of renewables is one identified solution to the dry year problem, as discussed by the NZ battery project. [17] This requires excess renewable generators to be installed, that could meet electricity demand throughout a dry year deficit. As most renewables are variable, this can increase the unpredictability of the energy market, and lead to large amounts of energy spill during non-dry-year periods. Recent developments in green energy storage technologies such as hydrogen stored as ammonia could provide an outlet for this spill energy and could be exported to other countries looking to purchase green energy. This introduces flexible demand that can be exploited during high generation periods but stopped to conserve power. Exportation of this extra stored energy would benefit New Zealand economically and could potentially replace fossil-fuelled industries. Modelling of offshore wind overbuild scenarios alongside green energy manufacturing could further show the benefits of investing in offshore wind.

Another “Dry-year Solution” currently being investigated is the Lake Onslow pumped hydro scheme, which would act as a large-scale battery for hydro generated electricity. Using excess electricity during high generation, low demand times, water is pumped to storage lakes where it is stored until needed. Amongst environmental and initial cost concerns, this also increases NZ’s dependency on hydro generation and the South Island. This questions the efficacy of investing in South Island hydro schemes, as the North Island has a higher population and thus demand, introducing transmission losses to get the electricity where it is needed most. Diversification of the energy generation fleet in terms of both location and source is important to consider as it will decrease reliance on the South Island, large scale transmission networks, and weather.

Detailed analysis and modelling of hydro inflows in New Zealand and the effects of climate change on these could provide a more complete picture of how these are likely to change and aid in dry-year predictions and thus preparations. As the atmosphere warms, more moisture is involved in atmospheric cycling, which can increase both rainfall and drought [18]. More damaging floods and extended drought periods both could have significant effects on energy availability and infrastructure in New Zealand. Additionally, the influence of climate patterns such as the El Nino Southern Oscillation, Southern Annular Mode, and the

Interdecadal Pacific Oscillation have been shown to affect rainfall in New Zealand [19]. Determining the correlation between phases of these climate patterns and dry years (e.g., La Nina years) could provide further background and predictability.

6. Conclusion

This report has analysed current electricity demand and generation in New Zealand, alongside potential offshore wind generation at three proposed sites in Taranaki, Waikato, and Southland. Analysis of offshore wind and correlations with existing generation and demand presented some promising points.

The offshore wind production models revealed relatively high-capacity factors and generation profiles, particularly for Taranaki and Southland, where generation was at 60% or above for more than 50% of the time (30% of time for Waikato). This provides a relatively high reliability, where the turbines are producing at least 10% of capacity for 80% of time (70% of time for Waikato).

A strong correlation of the 20-year average annual offshore wind production with winter demand suggests additional security of electricity supply during these high demand months when other renewables tend to decrease in production. The daily profile of offshore wind being relatively flat but consistent shows potential consistency and reliability. During dry years, the offshore wind production may decrease however this was shown to be at a lesser extent than hydro inflows.

Overall, the investment of offshore wind in New Zealand would add to the security of supply by adding generation diversity, while decreasing the reliance on fossil fuels. The Taranaki and Southland locations show greater production than Waikato. The proximity to demand centres however means Taranaki and Waikato may be more practical sites.

7. Acknowledgements

Numerous discussions, meetings, and people made this work possible. Many thanks to all those who have provided ideas, insights, and aid in the writing of this report. Thank you to Peter McComb at Oceanum, Dougal McQueen, Nathan Turner at BlueFloat Energy, and everyone at Elemental Group. Specifically, great appreciation for Will Thorp and Ngaio Fulton for their continued guidance, support, and expertise.

References

[1] Interim Climate Change Committee, “Accelerated Electrification,” New Zealand, 2019.

[2] Transpower, “Whakamana i Te Mauri Hiko - Empowering Our Energy Future,” 2020.

[3] New Zealand Wind Energy Association, “Wind farms operating and under construction,” [Online]. Available: www.windenergy.org.nz/operating-&-under-construction. [Accessed January 2023].

[4] Venture Taranaki, “Offshore Wind,” 2020.

[5] Global Wind Energy Council, “Global Offshore Wind Report,” 2022.

[6] C. Ishwar and I. Mason, “Offshore Wind for New Zealand,” 2019.

[7] BlueFloat Energy and Elemental Group, “South Taranaki Offshore Wind Project,” [Online]. Available: https://southtaranakioffshorewindproject.com/. [Accessed 16 March 2023].

[8] D. McQueen and A. Wood, “Quantifying the benefits of Wind Power diversity in New Zealand,” 2017.

[9] Concept Consulting, “New Zealand Renewable Generation Diversity Investigation,” New Zealand Wind Energy Association, 2022.

[10] Transpower, “Market Operations - Tracking hydro inflows and storage,” October 2021.

[11] L. Fox and C. Bremner, “Hydrological Modelling Dataset - Report 2: Flow Series Description and Methodology,” Electricity Authority, 2021.

[12] Electricity Authority, “DerivedSeriesForStorageCapacityAndSpecificEnergy,” Jan 2023. [Online]. Available: https://www.emi.ea.govt.nz/Environment/Datasets/HydrologicalModellingDataset_2020/1_InfrastructureAndHydroConstraintAttributes/DerivedSeriesForStorageCapacityAndSpecificEnergy.

[13] D. M. Lane and R. Guerra, “Describing Bivariate Data,” in *Introduction to Statistics*, 2003, pp. 164-177.

[14] Transpower, “Te Mauri Hiko - Energy Futures,” 2018.

[15] S. Poletti and I. Staffell, “Understanding New Zealand’s Wind Resources as a Route to 100% Renewable Electricity,” *Renewable Energy,* vol. 170, pp. 449-461, 2021.

[16] EECA, “Commercial-scale solar in New Zealand: An analysis of the financial performance of on-site generation for businesses,” Energy Efficiency and Conservation Authority, Wellington, New Zealand, 2021.

[17] Ministry of Business, Innovation & Employment, “Possible alternative approaches to the dry year problem,” 16 March 2023. [Online]. Available: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/low-emissions-economy/nz-battery/dry-year-problem/. [Accessed May 2023].

[18] NIWA, “Climate change scenarios for New Zealand,” [Online]. Available: https://niwa.co.nz/our-science/climate/information-and-resources/clivar/scenarios. [Accessed May 2023].

[19] Stats NZ, “Interdecadal Pacific Oscillation,” 19 October 2017. [Online]. Available: https://www.stats.govt.nz/indicators/interdecadal-pacific-oscillation. [Accessed May 2023].

[20] NIWA, “El Niño and La Niña,” [Online]. Available: https://niwa.co.nz/climate/information-and-resources/elnino. [Accessed 09 12 2022].

[21] L. Fox and C. Bremner, “Hydrological Modelling Dataset - Report 3: Storage and Spill Series,” Electricity Authority, 2021.

[22] Energy Link, “Electricity Market Modelling 2035,” Interim Climate Change Committee, 2019.

[23] Electricity Authority NZ, “Generation output by plant,” [Online]. Available: https://www.emi.ea.govt.nz/Wholesale/Datasets/Generation/Generation_MD.

[24] Electricity Authority NZ, “Grid Export Data,” [Online]. Available: https://www.emi.ea.govt.nz/Wholesale/Datasets/Metered_data/Grid_export.

[25] Electricity Authority NZ, “Embedded Generation,” [Online]. Available: https://www.emi.ea.govt.nz/Wholesale/Datasets/Metered_data/Embedded_generation.

[26] Electricity Authority, “Hydrological Modelling Dataset - Flows,” [Online]. Available: https://www.emi.ea.govt.nz/Environment/Datasets/HydrologicalModellingDataset/2_Flows_20211231.

APPENDIX I

Table 7 - Hydrological Modelling Dataset flow descriptions

Aoraki	*"For the HMD modelling, the flows in the Waitaki River are considered in two components, inflow to Lakes Pukaki and Tekapo; and tributary inflows below the lakes at Benmore and Waitaki Power Stations."*
Waikato	*"Tributary flows at Arapuni are calculated simply by subtracting the Taupo outflows from the outflows at Arapuni. Karapiro tributary flows are calculated similarly…"*
Southland	*"… two separate files are required for the HMD. Inflows and outflows for Lake Te Anau are available from 1926 and for Lake Manapouri from May 1932."*
Clutha	*"Hawea – Inflows to Lake Hawea are read directly from the Power Archive and daily averaged. Wanaka - Outflows from Lake Wanaka are read directly from the Power Archive and daily averaged. Roxburgh - Roxburgh inflows are read directly from the Power Archive and Hawea outflows are subtracted to provide a local inflow dataset. This is daily averaged."*

Data was imported, wrangled, and analyzed using python via Jupyter Notebooks. The script for this is located in the Elemental Group OneDrive: OffshoreWindFinal.ipynb

This uses Python 3.10.5 and Jupyter Lab 3.64, with the packages NumPy, pandas, seaborn, and matplotlib.

Most of the data was automatically read in from the webpage source. If these change, the code may need updating. The exception of this is the offshore wind hindcast data, provided by BlueFloat, and the Network Supply Points Table. These should be in the working folder of the notebook, or the file path added to the code.

NEW PLYMOUTH OFFICE

8 Young Street
New Plymouth 4310, New Zealand
PO Box 1085, New Plymouth 4310
+64 6 757 8161

AUCKLAND OFFICE

c/- The Generator
12 Madden St
Wynyard Quarter
Auckland CBD 1010
+64 (0)21 974 899