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Offshore Wind for New Zealand

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Abstract

This paper presents an assessment of the potential for offshore wind in New Zealand to meet a previously estimated electricity demand of 26,620 GWh/y for electrification of stationary energy and transport. A study area off the coast of South Taranaki was selected due to initial indications of the presence of a shallow shelf and the availability of a 5-year record of 10-min wind data from the Maui A and Maui B platforms. The assessment incorporated wind resource analysis, bathymetric assessment for spatial analysis, comparison of onshore vs offshore generation, and a preliminary investigation of logistical issues. The wind resource was assessed using Weibull and Rayleigh frequency probability distributions of observed wind speed data, wind rose analyses and estimation of the electricity production using power curve modelling. Suitable sites were identified from bathymetric mapping, ascertaining areas of low slope, and applying physical constraints. The logistical and other issues investigated included the capacity of Port Taranaki to host the necessary support vessels, potential construction times, visual, regulated and reduced wind buffer zones, and the proximity of the existing electricity grid.

The analysis showed that offshore South Taranaki has an exceptional wind resource, and that there is approximately 1065 km^2 of bathymetrically suitable area for fixed foundation wind turbines. Additional suitable space for floating turbines was also identified. Mean 5-year wind speeds at the Maui A and Maui B sites were 10.12 m/s and 10.73 m/s at 105 m above MSL. Expected capacity factors for an offshore wind farm based on the Maui A wind resource were 56.9% on a gross basis and 46.3% accounting for array and downtime losses. The site would accommodate a 7016 MW wind farm using 877 x 8.0 MW turbines, and would produce an estimated 28,456 GWh/yr which is approximately 7% over the target. All fixed foundation sites were within a 53.6 km visual buffer distance, but 32% of floating sites were outside this zone. Further research into the geotechnical suitability of the seabed, detailed wind modelling, transmission issues, visual impacts and financial analysis is needed. Upgrades would likely be required to Port Taranaki, and the construction rate would need acceleration in order to achieve New Zealand's climate change goals in a timely manner.

1. Introduction

As part of a transition to a low-emissions economy, New Zealand will need to achieve major reductions in greenhouse gas (GHG) emissions from the energy sector. Electrification of stationary energy and transport has been identified as a key strategy in this regard, and it has been estimated that an additional 26,620 GWh/y of electricity in comparison to 2014 generation would be required [1]. New Zealand has an excellent onshore wind resource, however little is known about the potential for offshore wind farms and the engineering potential for offshore wind to supply some, or all, of the additional demand required.

Internationally, the offshore wind industry has developed rapidly in recent years and reached a total installed capacity of 18,814 MW in 2017 [2]. Almost 84% global offshore wind is in Europe [3], particularly in the North Sea and the Baltic Sea, with the remainder in China, Vietnam, Japan, South Korea, Taiwan and the United States. A 2000 MW offshore wind farm off the coast of Victoria, Australia is presently in the conceptual/early planning stages [4]. In 2017, the world's first floating wind farm consisting of five 6 MW turbines in water depths between 96 – 110 m, with a mean wind speed of 10.1 m/s, was commissioned [5, 6]. Capacity factors for this wind farm as high as 65% have been reported.

Advantages of offshore wind include access to higher speed, more consistent and less turbulent wind resources than typically available onshore, economies of scale from the easier deployment of turbines over 3 MW in capacity and the potential to either avoid or minimise the NIMBY effect. Disadvantages include the typically higher financial costs compared to onshore generation [7], including higher cabling costs [8], exposure to a more corrosive environment[8, 9], and more difficult and expensive access for maintenance and repairs [8].

A potentially shallow (< 50 m depth) shelf suitable for fixed foundation turbines was identified off the coast of South Taranaki, New Zealand from existing bathymetric maps [10]. In addition a record of 10-min wind data from the Maui A and Maui B platforms in this region was available. Accordingly, the South Taranaki basin was selected as the study area for the present research.

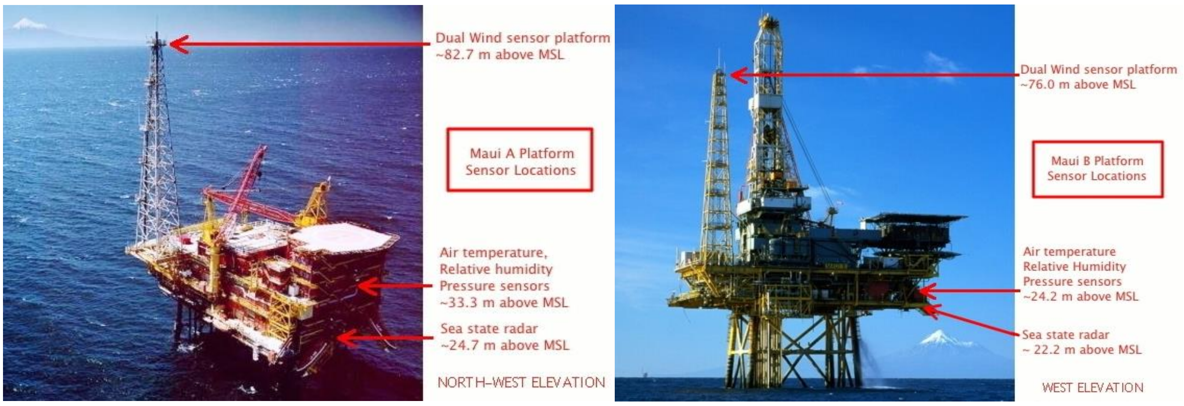
This objectives of this research were:

- To quantify the wind resource and the potential electricity generation for an offshore wind farm located within the study area;
- To evaluate the physical constraints in siting this offshore wind farm;
- To understand any correlations in the power production between this offshore wind farm and existing onshore wind farms;
- To understand the logistical issues in the installation of this offshore wind farm.

2. Methods

Wind speed, wind direction and air temperature data measured on the Maui A (39.64543 ^{o}S, 173.3162 ^{o}E) and Maui B (39.55525 ^{o}S, 173.4491 ^{o}E) offshore oil platforms were obtained from MetService NZ (R. Marsden, personal communication, August 6, 2018), with the kind permission of Shell Todd Oil Services Ltd (Simon Elliot, personal communication, August, 2017). The dataset covered the period 2012-2016 inclusive and consisted of ten-minute-average recordings of wind speed in knots, wind direction in degrees and air temperature in degrees Celsius, time-stamped at Coordinated Universal Time (UTC). Anemometer heights for Maui A and Maui B were 82.7 metres above mean sea level (MSL) and 76 metres above MSL respectively (Figure 1).

A Vestas V-164 8 MW wind turbine was selected for modelling purposes[11]. Wind speeds were scaled to the turbine hub height of 105 m using a power law with a shear exponent value of 0.11 for winds at sea [12]. The power curve was modelled using the piecewise function shown in Eq. 1.



a) b)

Figure 1: Maui A and B sensor locations. Source: MetService NZ (R. Marsden, personal communication, August 6, 2018).

$$Power\ Output = \begin{cases} 0, & 0 \le U < 3 \\ 100U - 300, & 3 \le U < 4 \\ -4.1667U^4 + 133.33U^3 - 1395.8U^2 + 6516.7U - 11100, & 4 \le U < 8 \\ 9.375U^4 - 449.77U^3 + 7755.3U^2 - 56142U + 147593, & 8 \le U < 13 \\ 8000, & 13 \le U < 25 \\ 0, & U \ge 25 \end{cases} \quad (\mathbf{1})$$

where: Power Output is in kW; U = wind speed (m/s)

Wake losses (L_1) of 15% were adopted for a conservative base-case scenario as this figure lies in the mid-point of the range proposed by Barthelmie et al.[13]. Repair time losses (L_2) were derived from a 5-year study of offshore wind farm maintenance requirements [14]. Electrical transmission losses (L_3) for the baseline case were assumed as 3% which is the mid-point of the range outlined by Musial et al. [15]. For individual sites transmission losses were calculated from Eq. 2.

$$\begin{matrix} Electrical \\ Losses \end{matrix} = \frac{\begin{bmatrix} 2.073+0.073D_S - 0.002{D_S}^2 + 1.712\times10^{-5}{D_S}^5 - 8.563\times10^{-8}{D_S}^4 + 1.57\times10^{-10}{D_S}^5 \\ +0.001W_D - 4.85\times10^{6}{W_D}^2 + 8.158\times10^{-8}{W_D}^3 - 4.131\times10^{-12}{W_D}^4 \end{bmatrix}}{100} \quad (\mathbf{2})$$

where: D_S = distance to shore in kilometres; W_D = water depth in metres; Electrical Losses are expressed as a fraction of the gross output.

Net energy production was given by:

$$AEP\ (Net) = AEP(Gross) \times (1 - L_1)(1 - L_2)(1 - L_3) \quad (\mathbf{3})$$

where: AEP = annual energy production (kWh); L_1, L_2, L_3 as described above.

Frequency distributions were calculated using 1 m/s bins, and wind roses plotted using a Matlab function (D. Seto, personal communication, August 2, 2018) with a bin size of 10^o (i.e. 36 bins). Bathymetry and site analyses were carried out using ArcMap v10.4.1 in ArcGIS. The Maui platform locations were modelled as point features in Arc-Map. The mapping co-ordinate system was set to NZGD_2000_New_Zealand_Transverse_Mercator. Water depth data with a spatial resolution of 250 m was downloaded from the National Institute of Water and Atmospheric Research (NIWA) website [10]. A grid with a resolution was 20km x 20km was overlaid on the bathymetry layer using the fishnet tool in Arc-Map. Depth profile graphs were generated by taking horizontal and diagonal transects over the area from the coastline and detailed profile graphs for each cell generated in vertical, horizontal and two diagonal directions. Regions of < 50 m depth and < 0.1° slope, or 'plateaux' were identified using the 250 m resolution bathymetric map in combination with the profile graphs.

Substation locations were sourced from Transpower [16], shipping routes identified from [17] and the location of Port Taranaki obtained from [18]. The reduced wind speed (RWS) buffer zone was estimated using [19] and increased regulation zone (IRZ) using [20]. Berth information in Port Taranaki was retrieved from [21] and offshore wind farm boat sizes were retrieved from the 4COffshore database [22]. The visual buffer zone (VIZ) was calculated for an overall turbine height to the blade tip of 187 m, comprising 105 m hub height, a 2 m hub radius and an 80 m blade length [11], with a 1.8 m observer eye level and assuming a spherical earth. Wind farm layout for the baseline case used a 5D (crosswind) x 9D (downwind) configuration. Wake losses of 15% were adopted from the 10-20% range reported by Barthelmie et. al. [23]. An alternative 10D x 12D configuration with wake losses estimated at 8.25% was adopted from [24]. New Zealand electricity generation data from 1 April 2011 – 1 April 2013 was sourced from the NZ Electricity Commission [25].

3. Results and Discussion

3.1 Wind resource

The wind speed data sets over the 2012-2016 period were approximately 97% complete, and the indicated mean wind speeds at 105 m for the Maui A and Maui B platforms were 10.12 m/s and 10.73 m/s respectively, with a relatively high standard deviation as expected (Table 1). Wind speeds above 8.5 m/s are indicative of a 'superb' wind resource [26]. The wind speed frequency distributions were well fitted by both Weibull and Rayleigh functions as shown in Figure 2, which also lists the fitted parameter values.

Table 1: Wind resource characteristics (2012-2016)

	Maui A	Maui B
Mean wind speed at 105m above MSL (m/s)	10.12	10.73
Standard deviation	5.35	5.16
Data completion (%)	96.8	97.6

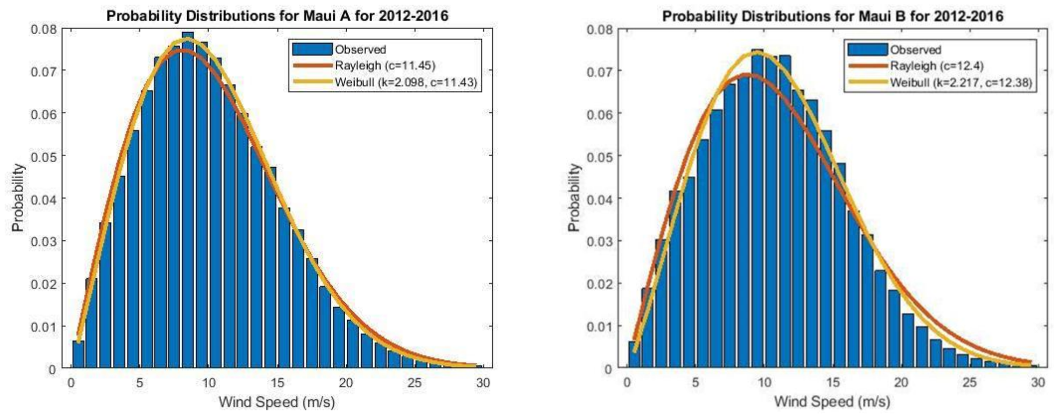
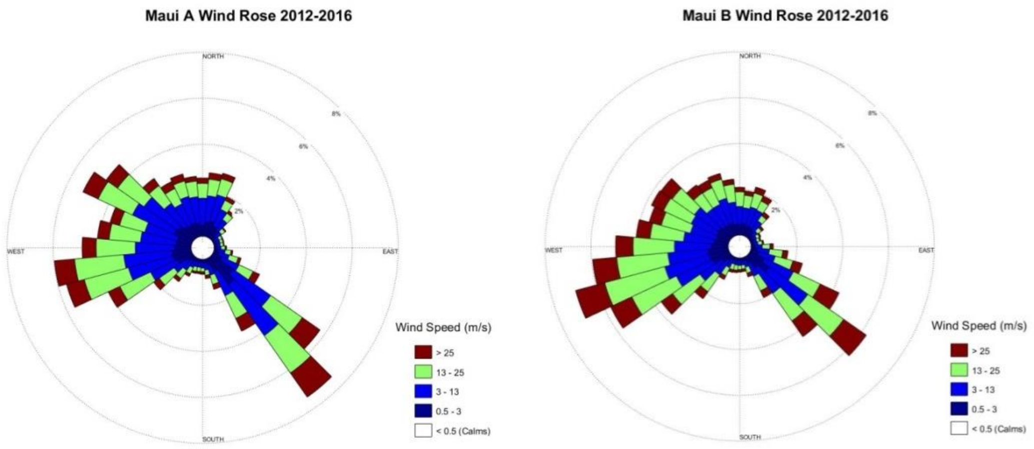


Figure 2: Maui A and Maui B wind speed frequency distributions

The predominant wind direction was westerly, with south-easterly winds also significant (Figure 3). The westerly orientation was best in terms of percentage of AEP generated (Table 2). This suggested a preferred wind farm orientation with wind turbines in rows perpendicular to the west, subject to spatial constraints.



a) b)

Figure 3: a) Maui A wind rose; b) Maui B wind rose

Table 2: Gross energy from westerly (225 - 315 degrees) and south-easterly (90-180 degrees) directions

Platform	Quadrant	Gross Energy (GWh/year)	Percentage of gross AEP
Maui A	West	20.4	47 %
	South-East	11.2	26 %
Maui B	West	16.8	42 %
	South-East	10.9	27 %

3.2 Electricity Generation

The mean annual gross electricity production for a single turbine was approximately 40 GWh/y for the Maui A site and 44 GWh/y for the Maui B site (Table 3). Wake, maintenance and electrical losses reduced these outputs by 18.6%. Net energy production, capacity factors and the number of turbines required to meet the target of 26,620 GWh/y are shown in Table 3. When wake losses were varied from 5-20%, the capacity factors and number of turbines at Maui A ranged from 43.6-51.7% and 734-872 respectively, whilst for Maui B they ranged from 47.6-56.6% and 672-798 respectively.

Table 3: Mean Annual Electricity Generation and Capacity Factors for the baseline case over the period 2012-2016

	Maui A	Maui B
Gross Annual Energy Production (GWh/yr)	39.9	43.6
Net Annual Energy Production (GWh/yr)	32.4	35.5
Net Capacity Factor (%)	46.3	50.6
Turbines Required	821	751

3.3 Bathymetry and Site Analysis

Potentially suitable shelf areas were indicated where 20 m contour lines diverged from each other south-east of the Maui platforms (Figure 4a). Further detail as provided by the vertical transects is illustrated in Figure 4b, which shows a 20 m depth shelf located between approximately 5 km and 20 km offshore. Suitable fixed foundation and floating sites are shown in Figure 5.

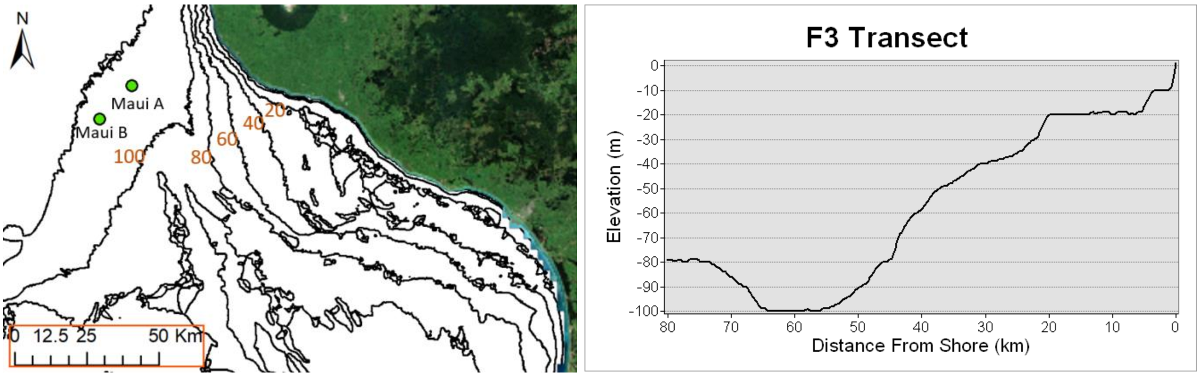


Figure 4: a) 20m Contour Map for Offshore South Taranaki; b) Example transect

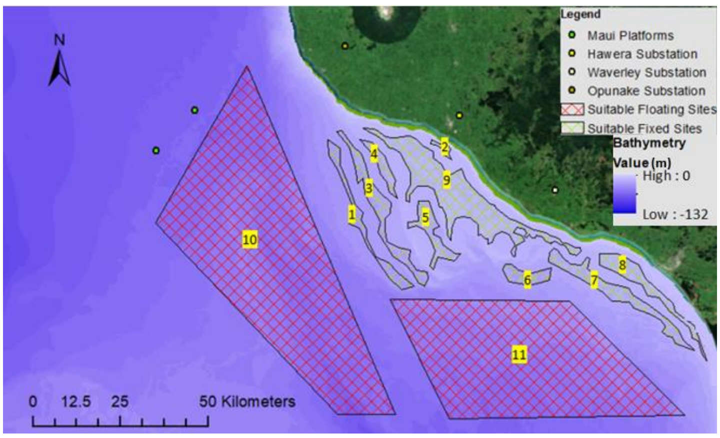


Figure 5: Suitable areas for fixed foundation and floating sites

The suitable area for fixed foundation turbines totalled 1065 km^2 (Table 4). This would accommodate 877 turbines at 5D (820 m) x 9D (1476 m) spacing, giving an installed capacity of 7016 MW, which would produce an estimated 28,456 GWh/yr, or approximately 7% over the target. A west-facing layout is shown in Figure 6. The three buffer zones of reduced wind speed (RWS), increased regulation (IRZ) and visibility (VIZ) were located 5 km, 22 km, and 53.6 km offshore (Figure 6). For the alterative spacing of 10D (1640 m) x 12 D (1948 m) 760 turbines, including floating turbines, would be required in order to meet the target output.

Table 4: Characteristics of suitable sites

Foundation	Site	Area (km^2)	Depth (m) Min	Depth (m) Max	Nearest Substation Location	Nearest Substation Distance (km)	Port Distance (km)
Fixed	1	91	49	53	Opunake	27	95
	2	10	9	10	Hawera	9	119
	3	130	36	40	Opunake	24	95
	4	44	29	31	Hawera	24	101
	5	77	27	30	Hawera	26	125
	6	50	39	40	Waverley	22	156
	7	146	29	30	Waverley	16	164
	8	105	19	20	Waverley	22	177
	9	412	16	21	Waverley	12	100
	Total	1065	-	-	-	-	-
Floating	10	2700	84	120	Opunake	28	72
	11	1980	63	110	Waverley	32	142
	Total	4680	-	-	-	-	-

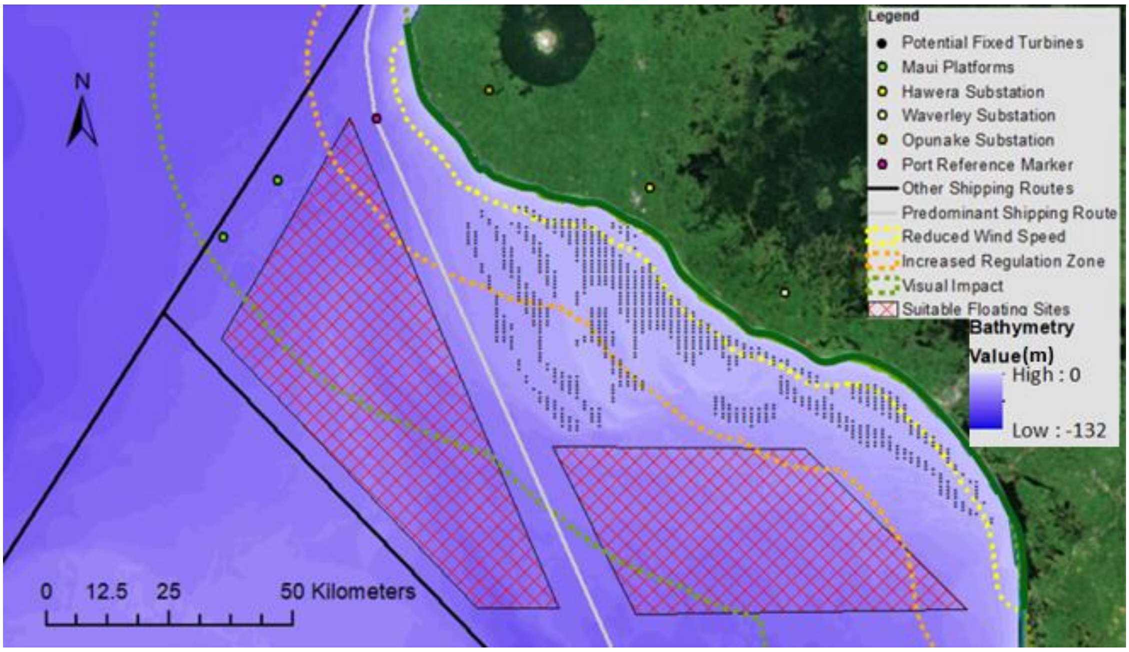


Figure 6: 5D x 9D turbine array layout - West orientation (877 turbines)

3.4 Logistics

Fixed sites 1 and 3 had the least distance (95 km) to Port Taranaki and sites 6-8 were farthest from Port Taranaki, with distances ranging from 156 to 177 km (Table 4). These distances are somewhat greater than the 30-40 km typical for Northern Europe, although there are some cases of 90-100 km [3]. For this study it was assumed that Port Taranaki was the only suitable port for offshore construction vessels, partly due to the established offshore oil and gas industry in the region. A comparison of existing berth capacities at Port Taranaki (Table 5) with the dimensions of offshore wind farm construction vessels indicated that some upgrading of the facilities would be required. Vessels tended to exceed the Port Taranaki berth dimensions in both breadth and draft and all recorded heavy lift vessels exceeded the maximum breadth of the Port Taranaki berths.

Horizontal distances from the fixed foundation sites to existing sub-stations ranged from 9 km to 27 km, and for floating sites from 28-32 km (Table 4). Transmission losses determined for these distances on a site by site basis showed that the baseline case assumption of 3% to be realistic with only minor variations around this value (Table 5). The maximum power inputs to each sub-station from fixed foundation sites were 1406 MW for Opunake, 886 MW for Hawera, and 4527 MW for Waverley. At present only Hawera is a grid injection point (GIP) [27], receiving input from the Whareroa co-gen plant. It is considered likely that a purpose built GIP for an offshore wind development would be required in the long-term.

Table 5: Berth capacities for Port Taranaki [21]

Berth	Max Length (m)	Max Beam (breadth) (m)	Max Draft (m)
Breakwater No 1	78	20.0	6.5
Breakwater No 2	150	25.0	9.0
Moturoa No 1	98	20.0	7.5
Moturoa No 2	196	35.0	12.5
Newton King No 1	211	35.0	12.5
Newton King No 2	211	35.0	12.5
Blyde No 1	225	35.0	10.5
Blyde No 2	225	35.0	12.5
Blyde No 3	78	20.0	6.5

Table 6: Transmission losses and sub-station power variation between sites

Site	**Transmission Losses (L_3)**	**Maximum Power (MW)**
Fixed		
1	0.0293	582
2	0.0259	78
3	0.0292	823
4	0.0291	280
5	0.0290	528
6	0.0291	326
7	0.0283	902
8	0.0289	645
9	0.0272	2654
Floating		
10	0.0301	17264
11	0.0295	12671

For an offshore wind farm to meet the target of 26,620 GWh/y to be constructed between 2020 and 2050, a build rate of 0.0046 years/MW would be required. Build rates of less than 0.005 years/MW for offshore wind projects in Europe have been reported [28], suggesting that this is potentially achievable. However the build rate is dependent on a variety of factors such as the number of components, foundation type, seabed characteristics and number of workers and tasks [28]. There is significant spread in construction rates in offshore wind projects in Europe, indicating that offshore wind farm installation is site-specific and that there is a lack of standardisation within the industry [28]. For an offshore wind farm to be installed in a timely manner in New Zealand, a partnership would likely need to be formed with an established offshore wind installation company, most probably from Europe. Maintenance and repair of component failures, would involve an estimated average of 117 hours of repair time per turbine/y, totalling 96,000 hours/year. This would involve approximately 11 permanent maintenance vessels carrying out constant repairs. Additional maintenance vessels may be needed to deliver components from onshore to the wind farm site. The environmental impact would be increased if these ships, as is likely, utilised fossil fuels.

3.5 Limitations and Further Research

A major limitation of the present study is that it utilised wind data from locations outside the bathymetrically suitable areas. Additional data from within the identified zones, along with advanced wind modelling will be required in order to accurately assess electricity generation potential. Models by Hsu [29, 30] and Soler –Bientz et al. [31] for estimating the variation in wind resource with distance from the coast would be valuable in this regard. Turbulence evaluation is needed for which sound detection and ranging (SODAR) wind profiling with a resolution one second or 1 Hz frequency is suggested and the appropriate shear exponent factor should be determined experimentally. Bathymetry resolution was limited to 250 x 250 m grids and finer resolution is required. It was assumed in the present study that offshore wind turbines with fixed foundations could be built in up 50-metres of water, however the maximum reported depths of fixed foundation offshore wind farms in transitional waters are 41-42 metres [3, 32] and for one demonstration offshore wind farm up to 45 metres [32]. Investigation of the geotechnical and wave properties of the sites, including the shear modulus, shear strength, and Poisson's ratio [32] will be a key next step to assist in deciding which of the foundation types, i.e. monopole, jacket, tri-pod or gravity-base, are best suited.

Electrical substation design, transmission to shore and power quality issues were excluded from the scope of the present study. These factors along with potential upgrades to the electricity grid and the existing onshore substations, and the need for a new GIP, require evaluation. Environmental impacts were not analysed in this study due to a lack of available data. Comprehensive geotechnical and environmental data would help identify sensitive areas and environmental buffer zones. Visual impact will be of particular interest, and will require detailed social science research. Financial analysis including the levelised cost of energy should occur in parallel with other research. A watching brief on the progress of the 2000 MW 'Star of the South' offshore wind project 10-25 km off the coast of Victoria, Australia [4] should help to provide insights into many of these issues and to identify potential infrastructure and capability for offshore windfarm development in New Zealand.

4. Conclusions

The wind resources at both Maui A and Maui B offshore platforms were found to be exceptional, with mean wind speeds at 105 m above MSL of 10.12 m/s and 10.78 m/s respectively. Wind speed frequency distributions were well described by the Weibull model. The dominant wind directions were westerly and south-easterly, with the majority of energy arising from the westerly quarter. For a baseline case the average annual energy production per turbine within a wind farm using the Maui A wind resource data was 32.4 GWh/year, with a net capacity factor of 46.3%. Nine sites with water depths less than 50 m and seabed slopes less than 0.1 degrees were identified, and these provided 1065 km^2 of suitable area for fixed foundation offshore wind turbines. For the baseline case, the site would accommodate a 7016 MW wind farm using 877 x 8.0 MW fixed foundation turbines, and would produce an estimated 28,456 GWh/yr which is approximately 7% over the target.

All fixed foundation sites were within the 53.6 km visual buffer distance, but 32% of floating sites also identified were outside this zone. The estimated construction rate for an offshore wind farm to meet the target by 2050 was 0.0046 years/MW. Current offshore construction vessels would exceed the maximum allowable dimensions of most current berths at Port Taranaki and an upgrade would likely be required.

Further research is required to assess the geotechnical conditions of the seabed and to provide a finer resolution bathymetric map of the site areas. More detailed wind modelling is needed to establish the likely wind regimes at the individual sites and within turbine arrays. Transmission issues, offshore and onshore sub-station options, plus visual, environmental, social and financial impacts require further investigation.

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