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Assessment of Two Offshore Sites on the Irish Coast for HAWT installation suitability.

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A report submitted in partial fulfilment of the degree of MAI (Mechanical & Manufacturing Engineering)

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Nomenclature

P/A	Power Per Unit Area	(W/A)
U	Average/Yearly Wind Speed	(m/s)
$\mathbf{u_i}$	Wind Speed	(m/s)
$\bar{\boldsymbol{P}}$	Average Power	(W)
H_{ref}	Reference Height	(m)

Abstract

Wind data taken from two marine weather buoys, one in the Atlantic Ocean, and one in the Irish Sea, was analysed in order to determine the energy potential of the sites for use in the consideration of installing offshore wind turbines. From direct data analysis and using the method of bins it was possible to ascertain that the average obtainable wind energy resource from site M4 was greater than that for site M2, and the power curve of a DTU 10MW turbine was used to calculate a theoretical average wind machine power. Rayleigh and Weibull distributions were fitted to the data from both sites and a Kolgomorov-Smirnov test was used to determine goodness of fit. The results obtained as well as environmental and social factors were then considered to determine the suitability of both sites for the installation of a 10MW turbine with a hub height of 100m and which site was more suitable for a floating offshore wind turbine.

1 Introduction

The wind energy industry in Ireland is a vital part of the economy responsible for thousands of jobs and millions of euro of revenue yearly, and its growth is a necessity for meeting the sustainability targets set out to be achieved by the irish government for 2030 [1]. The development of offshore wind farms in Irish coastal waters is a necessity of that necessity without which we may fall short of our sustainability goals as the potential energy production of offshore wind farms is far greater than onshore [1].

Identifying suitable sites for the deployment of wind farms is a requirement of meeting these goals. Site suitability requires the assessment of the geological constraints as well as the behaviour of wind at a site, the potential energy production of a site and the social and environmental factors unique to said sites.

The potential wind energy resource and the behaviour of wind at an offshore location can be assessed using direct data analysis and statistical methods [2-4]. This report analyses data obtained from two marine weather buoys in Irish coastal waters, labelled M2 and M4, in the Irish Sea (East coast) and Atlantic ocean (North West coast) respectively to assess the suitability of both sites for the installation of wind turbines, as well as the type of wind turbines that could be deployed at either location.

1.1 Structure

The remainder of this report is structured as follows. Section 2 contains a brief literature review of the necessary factors to be considered in the assessment of a site for the suitability of wind turbine installation, as well as outlining briefly the usefulness of statistical methods of analysis using Weibull and Rayleigh distributions. Section 3 contains the results of direct data, method of bins and weibull and rayleigh analysis as well as theoretical performance of a 10MW turbine in graphical and tabular form. Section 4 contains discussion of the results as well as specifics relative to the geographical locations of M2 and M4. Section 5 contains the conclusions of this report. Section 6 contains the bibliography. Appendices containing nonessential graphs and tables are then presented.

2 Background

2.1 Assessing Site Suitability for Offshore Wind Turbine Installation

When assessing the suitability of any site for the installation of wind turbines it is important to consider the full range of relevant factors.

2.1.1 Potential Harmful Effects on the Environment and Marine and Avian wildlife

It has been well documented that offshore wind farms have the potential to harm marine and avian wildlife, both during and after construction, however the degree to which different variants of turbines are harmful varies depending on environment and the specific flora and fauna [5-8]. A comprehensive literature review of the environmental effects of floating offshore wind turbines found that the effect of floating turbines on environmental conditions are minimal to moderate with the negative effects above the water line being potentially more impactful due to reduction in wind speed downstream of the turbine, with an average reduction of 8-9%.

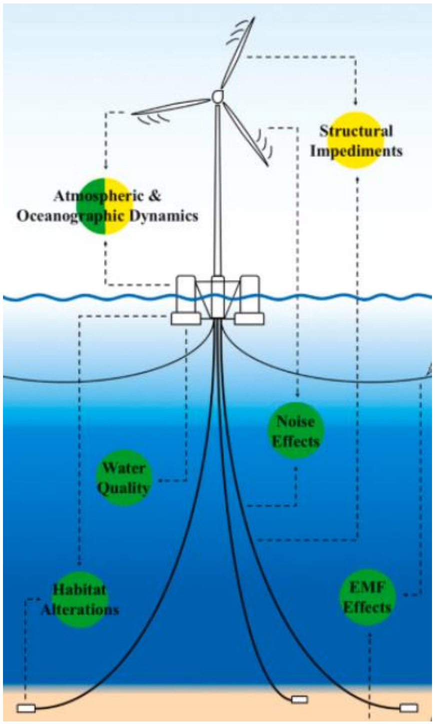


Figure 2-1 Potential Harmful Effects of floating OWF, © CC BY 4.0

Structural impediments were found to be the largest danger to birds, with certain species having a higher probability of collisions [5, 6]. The alterations in wind speed may also cause behavioural changes including avoidance of turbines which causes migratory patterns to increase in length, requiring birds to expend more energy to reach their destination. Marine wildlife appear to be much better at navigating structural impediments, especially if high contrast colours are used for the cables which moor floating offshore turbines [5]. The changes to environmental conditions underwater are less well understood, but likely not as great [5].

Fixed turbines may also introduce negative changes to the environment although It is important to note that they may also have positive environmental effects, such as their foundations acting as artifical reefs. The requirement for boats to steer clear of wind turbines may also create safe zones for marine wildlife from which they cannot be reached by commercial fishing [8]. The greatest danger to marine wildlife is likely during the construction phase of fixed turbines, due to pile driving and the potential of collision with construction vessels [8].

The potential negative effects of wind turbines on birds could be negated by avoiding key areas of conservation and grouping wind turbines such that they are not coincidental with migratory flight paths [9].

2.1.2 Geological Constraints in the Atlantic and Irish Sea

The geology of the seabed and marine depth are key factors in the assessment of site suitability for offshore wind turbine installation [10]. The Irish sea can reach depths of up to 135 metre as seen in Figure 2-2 below. Non floating offshore turbines are generally considered viable in depths below or equal to 50m [11].

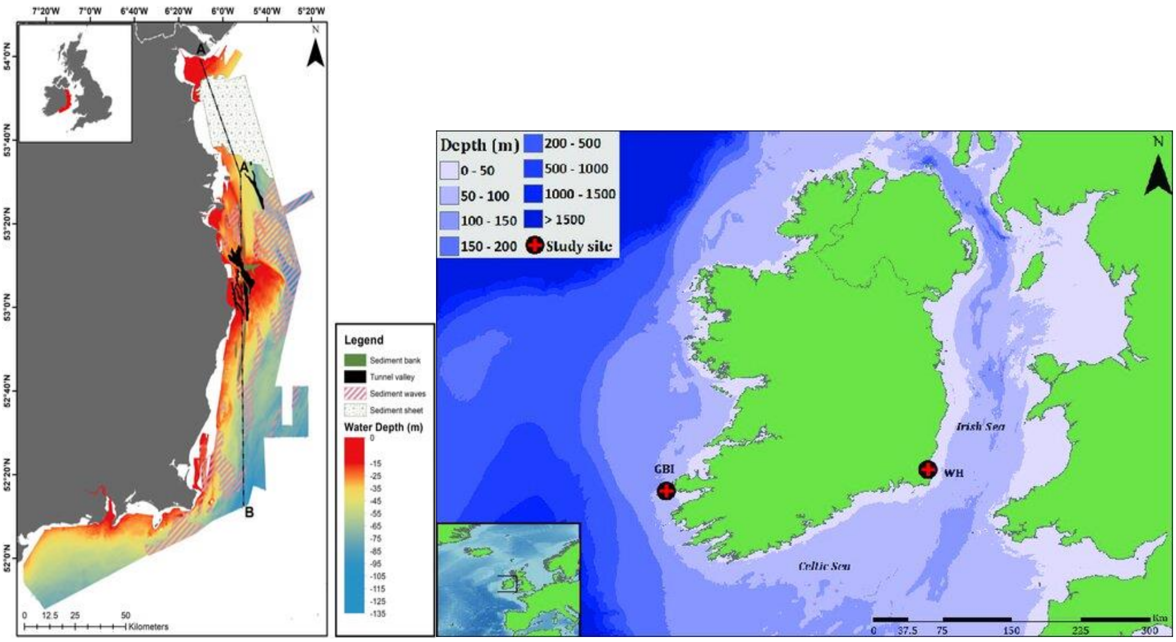


Figure 2-2 Water Depths on The Irish Coast from [10] & [12] © CC BY 4.0

Other geological constraints in the Irish sea include active seabed processes which may remove sediment from around the foundation of a non-floating wind turbine [10].

2.1.3 Economic Factors

The cost associated with the installation of wind turbines is high and as such requires significant investment. Cost is likely one of the largest barriers to wind turbine installation with the private sector unlikely to want to bear long term burden of the initial cost. Government support is therefore essential to incentivise the creation of new offshore wind farms [13]. Offsetting the installation cost, offshore farms have higher capacity factors and can therefore generate more power than onshore turbines [13]. The economic feasibility of offshore wind turbines may be determined by their lifecycle cost including the conception, design as well as potential dismantling costs [14].

The potential economic benefits of offshore wind turbines is huge. The gross value added to the irish economy in 2020 by onshore wind is estimated to be €431 million with a total of 5130 jobs in the sector and its associated supply chain [15]. As of 2018, the offshore wind industry in Ireland was severly underdeveloped yet also identified as being essential in meeting sustainable targets set by the government for 2030 [1]. As of 2024, only 1 out of 77 offshore wind projects in Ireland is in operation [16].

2.1.4 Social Factors

The creation of jobs is perhaps the main social benefit of offshore wind energy with a potential 40000 jobs added to the economy by 2040 [1]. However there is a potential social cost associated with the installation of offshore facilities.Disruption to the fishing industry due to loss of fishing grounds as well as the interruption of water based social activities may occur even when activities are allowed in the vicinity of offshore installations [17]. Some areas identified for use as possible wind farms significantly overlap with the lands of indigenous communities, such as the Sami people of Scandinavia who fought a legal battle with the Norweigian government due to the illegal installation of wind farms on lands traditionally used for reindeer herding. The Native American Tribal Council is currently calling for a pause on offshore development to examine the effects on native sovereignty in the US [18, 19].

2.1.5 Use of Weibull and Rayleigh Distributions for Wind Analysis

The weibull distribution can be used to estimate the probability distribution of a range of natural phenomena and has been used in wind analysis for some time [2]. It is given by the below equation, with being a scale factor in m/s and k being a dimensionless shape factor [3].

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp^{-\left(\frac{v}{c}\right)^{k}} (2.1)$$

It is possible to estimate the values of c and k for large regions through data analysis. The shape and scale factors for the UK have previously been estimated to range between 1.43-

2.23 and 4.76- 8.71m/s respectively, although the conditions in the UK and by extrapolation Ireland (This data was calculated using data from Northern Ireland also) are largely affected by the Atlantic ocean which has large decadal discrepencies in weather conditions [3]. Wind power density can be calculated using the weibull distribution [3]. The weibull distribution also has the added benefit of being able to predict zero or near zero wind speed probabilities although it may fit these values poorly [20].

The Rayleigh distribution is a simplified application of the weibull distribution where the shape factor is set to be equal to 2, and thus it is only necessary to calculate the scale factor meaning in turn that the only necessary data for calculation is the mean wind speed used to obtain the scale factor [21].

3 Results

3.1 Direct Data Results

This subsection contains data and plots obtained through direct analysis of results. A plot of the combined wind speed data from both sites is shown in Figure 3-1below. See Appendix A.1 & Appendix A.2 for individual plots of data from each site.

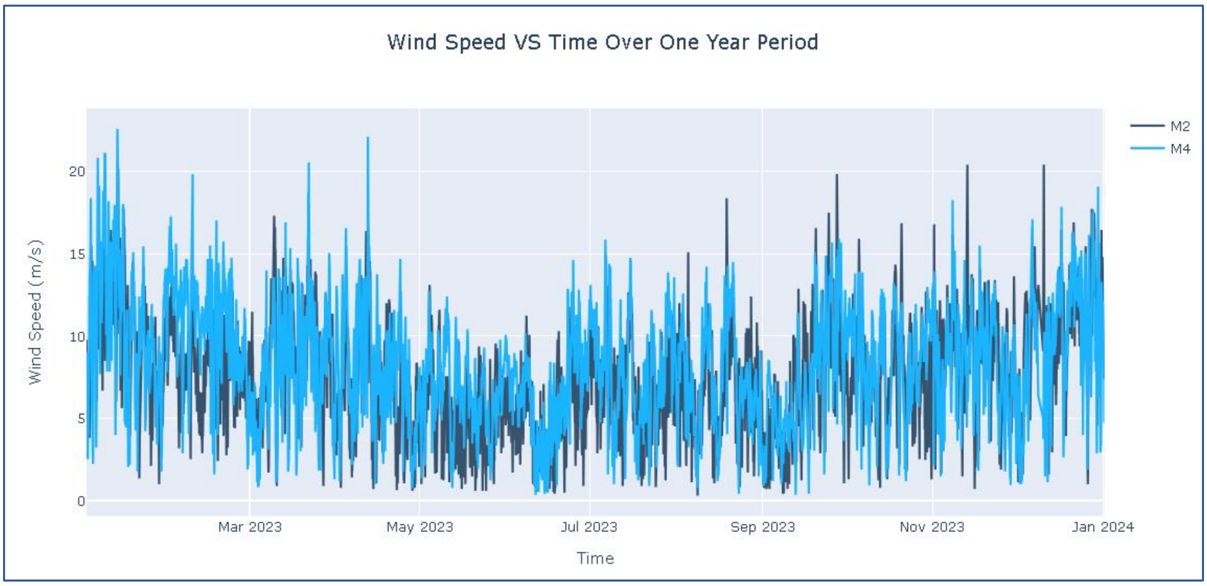


Figure 3-1 Combined Plot of Sustained Wind Speed Data from Site M2 and M4 Over One Year.

The weekly average wind speed is presented as a combined plot of data from both sites in Figure 3-2 below. Note that this plot was obtained using data in the ISO calendar format.

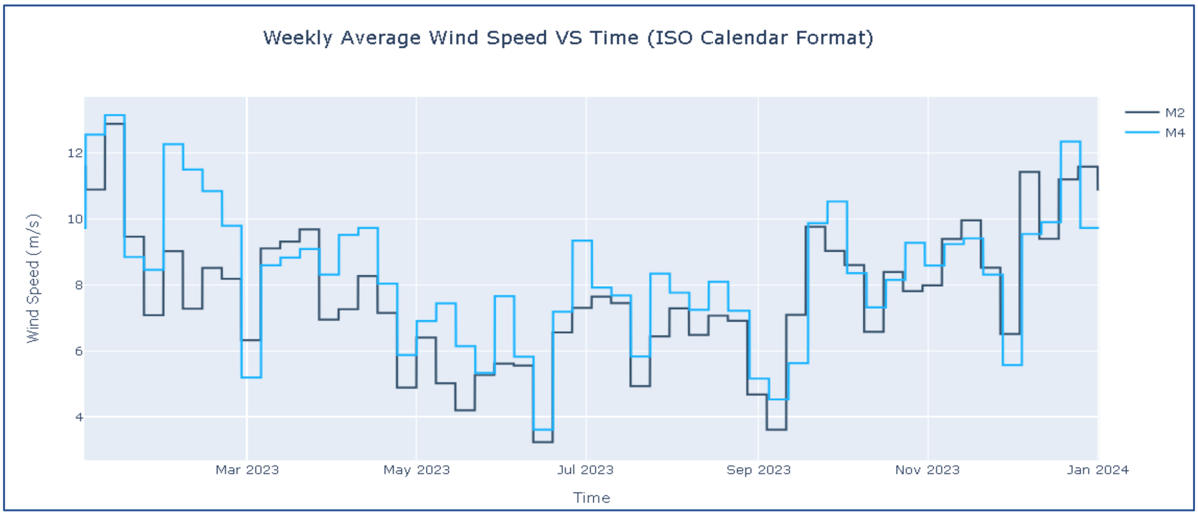


Figure 3-2 Weekly Average (ISO Format) Wind Speed Over One Year

The yearly average wind speed and standard deviation for both sites can be seen in Table 3-1 below.

Table 3-1 Average Wind Speed and Wind Speed Standard Deviation at Each Site

Site ID	U *(m/s)*	σ *(m/s)*
M2	7.64	±3.37
M4	8.30	±3.57

3.2 Method Of Bins

This section contains data and plots obtained using the method of bins to perform a statistical analysis of the wind data.

The mean wind speed, standard deviation and power resource in W/m^2 are given below.

Table 3-2 Average Wind Speed, Standard Deviation and Power/Unit Area, Method of Bins

Site ID	U *(m/s)*	σ *(m/s)*	P/A (W/m^2)
M2	7.6364	±3.3896	439.4181
M4	8.2871	±3.5595	546.5631

The histograms obtained through the method of bins for each site are plotted below with their associated probability density functions plotted as a line in Figure 3-3 and Figure 3-4. Note that due to starting the bins at zero, the PDF does not fit the histogram as well as it would if the bins started at the actual minimum value, although the difference is minimal. See Appendix A.3 for a graph automatically generated using seaborn for comparison.

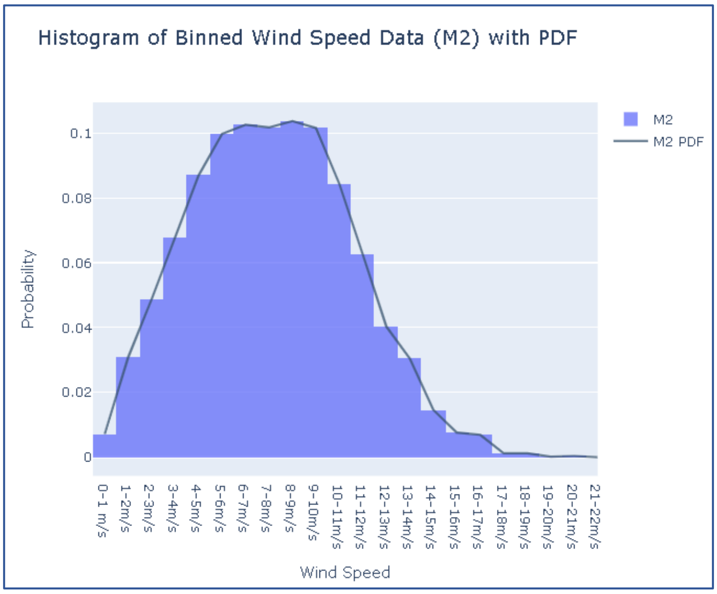


Figure 3-3 Histogram of Wind Speed Data from M2 with plotted PDF

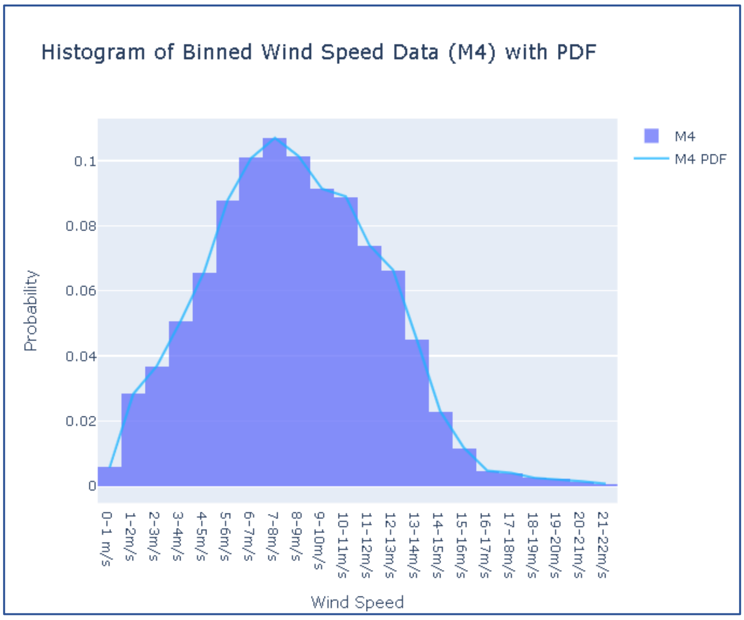


Figure 3-4 Histogram of Wind Speed Data from M4 with plotted PDF

3.2.1 Wind Direction

Data in wind speed magnitude bins of width = 2 from both sites are plotted with direction in Figure 3-5 and Figure 3-6 below. Bins of width = 2 were used as the percentage of wind speeds greater than 20m/s was too low to display on the plot with bins of width = 1 for M2.

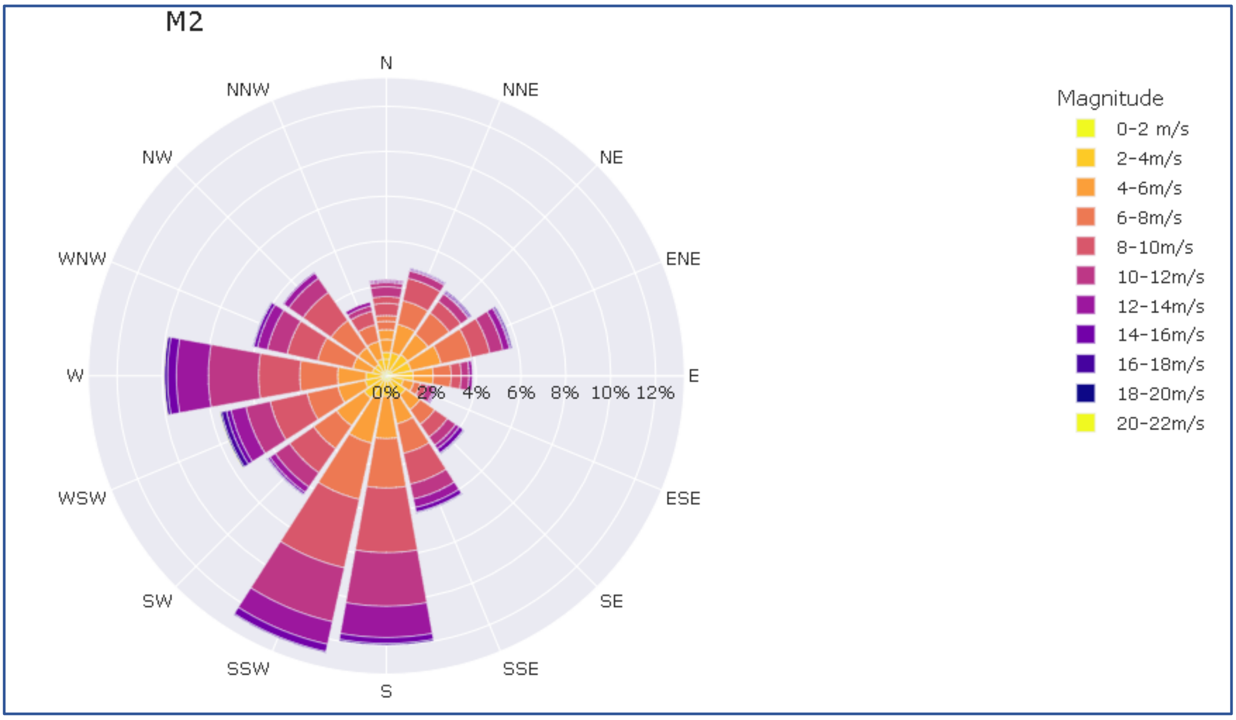


Figure 3-5 Wind Rose Plot for Site M2 Obtained From Directional Bins

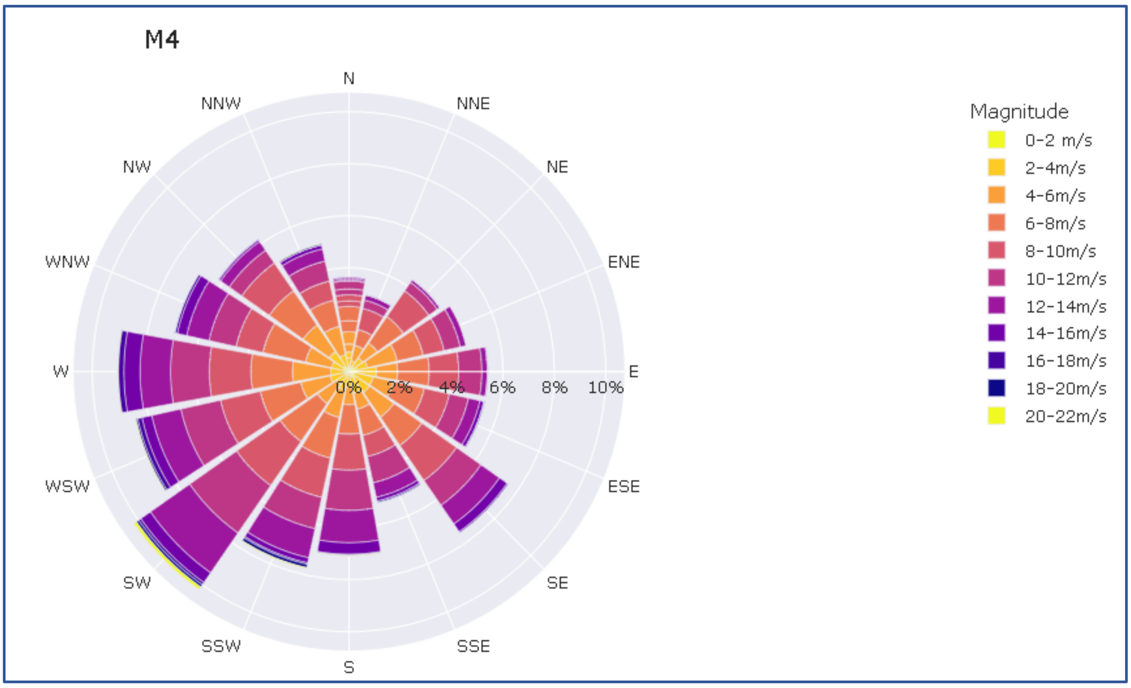


Figure 3-6 Wind Rose Plot for Site M2 Obtained From Directional Bins

3.3 Weibull and Rayleigh Distributions

Plots of the Weibull and Rayleigh PDFs as well as the PDF obtained from the method of bins are presented in this section. The cumulative distribution functions for each method are also presented. Note that the Weibull and Rayleigh Distributions were binned for plotting comparison. PDF, shape and scale parameters were calculated using the scipy.stats package.

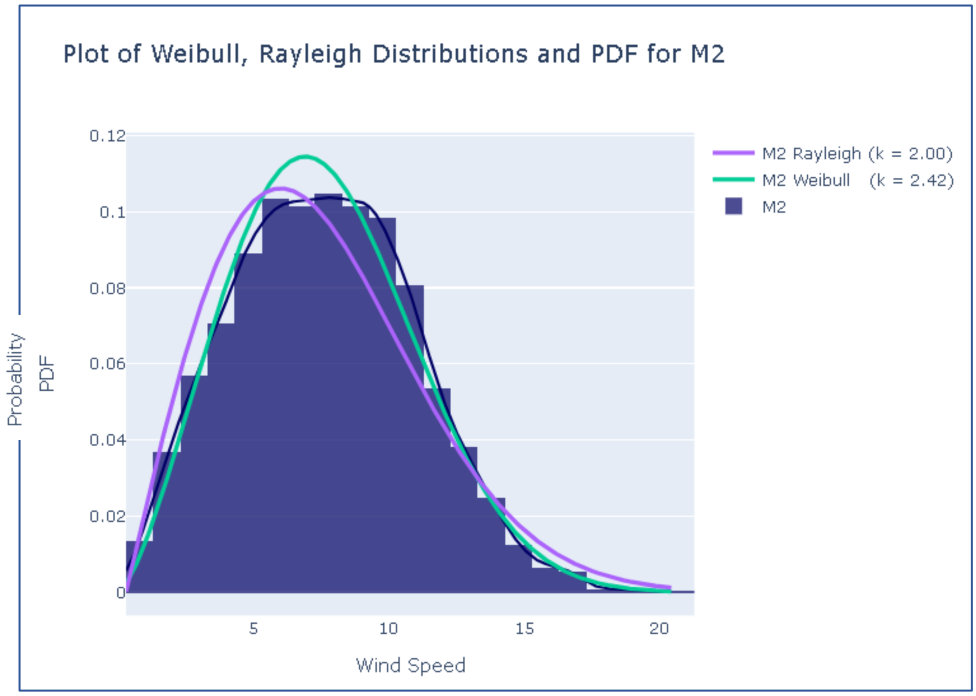


Figure 3-7 Weibull and Rayleigh Distributions VS Probability Density with Histogram (M2)

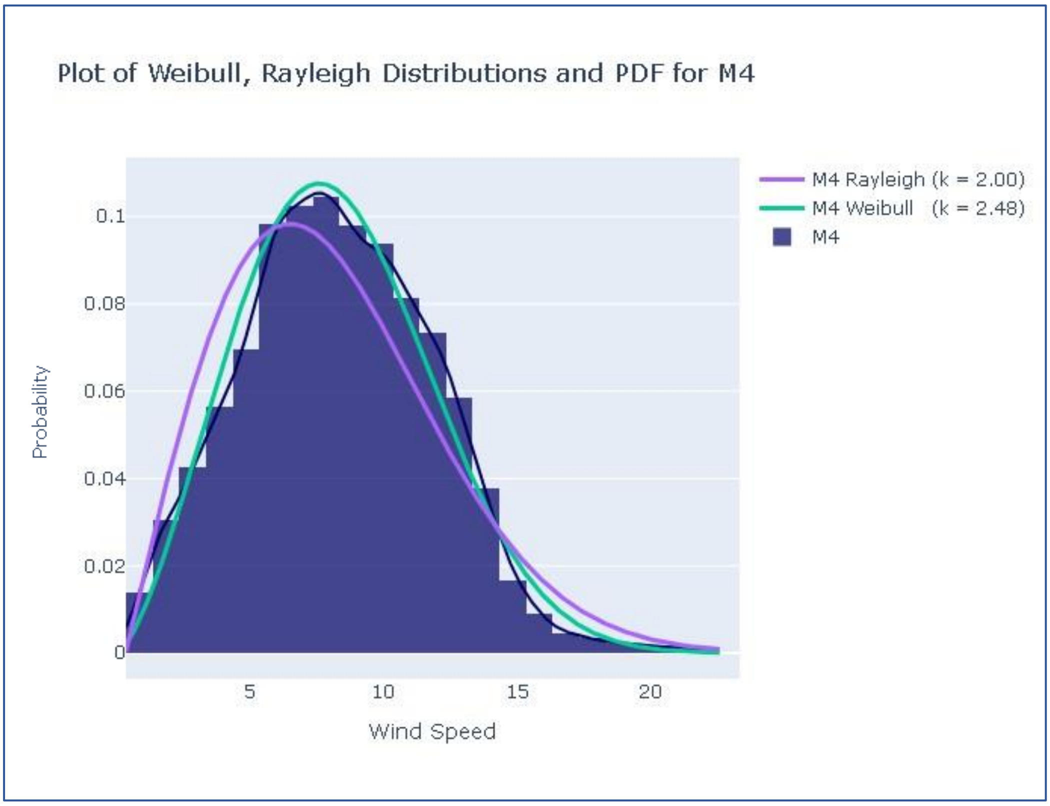


Figure 3-8 Weibull and Rayleigh Distributions VS Probability Density with Histogram (M4)

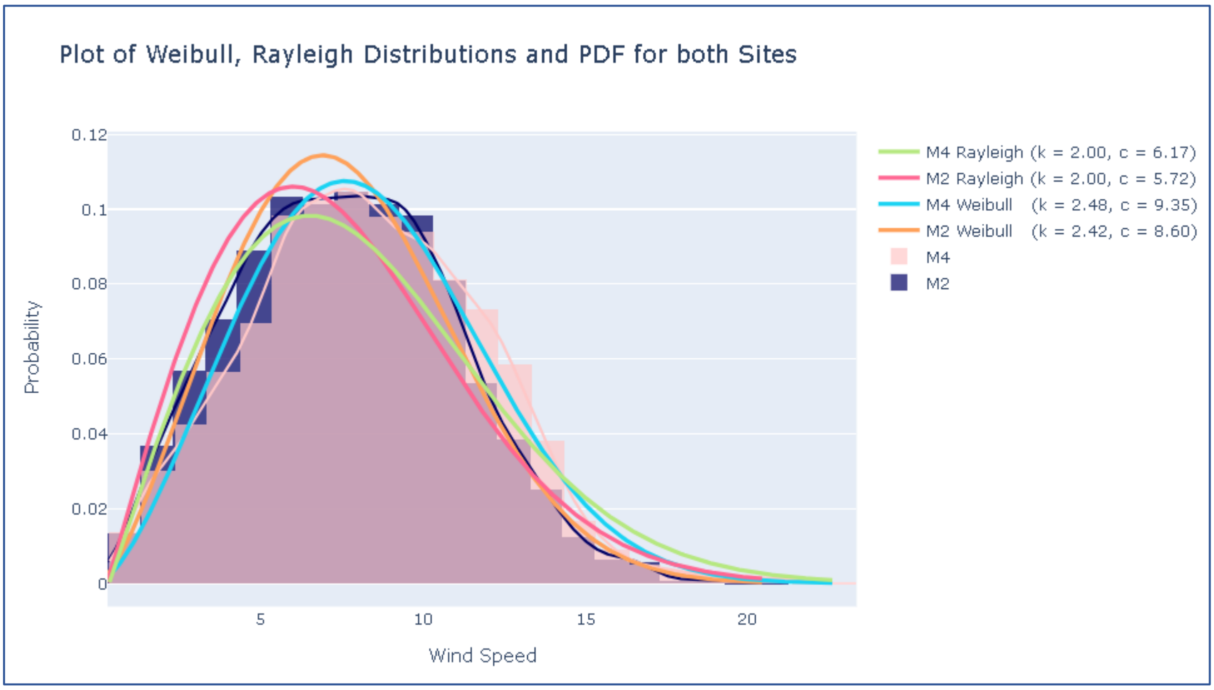


Figure 3-9 Combined Plot of All Distributions for Both Sites

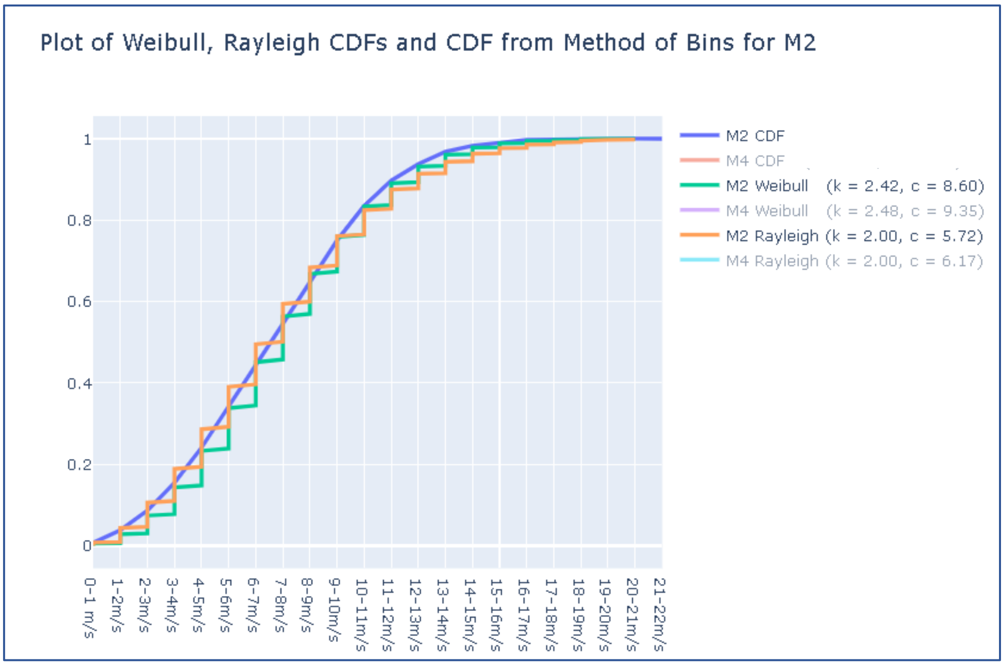


Figure 3-10 Plot of CDF functions for M2, Weibull and Rayleigh Values were binned for plotting

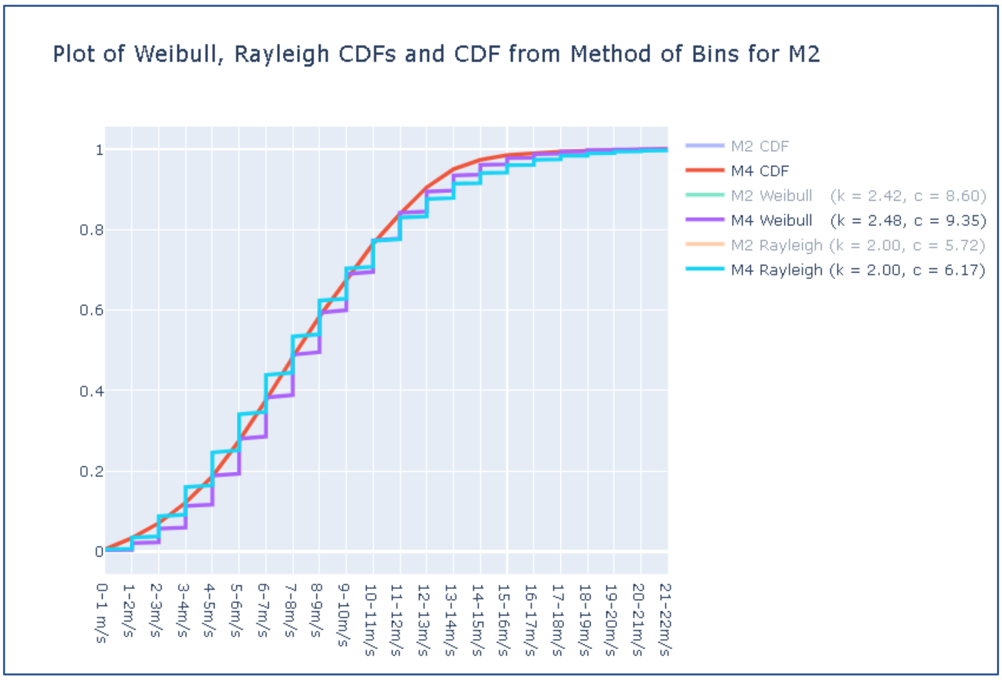


Figure 3-11 Plot of CDF functions for M4, Weibull and Rayleigh Values were binned for plotting

3.4 Power Obtainable by Theoretical 10MW Turbine at Sites M2 and M4

The latitude and longitude of both sites can be used to obtain an estimated elevation of 0m for both locations. The Average Hub Height windspeed for a 10MW turbine with 100m hub height can then be calculated using the average wind speed obtained using the method of bins earlier and the simplified power law [4]. H_{ref} has been set to 7.5m. The exact model of weather buoys used appear to be IL-4 navigation buoys, however exact specifications for this model could not be found. Metereological sensor heights appear to range between 5-10m. to estimate the hub height average wind speed and the theoretical max obtainable power resource for both heights, given by equation 3.1 below, where C_p is the Betz limit, rearranging the obtainable power equation for power/unit area [3]. A Hellman coefficient of 0.10 for ocean/sea surfaces [22] was used.

$$\bar{P}/A_{obtainable} = \frac{1}{2} \cdot C_p \rho v^3 \; (3.1)$$

$$\frac{U_2}{U_1} = \left(\frac{h_2}{h_1}\right)^a \; (3.2)$$

Table 3-3 Theoretical average power per unit area obtainable at 100m hub height at locations M2 and M4

Site ID	U_{ref} *(m/s)*	H_{ref} (m)	H_{hub} (m)	U_{hub} *(m/s)*	$\bar{P}/A$ (W/m²)
M2	7.6364	7.5	100	9.8942	350.03
M4	8.2871	7.5	100	10.7373	447.35

Using the power curve of a DTU 10MW wind turbine as an example, we can estimate that the sites would produce an average wind machine power $P_w(u_i)$ of around 7200kW at M2 and closer to 9800kW at M4. The DTU 10 has a cut in speed of 4m/s and cut out speed of 25m/s [14].

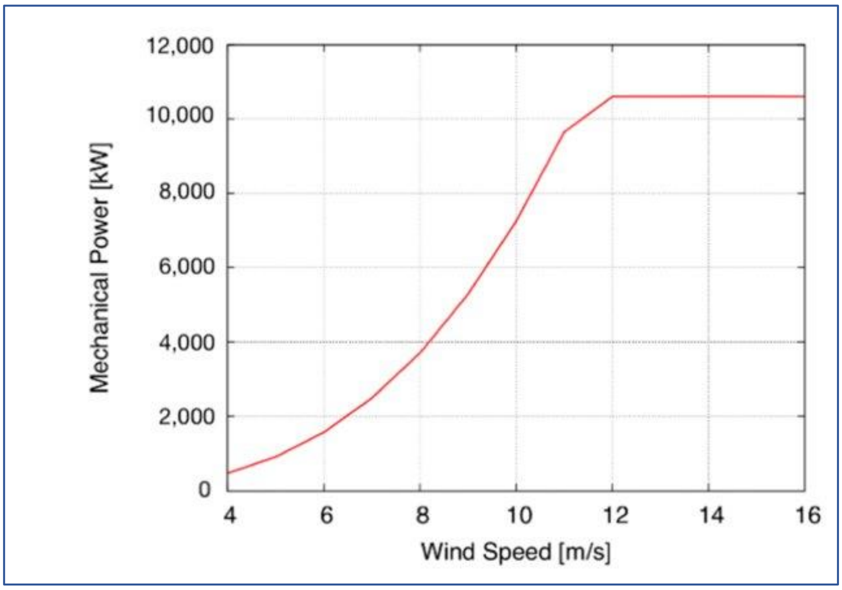


Figure 3-12 Power curve of the DTU 10MW wind turbine.

Using the Weibull and Rayleigh parameters calculated earlier it is possible to estimate some performance outputs for a theoretical installation of a DTU 10MW turbine In terms of time spent above the cut in speed.

Table 3-4 Performance Estimates for DTU 10MW

Rayleigh	M2	M4
k	2	2
c	5.72	6.17
%Time Above Cut Out	0.880	0.897
Weibull		
k	2.48	2.42
c (m/s)	9.35	8.6
%Time Above Cut Out	0.89	0.85

4 Discussion & Analysis

4.1 Analysis of Results

The results presented in the previous section clearly show that site M4 has a theoretically larger capacity for power generation than site M2, although both sites perform well. This is clearly represented by the yearly average wind speeds for both sites which were obtained through analysis of the direct data as well as using the method of bins with average wind speeds at M4 significantly higher than M2, although the standard deviation of wind speed at site M4 is also greater. From the wind rose plots for each site it can be ascertained that the wind speed direction at site M4 varies more than at site M2 where more than 20% of the winds recorded came from the south and southwesterly direction, this may indicate more consistent weather conditions at site M2. Site M4 also recorded a significantly higher maximum gust (31.03m/s) than M2 (26.58m/s). This is not surprising however as site M4 is located in the Atlantic ocean where the conditions are highly variable, whereas site M2 is in the Irish sea so wind losses likely occur over land.

The theoretical max obtainable power resource from the air at site M4 is much greater than M2 although both sites perform well. Using weibull and rayleigh estimates it was possible to estimate the time above cut in speeds at both sites from a theoretical 10MW turbine.

4.1.1 Weibull and Rayleigh Distribution Fit Error Analysis

The goodness of fit for the Rayleigh and Weibull distributions which were fitted to the data from both sites was evaluated using a Kolmogorov-Smirnov test. The results of the KS-test determined that for site M2, the Rayleigh distribution was a better fit, while results were inconclusive for site M4 with identical statistics recorded for both fits.

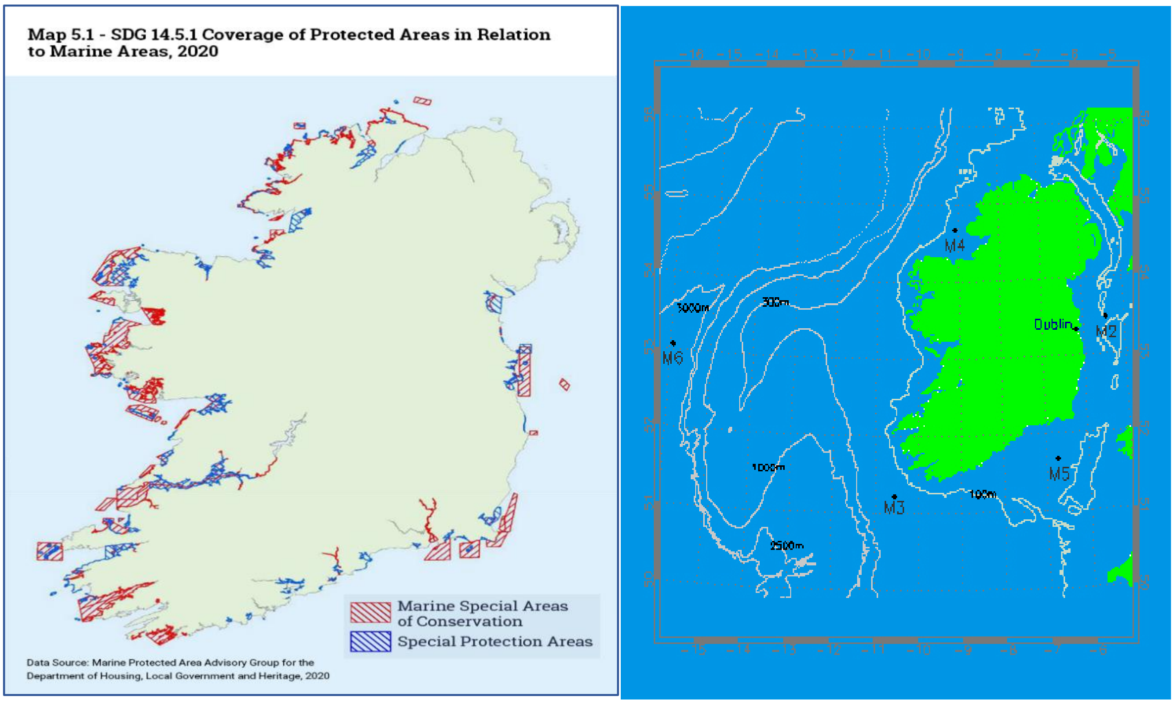
Table 4-1 Results of Kolmogorov-Smirnov Goodness of Fit Test

Site ID	Weibull KS-Statistic	Rayleigh KS-Statistic
M2	0.9928	0.9933
M4	0.9943	0.9943

Graphically, it is possible to reason that the Weibull Distribution may fit the data from site M4 better than the Rayleigh distribution. KS statistics are determined from the largest absolute difference between the Weibull/Rayleigh CDF and the actual CDF of the underlying data. It is possible that both models produced the same largest maximum difference. The results of the KS test show that all of the models are acceptable fits with high performance. The plots presented in the previous section show the binned CDF's but the values used to calculate the KS statistics were not binned. Using the Weibull and Rayleigh distributions the probability of zero or near zero wind can be estimated. This is not possible with the method of bins which in the form used here can only estimate the combined probability of winds between 0-1m/s.

4.2 Discussion of Environmental & Social Factors

The vicinity of site M2 to Dublin, the capital of Ireland and a shipping port, where there is likely greater sea vessel activity than near site M4, means that the impact of the installation of a turbine here on shipping, recreational and ferrying activities should also be assessed. The disruption to marine life also needs to be assessed as site M2 is located near to an area of special marine conservation.



A) b)

Figure 4-1 Maps of conservation areas on the irish coast a) and Marine weather buoys b)

Consultation with local fisheries as well as water sports clubs and marine conservation societies should be held prior to the installation of any offshore sites.

4.3 Suitability of M2 and M4 for Offshore Wind Turbines and Turbine Type

Using graphical water depth data from [10] and [12] comparing it to the positions of M2 and M4 it is possible to estimate that site M2 is in a region with a water depth of greater than 50m although regions with shallower water are nearby and similar wind speed distributions may exist at these locations. The region surrounding M2 is likely to be the better choice for the installation of a fixed foundation. The depths at site M4 almost certainly neccesitate that a floating offshore turbine be used. Both sites could be used for a 100m hub height 10MW turbine although the higher average wind speeds and higher average obtainable power, as well as obtainable wind machine power at site M4 make it the better candidate overall for pure energy production. The statistical analysis done is somewhat inconclusive, but based on rayleigh distribution estimates it appears that site M4 is the better site overall for a 10MW turbine as it spends more time above the cut in speed.

4.4 Limitations

There are a number of important limitations to consider when evaluating the contents of this report. The average power resource estimations in this report were obtained through relatively simple calculations and may not be representative of the actual average wind power resource at hub height for the sites, which will likely be lower than the the theoretically obtainable power based on the Betz limit. Furthermore the average wind speed was calculated using reference height equations (simplified power law), and may not represent the actual average windspeeds at hub height for sites M2 and M4. The theoretical maximum average power in the wind was not calculated.

Conversion of average wind speed from a reference height to a hub height of 100m was done using the previously obtained method of bins average value alone, which may introduce some error. Converting all of the wind speed values and then recalculating the average wind speed for a hub height of 100m might produce more accurate results.

An indepth analysis of the specific real world economic and social factors relative to the sites to consider as well as the potential lifecycle cost of a turbine at either of the locations is similarly not addressed in this report and so the exact economic and social viability of wind turbines at either site is not certain.

5 Conclusions

Both of the sites assessed are suitable for the installation of offshore wind turbines, with site M4 having greater potential from a pure energy generation standpoint, although both sites may perform similarly at the estimated average wind speeds obtained with a 10MW wind turbine of 100m hub height. Based on power alone, M4 is the better site, however the choice of which site is better suited to the installation of a wind turbine would likely come down to economic viability rather than pure energy production, which was not estimated in this report. The water depth at M4 necessitates the use of a floating offshore turbine.

Environmental and social considerations also necessitate that local community groups and businesses that may be affected by the installation of wind turbines be consulted before a turbine is installed at either location, especially at M2 which is nearer to a major port and marine conservation areas.

Analysis of the wind data obtained showed that both sites have wind distributions that can be accurately estimated using the Weibull and Rayleigh distribution, although the distributions are a better fit for site M4 than they are for site M2. Direct data analysis and the method of bins also produced similar results providing a degree of confidence in accuracy of the values of average wind speeds obtained.

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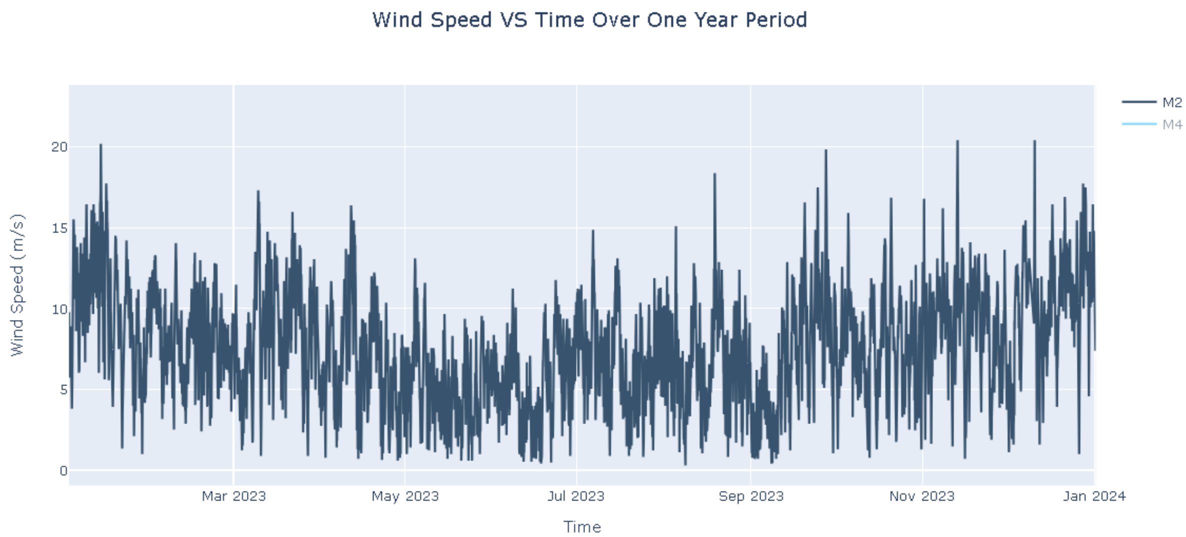
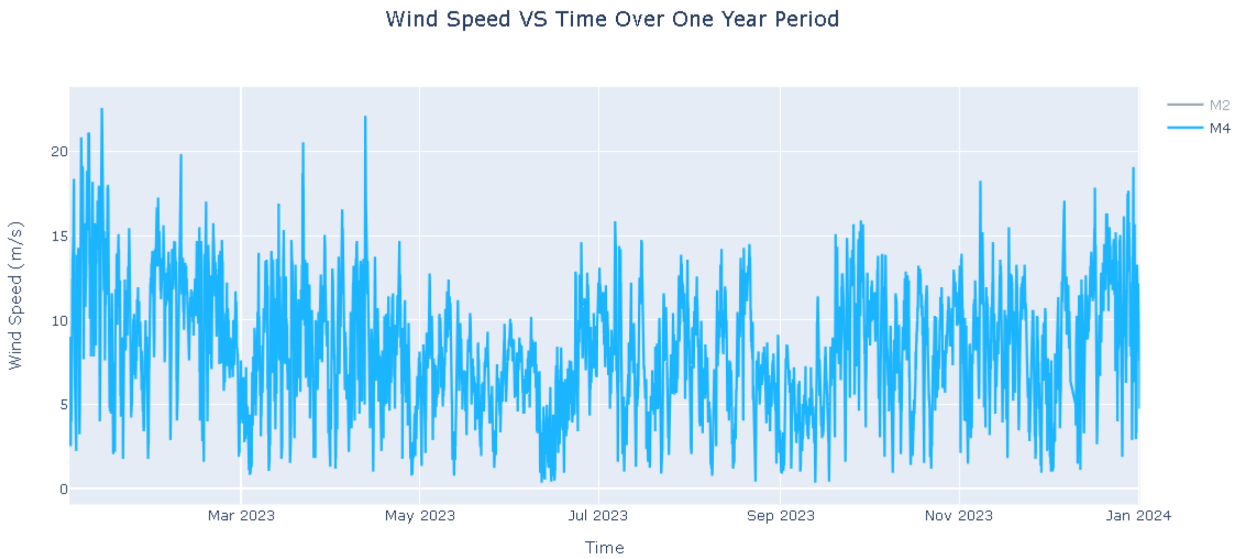
Appendix A Graphs and Plots

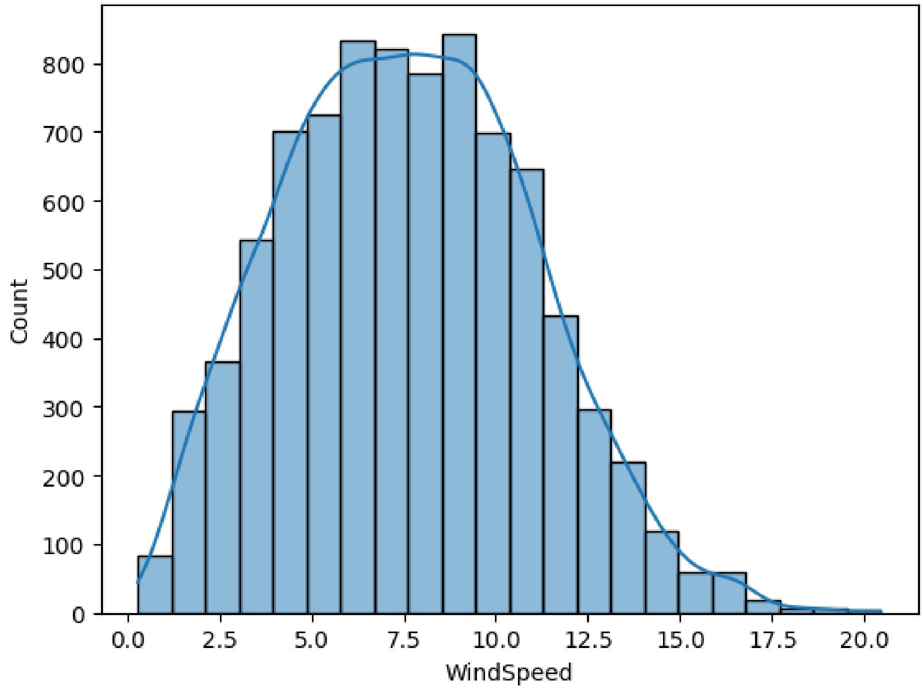
Appendix A.1 Recorded Sustained Wind Speeds Over One Year at M2



Appendix A.2 Recorded Sustained Wind Speeds Over One Year at M4



Appendix A.3 Wind Speed Histogram with PDF from Seaborn (M2)



Appendix B Method of Bins Analysis

Appendix B.1 Method of Bins Data (M2)

midpoint	freq	m*f	m^2*f	U	(m-U)^2	n(m-U)^2	STD Dev	m^3 f	P/A
0.5	61	30.5000	1860.5000	7.6364	50.9287	3106.6489	3.3896	7.6250	439.4181
1.5	264	396.0000	104544.0000		37.6558	9941.1327		891.0000	
2.5	417	1042.5000	434722.5000	Freq Sum	26.3829	11001.6862		6515.6250	
3.5	580	2030.0000	1177400.0000	8561.0000	17.1101	9923.8436		24867.5000	
4.5	744	3348.0000	2490912.0000		9.8372	7318.8841		67797.0000	
5.5	854	4697.0000	4011238.0000		4.5643	3897.9502		142084.2500	
6.5	878	5707.0000	5010746.0000		1.2915	1133.9187		241120.7500	
7.5	871	6532.5000	5689807.5000		0.0186	16.2127		367453.1250	
8.5	888	7548.0000	6702624.0000		0.7457	662.2247		545343.0000	
9.5	870	8265.0000	7190550.0000		3.4729	3021.4084		745916.2500	
10.5	722	7581.0000	5473482.0000		8.2000	5920.4129		835805.2500	
11.5	534	6141.0000	3279294.0000		14.9272	7971.0995		812147.2500	
12.5	345	4312.5000	1487812.5000		23.6543	8160.7291		673828.1250	
13.5	260	3510.0000	912600.0000		34.3814	8939.1697		639697.5000	
14.5	125	1812.5000	226562.5000		47.1086	5888.5696		381078.1250	
15.5	65	1007.5000	65487.5000		61.8357	4019.3199		242051.8750	
16.5	59	973.5000	57436.5000		78.5628	4635.2067		265035.3750	
17.5	10	175.0000	1750.0000		97.2900	972.8996		53593.7500	
18.5	10	185.0000	1850.0000		118.0171	1180.1710		63316.2500	
19.5	1	19.5000	19.5000		140.7442	140.7442		7414.8750	
20.5	3	61.5000	184.5000		165.4714	496.4141		25845.3750	

Appendix B.2 Method of Bins Data (M4)

midpoint	freq	m*f	m^2*f	U	(m-U)^2	n(m-U)^2	STD Dev	m^3 f	P/A
0.5	48	24.0000	1152.0000	8.2871	60.6387	2910.6587	3.5595	6.0000	546.5631
1.5	241	361.5000	87121.5000		46.0645	11101.5564		813.3750	
2.5	315	787.5000	248062.5000	Freq Sum	33.4904	10549.4682		4921.8750	
3.5	432	1512.0000	653184.0000	8534.0000	22.9162	9899.7990		18522.0000	
4.5	561	2524.5000	1416244.5000		14.3420	8045.8774		51121.1250	
5.5	751	4130.5000	3102005.5000		7.7679	5833.6581		124947.6250	
6.5	861	5596.5000	4818586.5000		3.1937	2749.7583		236452.1250	
7.5	914	6855.0000	6265470.0000		0.6195	566.2284		385593.7500	
8.5	866	7361.0000	6374626.0000		0.0453	39.2575		531832.2500	
9.5	780	7410.0000	5779800.0000		1.4712	1147.5033		668752.5000	
10.5	760	7980.0000	6064800.0000		4.8970	3721.7080		879795.0000	
11.5	632	7268.0000	4593376.0000		10.3228	6524.0161		961193.0000	
12.5	567	7087.5000	4018612.5000		17.7486	10063.4768		1107421.8750	
13.5	386	5211.0000	2011446.0000		27.1745	10489.3425		949704.7500	
14.5	196	2842.0000	557032.0000		38.6003	7565.6566		597530.5000	
15.5	100	1550.0000	155000.0000		52.0261	5202.6115		372387.5000	
16.5	40	660.0000	26400.0000		67.4519	2698.0776		179685.0000	
17.5	34	595.0000	20230.0000		84.8778	2885.8441		182218.7500	
18.5	21	388.5000	8158.5000		104.3036	2190.3755		132964.1250	
19.5	17	331.5000	5635.5000		125.7294	2137.4001		126052.8750	
20.5	12	246.0000	2952.0000		149.1552	1789.8629		103381.5000	
21.5	6	129.0000	774.0000		174.5811	1047.4864		59630.2500	