University of Exeter coursework header sheet

CSM3403 Renewable Energy Dissertation (T, TERM2 2015/6)

031299

1023089

630032145

Coursework: Dissertation (T) Peter Connor

Submission Deadline: Mon 25th Apr 2016 12:00

Personal tutor: Professor Lars Johanning

Marker name:	N/A
Word count:	9525

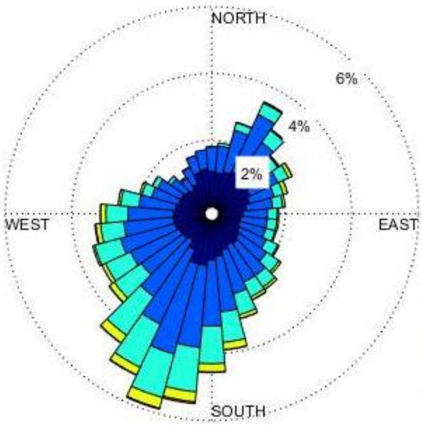
First marker's comments	Indicative mark
Second marker's comments	Second mark
Moderator's comments	Agreed mark

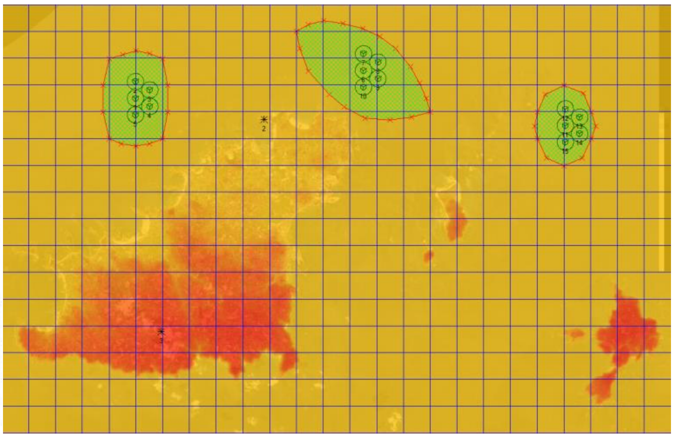
An Offshore Wind Resource Assessment for Guernsey

Student: Thomas Newitt

ID: 630032145

Supervisor: Richard Cochrane





Contents

List of Figures

List of tables

1. Acknowledgements

I would like to thank Richard Cochrane for the assistance given through out the making of this dissertation. I'm very grateful for the oppurtunity the Guernsey Renewable Energy Team have given me, to produce something for Guernsey in a field of interest for myself.

2. Abstract

This dissertation encompasses a Wind Resource Assessment (WRA) for the proposed offshore wind farms off the coast of Guernsey, a Channel Island in the English Channel. It's done using four met masts across the Channel Islands and produces wind speed averages for the offshore environment. This assessment uses a Measure-Correlate-Predict method to generate a longer-term resource prediction of a complete 3-year dataset. It also uses a numerical modelling method on WindFarmer to calculate a wind flow model around Guernsey and a conceptual model to produce another estimate of a general offshore wind resource.

3. Introduction

3.1 Energy in Guernsey

The Channel Island is just over 63km^2 with a population of 62,711 as of March 2014 (Guernsey facts and figures, 2015). The sources of electricity generation on the island are 6 diesel generators and 3 diesel powered gas-turbines, with respective cumulative ratings of 81.9MW and 50MW (Policy Council, 2014). These two types of diesel fuelled power generators both operate with a high carbon intensity and cost approximately 9.8p/kWh and 32p/kWh to run, the average of the electricity sold being 14.38p/kWh. In the financial year between March 2014 and 2015 the island saw 218,002MWh units of electricity imported whilst 156,426MWh were generated on the island. The Guernsey Electricity company rated the carbon intensity of their supply for the same financial year at 275g of CO_2 per kWh (Guernsey Electricity, 2016). The island's maximum electricity demand in the 2014 period reached 85MW, showing that the cheaper base electricity source of on-island generation is not enough to meet the demand the island experiences.

Relying heavily on imported electricity from the EU, the island first started importing electricity in November, 2000. The GJ1 cable, 60MW, connecting Guernsey to Jersey, was damaged in 2012 and repaired only a month later (Guernsey Electricity History, 2016). The original EDF1 cable connecting Jersey to the continent was damaged beyond repair in 2012, limiting electricity imports to the two Channel Islands to the sole remaining, 90MW, Normandie 2 cable. A 100MW replacement, Normandie 3, has recently been installed (2014) from France to Jersey with a second 100MW cable, Normandie 1, being installed in place of EDF1 in 2015-2016 (Jersey Electricity, 2016). Without the access to the French electricity grid there huge stresses in reaching the island's demand with clean and cheap electricity. The GF1 is being considered and the GJ2 could potentially be implemented in 2016.

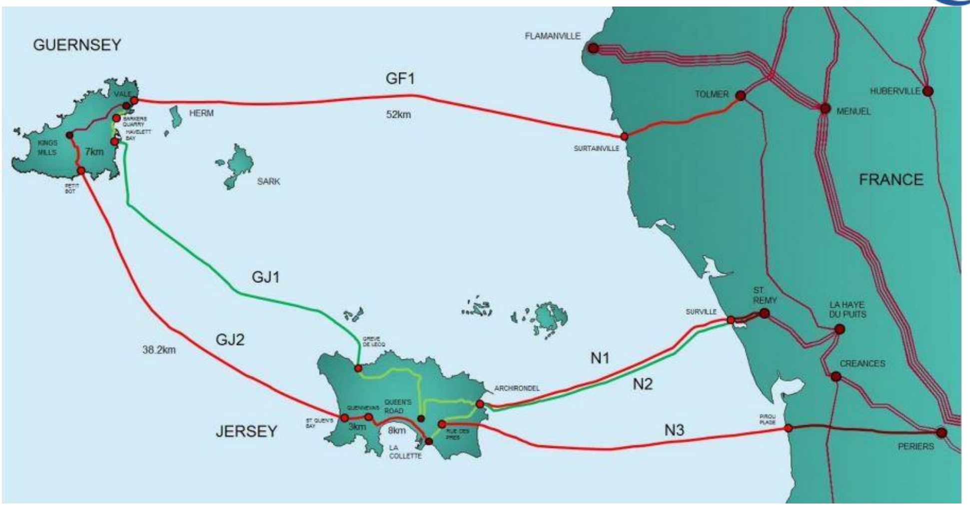


Figure 3-1: A map of current and potential interconnectors between the islands and France. (Policy Council, 2014)

Given the prices of the electricity produced by the island, looking for a cheaper, locally provided electricity resource is a sensible solution to filling the energy demands for occasions when access to the continental electricity grid is limited, whether based on the lack of connection or supply. Subsidised electricity for existing offshore wind projects in the UK's new Contracts for Difference (CfD) programme is marginally cheaper than the average generation cost of £143.8/MWh that was originally given as a base amount, ranging from £114.39/MWh to £119.89/MWh (HM Government, 2015). The limitations currently on development of offshore wind lying mainly in the depths of the coastal areas surrounding the island, varying from 45 to 50 metres of depth within the 5 mile limits of Guernsey in the proposed area for the offshore wind farm.

3.2 Current development of Renewable Energy

GRET has shown interest in developing a wide renewable energy portfolio to decrease the reliance on imported electricity and reducing the carbon intensity of the current generation supply. This is largely through technologies based on marine platforms, taking advantage of the coastal waters and the lack of available onshore resources.

Many reports and consultancies have been published in regard to the development of renewable energy for the island. Groups of students from both the universities of Exeter and Plymouth produced reports on the potential benefits marine renewable energies. In 2013 Exeter students identified and proposed two more sites and one variation on top of 3 reviewed sites to GRET (Renewable Energy Students, 2013).

There have been consistent mentions of the development of an initial 30MW offshore wind farm as a short term option and the potential of a larger offshore wind farm that exceeds the territorial water of Guernsey. These would both assist the island, with the second requiring a further increase in transmission between the islands on top of the existing GJ1 cable. All the sites suggested previously would be able to accommodate an initial 30MW project. The depths of water aren't necessarily too deep for fixed foundation turbines, with Beatrice wind farm being installed in 45m depths with jacket foundations (OWEC, 2013) off the coast of Scotland.

The aim of this report is to produce more information on the resource available to the island, as an initial offshore wind resource assessment. This will be carried out through the analysis of onshore meteorological masts (met masts) and modelling the onshore resource into the offshore environment. There is also a room in this assessment for the re-analysis of the short-term data; to measure, correlate and predict (MCP) future wind estimates in this climate against long-term data.

4. Literature Review and Methodology

The literature review encompasses a view into the varied methods that could be used to complete the study. The methods outlined in this chapter are not necessarily the paths taken but should give some context on the different outcomes that could be expected if they were. The literature reviewed was mainly online journals and articles concerned resource analysis and modelling.

The main sources of information were online journals and documents released by various organisations related to the industry and popular science journals. The University of Exeter library in Penryn also provided useful and contextual resources, on wind resource assessments and general offshore engineering.

A lot of context was also found in regards to the GRET site and project from previous documentation written by Marc Staddon and the Aquatera consultancy performed in 2014, as well as the group efforts of the Renewable students from Exeter University.

4.1 Wind Resource Assessment

This wind resource assessment's main purpose is to provide a base of information for assessing the Annual Energy Production (AEP) of the offshore wind farm sites. First an observation of the met mast and how its surrounding topography and terrain effect that measurement should be carried out, otherwise the estimate both at the hub height could be inaccurate. Correctly assessing the wind from the met masts will also assist in accurately modelling the wind flow from met mast points to the potential wind farm sites correctly, as the wind speed at hub height and general availability will have been extrapolated to a truer extent. Met masts that largely differ with surrounding terrain and topography for different directions should have each direction extrapolated for that sectors independent surroundings rather than an entire average. Doing it well is essential for producing an accurate AEP for the sites. Due to the last few points the main areas for research in the WRA are the methods of Wind Flow Modelling and methods for extrapolation of wind speeds in elevation, for the respective onshore and offshore sites and hub heights of the various turbines.

Before carrying out the wind resource assessment and obtaining results the acquired data must be reviewed for erroneous data, validating the data for use in the assessment. Validation criteria should require average wind speeds to be below 30m/s and the standard deviation to be below 3m/s (Brower, 2012). The direction variable should maintain suitable values between 0 and 360 degrees.

4.1.1 Extrapolation and Wind Shear Profile

It's important to find the wind speeds at hub height at the met masts, its use is to obtain an average wind speed at the turbines height so that a basic Annual Energy Production (AEP) can be produced. The AEP can then be manipulated to produce a more accurate representation of the wind resource. To extrapolate with the most accuracy the effect of the surroundings on the wind speed and determining the size of the effect of this on the wind flow model need to be properly observed. This range of elevation in which the wind speeds are affected by the earth's surface, creating turbulence, is defined as the atmospheric boundary layer (ABL), 'typically the lowest kilometre of the atmosphere' (Met Office,2010).

A range of literature provides mainly three methods for extrapolating the wind speed, namely the logarithmic wind profile law, Hellmann exponential (also commonly known as the power law) and the Monin-Obukhov method (Bañuelos-Ruedas, Angeles-Camacho, and Rios-Marcuello, 2011). All three produce the wind speed at different altitudes with varying detail. The logarithmic wind profile law and Hellmann exponential have the benefit of being able to calculate more accurate wind speeds at a higher altitude based on producing shear factors/exponents calculated from measurements taken at two different heights. This is usually a useful technique as the extrapolation is not reliant on observing and assessing the effects of the topographical surroundings on the recordings of the met mast. Unfortunately none of the met masts at any of the sites measure the wind speed at two heights and so the wind speeds recorded will have to be extrapolated using topographical observations. Below are the equations for the logarithmic profile law (L) and the power law (R).

$$\frac{v}{v_0} = \frac{\ln(H/z_0)}{\ln(H_0/z_0)} \qquad\qquad \frac{v}{v_0} = \left(\frac{H}{H_0}\right)^{\alpha}$$

(Brower, 2012)

The Monin-Obukhov method is a very accurate method that is particularly good for one-off calculations for extrapolating the wind speed in elevation. It utilises a ‘virtual temperature’, the heat flux at the surface of the earth and the friction velocity of the surface to model ‘the vertical behaviour of nondimensionalised mean flow and turbulence properties’ (Brower, 2012). These specific requirements that vary throughout the year and day, that are not available for this study, make it inappropriate for this study.

The chosen extrapolation technique will be used to calculate the shear of the site, showing a general change in wind speeds from the point of measurement to the range of hub heights for the specified wind turbines. The purpose of observing correct extrapolation exponents from the surroundings of the met mast are to also calculate a more accurate representation of the wind at that site. In short, to compensate for the surroundings and have a ‘true’ representation of the wind with the extrapolation.

Below is a table of a range of exponent values that should be used for extrapolating average wind speeds with the Power Law that flow over this sort of terrain and topography.

Terrain Type	Land Cover	Mean wind shear exponent (α)
Flat or rolling	Low to moderate vegetation	0.12-0.25
Flat or rolling	Patchy woods or forest	0.25-0.40
Complex, valley (sheltered)	Varied	0.25-0.60
Complex, valley (gap or thermal flow)	Varied	0.10-0.20
Complex, rigdeline	Low to moderate vegetation	0.15-0.25
Complex, ridgeline	Forest	0.2-0.35
Offshore, temperature	Water	0.10-0.15
Offshore, tropical	Water	0.07-0.10

Table 4-1: Shear exponent values for the power law

4.1.2 Turbulence Intensity

Turbulence Intensity (TI) is a calculated variable that will affect the wake dynamics of the wind farm and the type of turbine chosen for the site. The turbulence intensity from the met masts is calculated as the standard variation over the average wind speed for that same sample.

$$TI = \frac{\sigma}{\bar{v}}$$

The TI affects the turbine choice due to design constraints of turbines that wouldn’t be appropriate for a site of high TI. Turbine classes set out and standardised by the International Electrotechnical Commission (IEC) assist in making sure that the turbine will be suitably designed to withstand the conditions of the site. The turbulence conditions of the climate will impact the type of turbine available for the site, with the classes shown below. (IEC, 2005)

Wind Turbine Class	I	II	III
V_{ref} (m/s)	50	42.5	37.5
A (I_{ref})		0.16	
B (I_{ref})		0.14	
C (I_{ref})		0.12	

Table 4-2: Wind gust and turbulence standards set by the IEC for wind turbines

There are also various claims that the turbulence intensity calculated from the met masts can be used to represent the surface roughness surrounding the site and provide a more accurate extrapolation. Unfortunately the results vary largely and those found were mainly being used on onshore met masts with very simple surroundings, not suitable for sites with a large range of complex surroundings that the Channel Islands have.

However, the surroundings still have an effect on the measurement readings, with sheltering and obstacles causing turbulence in their wake. The TI values could be influenced greatly by these sorts of turbulent objects. The seasonal and daily changes in temperature can also have an impact on the turbulence of the wind. So the results given could have been impacted by a wide range of problems.

It's also important to show how the TI changes with wind direction, daily and seasonal variations for understanding how it might affect the readings and then the proposed offshore site over the day and year.

4.1.3 Weibull parameters and Frequency Distribution

The Weibull curve and parameters are formats of a frequency distribution, one that is used to portray the wind resource distribution, using strictly the Weibull parameters or from the frequency distribution of data resource provided. The Weibull shape parameter, k, is a non-dimensional shape parameter that defines the slope of the distribution of the wind resource. The Weibull scale parameter, A, is a value that represents the spread of the distribution (Bhattacharya, 2011).

The Weibull parameters will be calculated to give the data recorded at the met masts, characteristics that can be applied to an extrapolated wind speed at the same point, to give an estimated frequency distribution at that elevation. The validated datasets from the met masts can be put through the WBLFIT function available in MATLAB, producing a scale parameter, A, and the shape parameter, k.

The same process can be used on certain results of the wind flow models to present the characteristics of the offshore sites. The graph below, produced by the National Renewable Energy Laboratory, displays the variation in expected wind resource characteristics of onshore and offshore sites, with offshore sites having both higher scale and shape parameters.

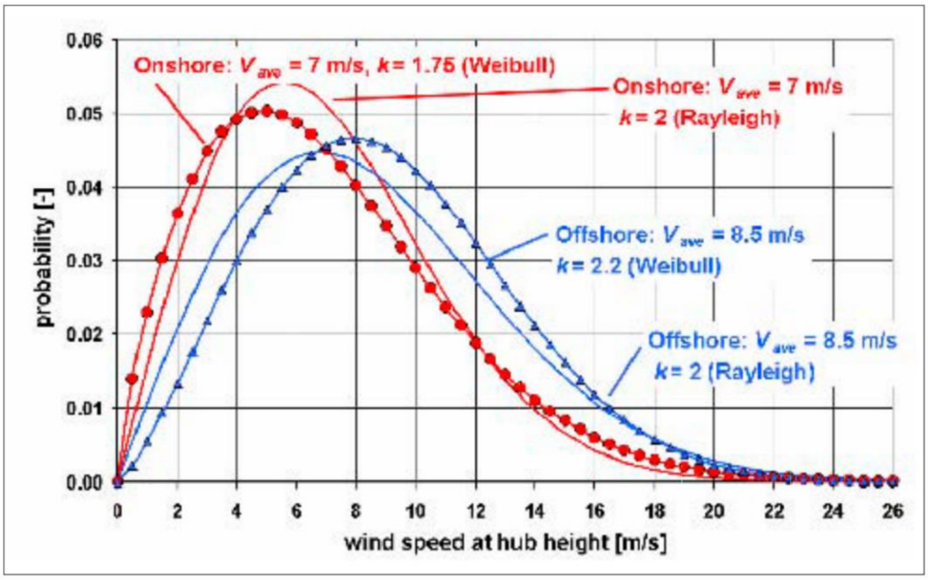


Figure 4-1: NREL figure

This NREL graph suggests that the average wind speed is the scale parameter in the Weibull distribution, however this is incorrect but a relationship can be resolved. A study on Weibull distributions for estimating the parameters showed that for shape parameters between 1.6 and 4 the scale parameters are 1.128 multiplied by the average speed (Bhattacharya, 2011).

The produced frequency distribution at hub-height can be combined with power curve of a wind turbine to produce an estimate of the net-yield for that turbine choice. The power yield for each rated speed is calculated by the amount of time in distributions wind speed bin (% probability multiplied by 8760) with the rated power of that same wind speed bin from the power curve. Doing the same process for all the wind speed bins will produce the total yield generated from that turbine for the site the Weibull distribution represents.

4.2 Measure Correlate Predict

Measure-Correlate-Predict methods produce linear correlation relationships used for deriving the long-term wind resource of a target met mast, with a recommended minimum of 12 months existing data, by comparing it against a reference met mast in the same or similar climate with long-term measurements. Both are compared and a relationship is drawn between them and applied to the reference met mast to provide a long-term frequency distribution of the site.

Garrad Hassan’s WindFarmer program, also being used for the wind flow modelling, has an MCP function that takes the speed and direction of the wind from two met masts and produces a resource distribution at the target site. The methodology choices in WindFarmer are either the Principle Component Analysis (PCA) method or the least squares method. Both produce a ‘general linear relationship between the site and reference wind speed’. WindFarmer includes an option to remove seasonal change within the MCP function for the incomplete data from the target site but the 3 complete years of data from Chouet will be used in this case and so the results will still include the seasonal changes in the predicted resource distribution (Hassan, 2009).

Methods for Measure-Correlate-Predict (MCP), most noticeably Principle Component Analysis and the least squares method, differ ‘fundamentally in the type of relationship established between the wind data’ of the reference and target sites (Carta Velázquez, and Cabrera, 2013). However, the main principle still stands that the greater the correlation between the two the better the result. Although suitable correlations can be found from differing heights, whether extrapolated or measured, using two met masts measuring at the same point above ground level (AGL) is preferred (Probst and Cárdenas, 2010).

4.3 Wind Flow Modelling

This modelling process is performed to determine the wind resource at the proposed offshore wind sites from the known wind resources at the onshore met masts. Modelling the wind from the 4 locations out to the site locations is recommended in any of 4 ways; conceptual, experimental, statistical or numerical modelling (Krueger, 2014). A preferred method would be to use the WAsP (Wind Atlas Analysis and Application Program) numerical model utilising the Jackson-hunt method.

The wind flow would be able to be modelled conceptually, based on changes to the wind as it flows from more onshore locations to offshore. The more met masts the conceptual model correlates with, the more acceptable the model would be as a method of identifying the wind resource offshore.

Experimental models could be used, incorporating scale models of the landscape and wind in a linear fashion from the source of the data to the sites in question, replicating real conditions of the offshore wind farm. Due to time constraints and a lack of skill and facilities to accommodate an experiment of this size, this is not an option that is entirely possible.

The popular numerical method, WAsP, utilises elevation data and surface roughness values representing the surroundings to calculate the flow of the wind across the terrain. The Jackson-Hunt method used in WAsP is portrayed below.

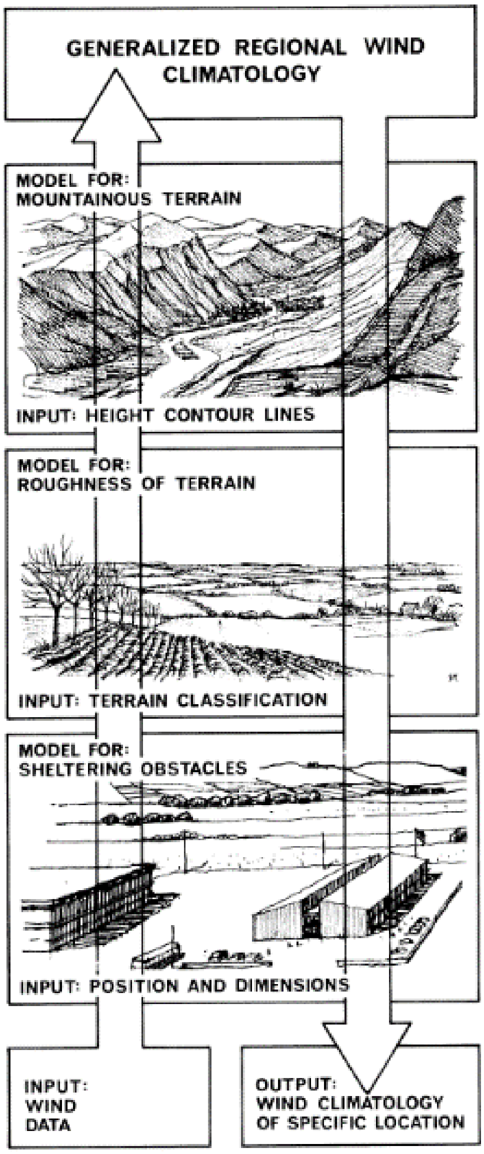


Figure 4-2: Illustration of the Jackson-Hunt method. (Brower, Vidal, and Beaucage, 2011)

A statistical model would be more useful in this scenario if the proposed site was onshore, as the principle is to compare met masts with similar surroundings in the proximity of the site, 'based entirely or mostly from on-site wind measurements' (Krueger, 2014). However, the Chouet met mast is positioned to be a closer representative of the resource offshore than the airport met masts, assisted by the surrounding low-lying terrain and immediate water. A statistical model for the Channel Islands could incorporate an offshore mast in another area or an onshore to offshore assessment from a similar scenario with a matching climate. It would be inherently important for the resources to be assessed for the regional wind systems to be similar. Use of measurements for planned wind farms in the surrounding areas between Normandy and Brittany would also be appropriate for this sort of model. This sort of statistical model is similar to the Measure-Correlate-Predict method mentioned previously.

Other methods would include Computational Fluid Dynamics, a large amount of time would need to be included to model the environment and there are better ways of performing this sort of model computationally. However, for exceptional instances of strong winds this would be a suitable method for modelling the conditions offshore.

An alternative to using WAsP is another numerical modelling program, generally used for much more than wind flow modelling, WindFarmer. WindFarmer's main method of generating a wind flow method is also through utilising WAsP, generating Wind Resource Grids (WRGs) that cover the area in question by simulating the flow over the roughness of the terrain. But there is another option of simulating the wind flow, with a simple flow model option in WindFarmers settings. It uses a range of inputs that are already being calculated in this report along with elevation data to calculate the flow of the wind from the met masts to the proposed sites mapped out in the software.

5. The Sites

The sites that provided the historical data all have different surrounding topographical features. For each site the intensity of the wind will be extrapolated to an elevated height using shear exponents dependant on the direction of the wind, as with each direction the topographical effects will be different.

So assessing the topography of the local areas around the sites will be an important factor in producing an accurate representation of the extrapolated wind speeds. The landscape will have an impact on the site with a distance up to 10 kilometers away (M. Ragheb, 2015) for simple terrain and 2km for complex terrain. Complex terrain can be defined as terrain that features significant variations in topography and terrain obstacles.

The topography and terrain of the area surrounding the sites will be classified as either simple or complex, but there is no black and white, and shear exponents can also represent a medium. The values will represent 30^{O} sectors around each mast, counting 12 observations. Each of these decisions on the values representing the sector areas has been justified but they are discretionary, having been valued from digital maps.

Each airport site has the following coordinates and altitude:

	Alderney	Guernsey	Jersey
Latitude	49.7067° N	49.4350° N	49.2081° N
Longitude	2.2144° W	2.6019° W	2.1953° W
Altitude	88m	102m	84m

Table 5-1: Met mast site coodinates and elevation

5.1 Alderney Aiport Met Mast

The airport in Alderney is in the South-West of the island with the airport terminal being directly 780m, 1.28km, 1.35km and 2km in Northerly, Easterly, Southerly and Westerly directions from the coast. The direction that the wind would take the furthest to travel in would from the North-East, travelling 4.6km across the island.

Direction of scope	Wind Shear Exponent (α)	Justification
360/0	0.12	Simple, rolling terrain from water
30	0.23	Simple, rolling terrain with small buildings from water
60	0.23	"
90	0.17	Simple, rolling terrain
120	0.25	Complex, ridgeline
150	0.25	"
180	0.25	"
210	0.25	"
240	0.25	"
270	0.25	"
300	0.25	"
330	0.25	"

Table 5-2: Shear exponents for Alderney.

5.2 Chouet Met Mast

From the coordinates given in communication with Peter Barnes, the met mast is supposedly positioned to the North of the island on Chouet headland at an altitude of 6m. Open Street Maps shows a rifle range just to the north, a 'loophole tower' further to the south and Mont Cuet recycling and landfill even further to the west. Chouet and the surrounding area are much lower than the rest of the island, shown below the table of exponent justifications.

Direction of surface	Wind Shear Exponent (α)	Justification
360/0	0.16	Simple, rolling terrain with no vegetation to immediate temperate water
30	0.17	Simple, rolling terrain to in temperate water
60	0.18	
90	0.18	"
120	0.23	Simple, rolling terrain with low urban impact
150	0.24	"
180	0.3	Simple, rolling terrain with urban conditions
210	0.23	Simple, open water from rolling terrain with moderate vegetation
240	0.23	"
270	0.23	Simple, rolling terrain with open water and distant urban conditions
300	0.16	Simple, rolling terrain with no vegetation to temperate water
330	0.16	"

Table 5-3: Shear exponents for Chouet

5.3 Guernsey Airport Met Mast

From the airport in Guernsey, straight lines in the Northerly, Easterly, Southerly and Westerly directions to the coast are 4.6km, 4.55km, 1.7km and 5.4km, centring the airport in the south of the island.

Direction of surface	Wind Shear Exponent (α)	Justification
360/0	0.25	Simple, rolling terrain with moderate vegetation
30	0.3	Simple, rolling terrain with urban impacts
60	0.3	"
90	0.25	Simple, rolling terrain with less urban impacts
120	0.25	Complex, slightly sheltered ridgeline with moderate vegetation
150	0.25	"
180	0.23	Complex, ridgeline with moderate vegetation and water
210	0.23	"
240	0.23	"
270	0.25	Complex/simple, rolling terrain with a ridgeline to water
300	0.19	Simple, rolling terrain with water
330	0.19	Simple, rolling terrain with water

Table 5-4: Shear exponents for Guernsey

5.4 Jersey Airport Met Mast

Jersey is the largest of the three islands, but the met mast is positioned further away from the proposed sites than any of the other sources. It's positioned so that it's directly 4.50km, 12.60km, 2.55km and 2.05km from the North, East, South and West coast.

Direction of surface	Wind Shear Exponent (α)	Justification
360/0	0.25	Rolling, ridgeline with moderate vegetation
30	0.3	Complex, immediate urban environment
60	0.27	Rolling, moderate vegetation
90	0.27	"
120	0.3	Complex, immediate urban environment
150	0.2	Rolling, moderate vegetation and water
180	0.3	Complex, immediate urban environment
210	0.3	"
240	0.25	Complex, ridgeline with moderate vegetation
270	0.23	Rolling, moderate vegetation and water
300	0.23	"
330	0.23	"

Table 5-5: Shear exponents for Jersey

5.5 Roughness Roses

From the justified wind shear exponents 'roughness roses' can be made to show how the roughness changes for each 30^{O} degree sector around the met masts. These are summaries of each site and make good comparisons for confirming that they are a valid representation of the varied terrain. The roughness roses are shown in the appendix 10.1 Roughness Roses.

5.6 Proposed Offshore Wind Farms

The sites for the proposed offshore are situated off the north coast of Guernsey, spanning from West of Chouet headland to the East, just North of Sark. There are four sites in total, three relatively close to the coast and one further out towards shallower water that is up to 2m deep, the Banc de la Schole. The three close to the coast highlight areas with a range of depths, up to 40m. The Chouet met mast is the closest measurement site.

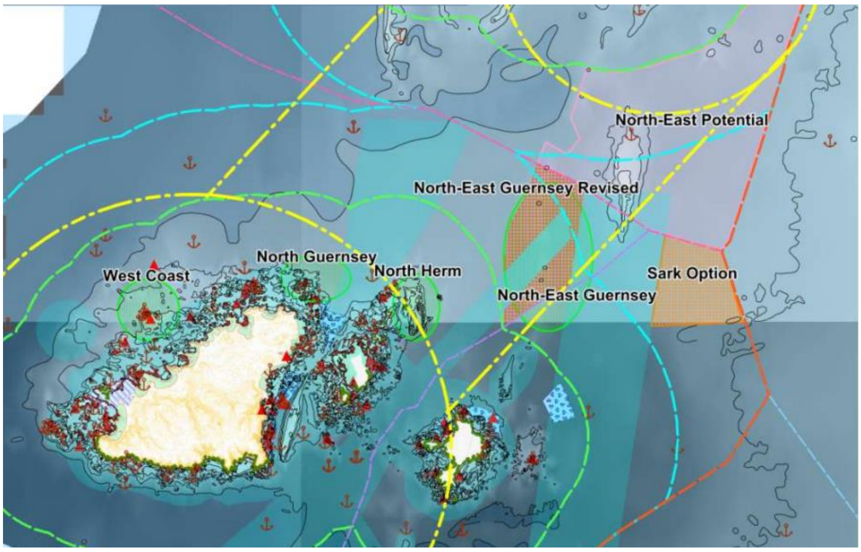


Figure 5-1: Original and suggested site from the Exeter students. (Renewable Energy Students, 2013)

The University of Exeter reviewed these sites in 2013, indicating that all the near coast sites would have a large visual impact on the surrounding coastline, with the turbines being within 3 miles of the coastline. The group also suggested two further sites off the north-east coast that would share waters with Alderney and Sark.

6. Wind Resource Assessment

Historical data for three met masts positioned at airports across the Channel Islands were acquired from Wunderground.com, consisting of the timestamp, wind speed and wind direction. The Guernsey Renewable Energy Team provided just less than 4 years of data from their met mast on Chouet headland at the North of Guernsey. Throughout this assessment the meteorological masts are referred to in short, as Alderney, Chouet, Guernsey and Jersey. The data recorded at the Chouet met mast was in minute averages, but was reshaped to the recommended 10 minute averages for the assessment. The data assessed from the airport met masts was given in half-hourly averages, not the recommended time intervals but they are more reference sites whereas although it's not the target site it's the closest and most representative of the offshore climate. It's assumed throughout this assessment that the measurements are taken from 10m AGL.

Throughout the majority of this dissertation throughout the data handling process from acquiring to publishing, there was a vast amount of learning to use MATLAB. The software had been used minimally before and the majority of the time was spent learning how to use it properly. Knowing what has been learnt, the entire process could be substantially shorter if repeated.

6.1 Data Recovery & Validation

The validation criteria given in the wind resource assessment part of the literature review and methodology were used to clean up the data being used in the wind resource assessment. The data recovered from the airports had a small amount of error with Alderney airport having 10 instances of data below 0 m/s (-9999km/h) Jersey airport having 25 instances of data below 0 m/s (-9999km/h) and 6 instances of data above a given offset of 30m/s. Guernsey airport provided data with 3 records of data above 30m/s. These records were removed from all calculations. All of the data provided by GRET for the Chouet met mast was within the validation boundaries specified. The overall data recovery instances for the three airports are shown below.

	Alderney	Guernsey	Jersey
Records Retrieved	75439	152997	150990
Records Validated	75406	152990	150963
Data Recovery (%)	99.956	99.995	99.982

Table 6-1: Data recovery for airport met masts.

6.2 Wind Shear Profile

The wind shear calculations were performed on all four met masts up to 110m, using the power law stated in the extrapolation methodology, utilising shear exponent values observed for the sites. The average shear for each site was produced by multiplying the shear for each direction by the frequency of the measurements of that direction and dividing the sum of this product, from all 12 directions, by the total number of measurements provided by the validated data. This produced the following four shear values.

	Alderney	Chouet	Guernsey	Jersey
Average Wind Shear Exponents	0.232	0.214	0.232	0.257

Table 6-2: Average wind shear exponents calculated for each met mast site

These average wind shear exponents can be then used in the power law to extrapolate the average wind speed for each site. These extrapolations can then make a wind profile graph, showing how the wind speeds increase with elevation. The following graph was produced using 5m intervals for the elevation in the power law.

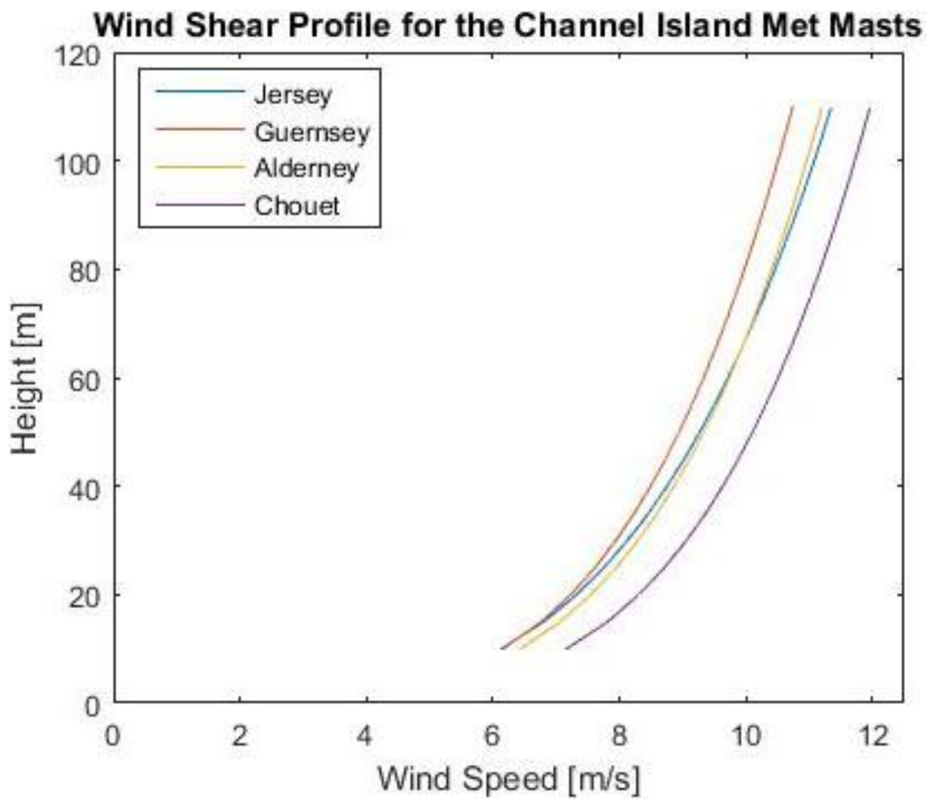


Figure 6-1: Wind profile for all four met masts

The wind shear and profile can be used to provide an estimate of the average wind speed at different hub heights. A table of the Annual Mean Wind Speeds (AMWS) extrapolated from the met mast's AMWS at 10m (AGL) to 90m and 100m, for all four sites.

	Alderney	Chouet	Guernsey	Jersey
AMWS at 10m (m/s)	6.42	7.16	6.15	6.13
AMWS at 90m (m/s)	10.69	11.46	10.25	10.78
AMWS at 100m (m/s)	10.96	11.72	10.50	11.08

Table 6-3: Annual Mean Wind Speeds for the four met masts from 10m AGL to 100m

6.3 Monthly Mean Wind Speeds

Monthly average data over the entire data series for each met mast produced graphs which showed obvious seasonal changes that would impact the volatility of the local electricity supply. These are given below, each representing the 10 years of data from the airports and the 3 complete years of data obtained from the Chouet met mast. The airport met masts show a more consistent monthly average output that could be down to the longer time period available to average. The monthly values generally portray higher values for the Chouet met mast, due to it being less sheltered, lower and closer to the sea, reducing applicable surface roughness and obstacles. This graph also shows how important it was to install this mast to record data closer to the proposed sites, there could still be potential for higher wind speeds with further, offshore resource measurement.

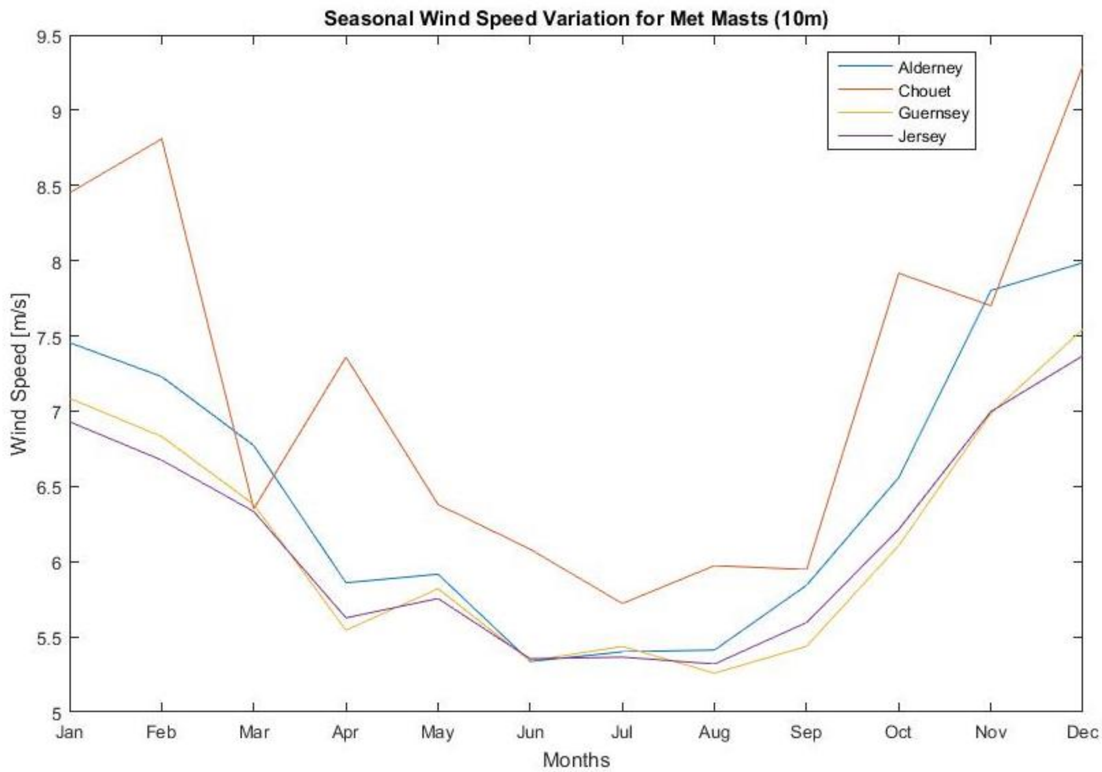


Figure 6-2: Seasonal variation of average wind speeds for all met masts, at 10m AGL

The graph indicates that Chouet has the highest averages but it also indicates that it has the largest seasonal variation as well, showing that the yield of any offshore wind farm could have a large variation in seasonal output. The minimum and maximum monthly averages for each met mast will be useful for determining the maximum and minimum monthly yield per year. These lower and upper figures are shown below. The full table of all the values are in the 10.2 - Monthly data.

		Met masts			
		Alderney	Chouet	Guernsey	Jersey
Monthly Averages [m/s]	Min	5.34	5.72	5.26	5.32
	Max	7.99	9.3	7.55	7.37

Table 6-4: Min and max monthly averages from the met masts

The annualized graph and figures are also useful for understanding which long-term wind measurements are the most similar to the Chouet met mast, to correlate the reference and target site and predict the long-term resource at the target site (Chouet). The graph shows that Alderney would be the best reference station for Chouet.

These variations are applied to the overall wind resource later by defining the max and min resources for each month.

6.4 Turbulence Intensity

Turbulence Intensity was calculated per direction for the sites with the average standard deviation and mean for all the measurements in each sector. These results made turbulence intensity roses which were hopefully going to be used to derive the surface roughness around the site, unfortunately there was no correlation with the actual site topography and terrain for the sites. The turbulence intensity for the Chouet met mast shows the issues below. The sectors facing offshore are generally less than the onshore sites and the greater reduced TI at $0^{O}/360^{O}$ could be the sheltering from the rifle range.

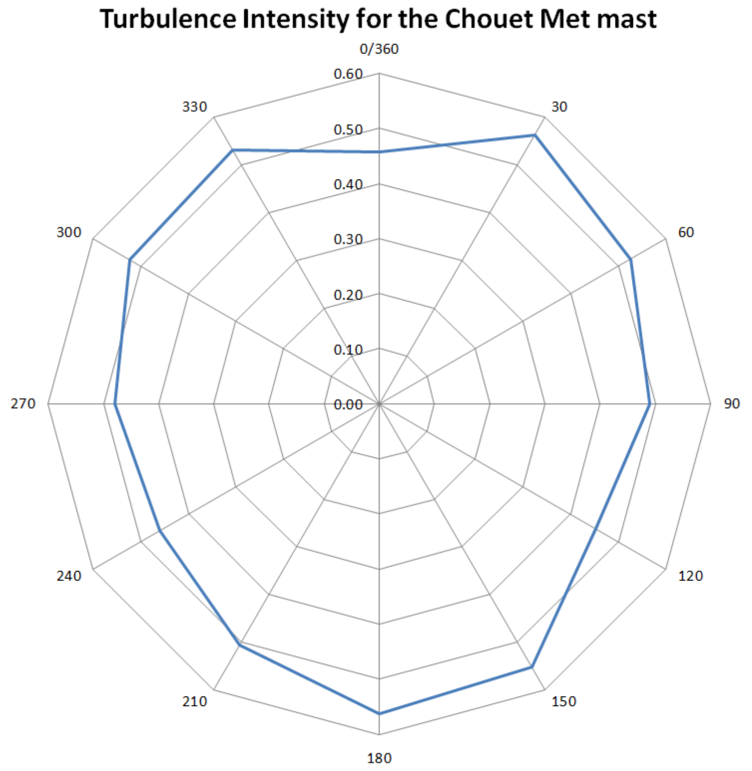


Figure 6-3: Turbulence intensity rose for Chouet met mast.

Only data from the Chouet met mast was used to determine the annual and daily variations of the TI, it was felt that the site nature of Chouet would best represent the conditions that could be present offshore. Also, the data received from the airport met masts didn't have 24 hour measurements and so unable to give complete data on daily variations. The daily variation was calculated from 10min averaged wind speeds, shown below, and the values reflect expected TI for an offshore site given in another similar study in Europe (Westerhellweg, Canadillas, and Neumann, 2011).

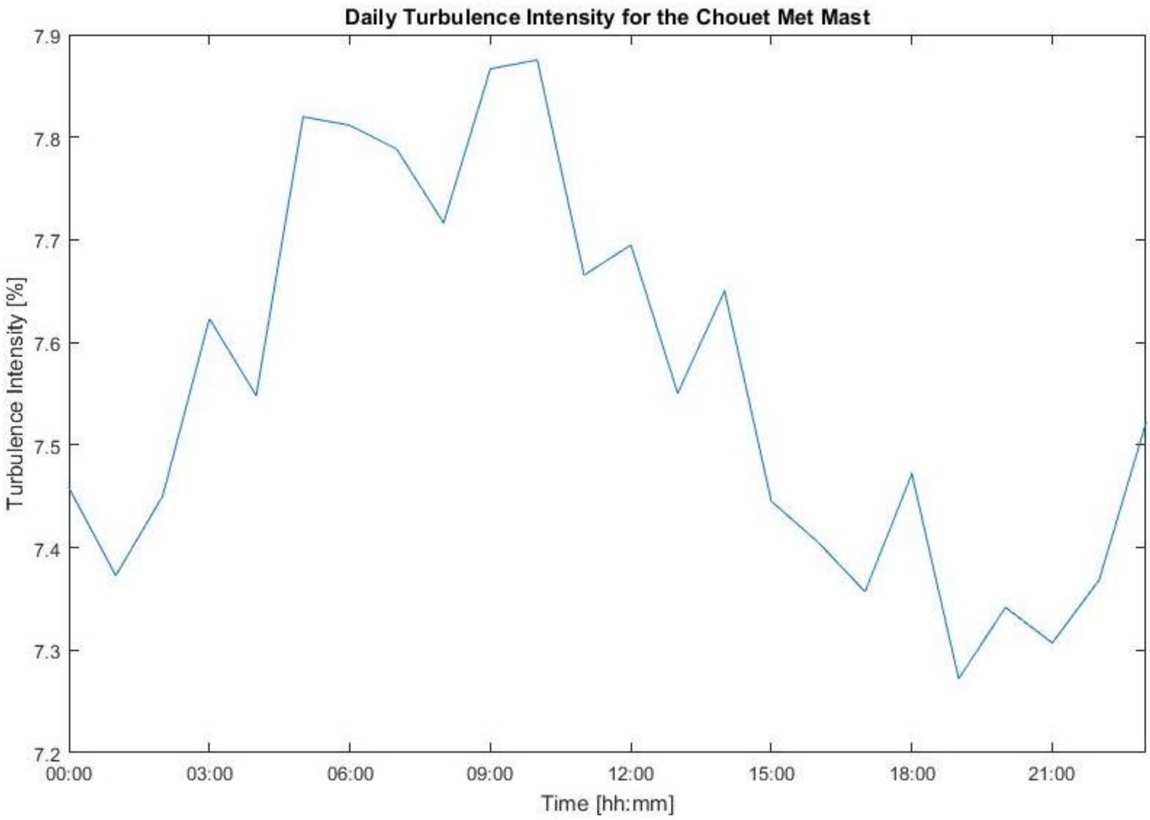


Figure 6-4: Daily variation in average turbulence intensity

The annual turbulence intensity variance was calculated and mapped and although there is evidence to show that there is lower TI during the summer than the winter, there was no clear pattern and so it has been left out of this part of the assessment, it is shown in the appendix, 10.3 - Turbulence Intensity and shear average calculations.

6.5 Speed Frequency Distribution and Weibull Parameters

The validated data was processed by MATLAB to produce the following Weibull parameters to represent the met mast resources.

	Alderney	Chouet	Guernsey	Jersey
Weibull parameter (k)	2.23	1.98	2.27	2.35
Scale Parameter (A)	7.26	8.09	6.96	6.92

Table 6-5: Weibull shape and scale parameters for the measured datasets.

Looking back at figure 3-1 the shape parameter values heavily suggest that the sites are in an offshore environment, given the larger spread of possible wind speeds. The plotted Weibull distributions for the met masts at 10m AGL are shown on one figure on the next page.

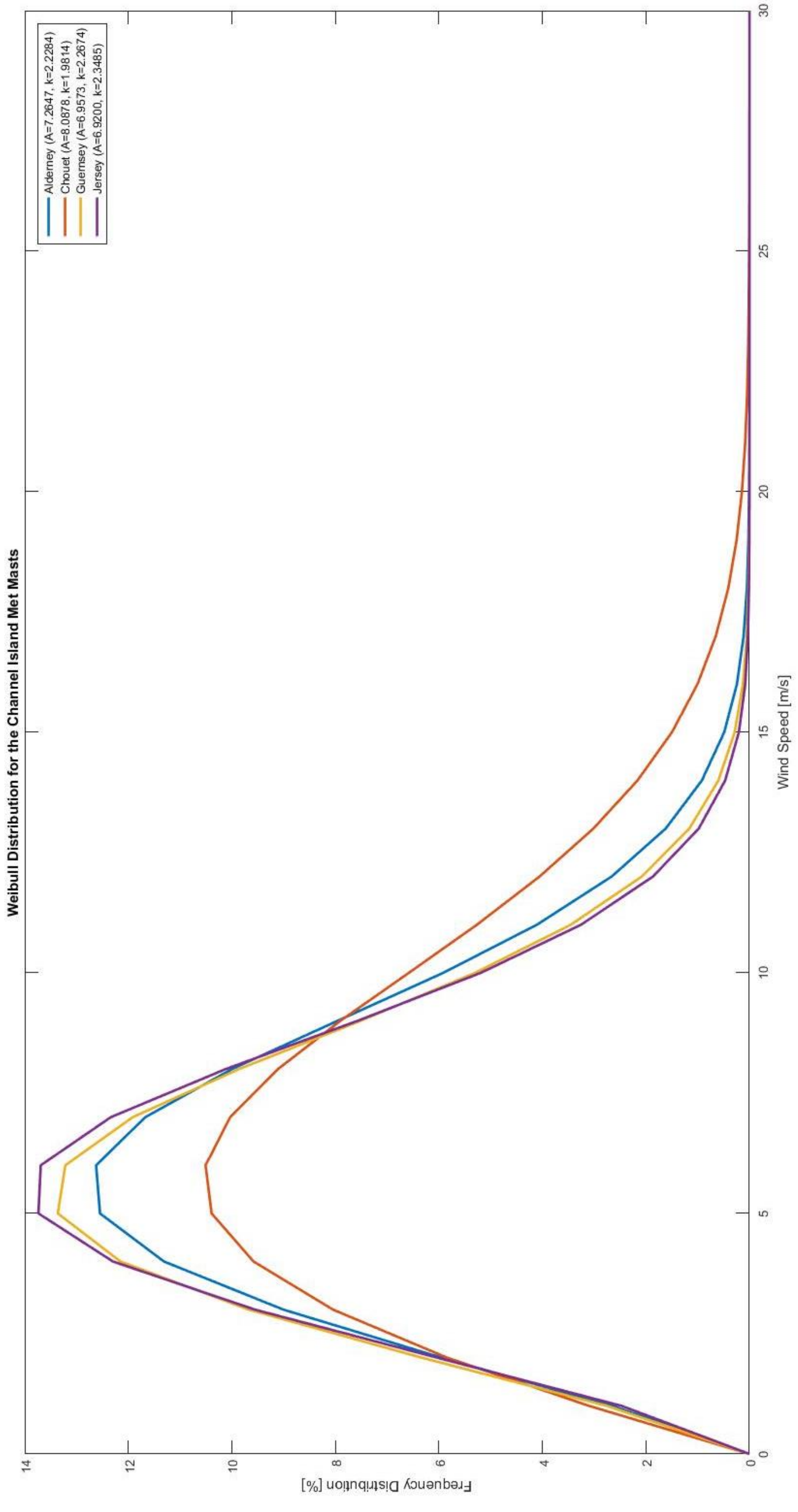


Figure 6-5: A plotted Weibull distribution for measured datasets at all four met masts.

A Weibull distribution for the extrapolated height of 100m at the Chouet met mast can be produced by calculating the scale factor from extrapolated average wind speed (11.06m/s) using the method mentioned in the methodology, multiplying the average by a factor of 1.128, giving a scale factor of 13.22. The same shape factor will be used in generating the resource distribution at the extrapolated height. The table below shows the averages and scale factors at the point of measurement (10m AGL) and the extrapolated elevation. The scale parameters at 10m are the ones produced by MATLAB, for reference to the accuracy of this method.

		Met masts			
		Alderney	Chouet	Guernsey	Jersey
Annual Mean Wind Speed at elevation, [m/s]	10	6.42	7.16	6.15	6.13
	90	10.69	11.46	10.25	10.78
	100	10.96	11.72	10.50	11.08
Scale parameters at elevation, [m]	10	7.26	8.09	6.96	6.92
	90	12.06	12.92	11.56	12.16
	100	12.36	13.22	11.85	12.49

Table 6-6: AMWSs and scale parameters at 10m, 90m and 100m

The graph below shows the distributions from the three heights of the Chouet met mast, showing how the resource varies at different heights.

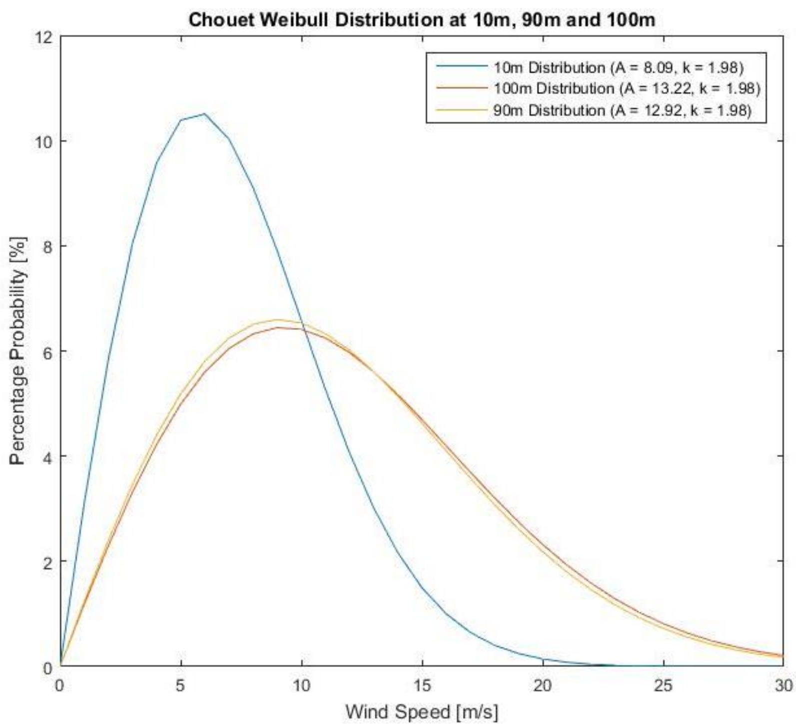


Figure 6-6: Weibull distributions showing how the wind resources vary with elevation.

The same process can be used to determine the distribution at the months that average the minimum and maximum overall monthly average wind speeds. For this the minimum and maximum from table 10 were extrapolated to find these scale factors for the same heights.

		Met masts			
Min and max scale parameters at x, height [m]		Alderney	Chouet	Guernsey	Jersey
10	Min	6.02	6.45	5.93	6.00
	Max	9.01	10.49	8.52	8.31
90	Min	10.03	10.33	9.89	10.56
	Max	15.00	16.79	14.19	14.63
100	Min	10.28	10.57	10.13	10.85
	Max	15.37	17.18	14.54	15.03

Table 6-7: Min and max scale parameters for elevated resources.

The following graph shows the seasonal variation of the distribution, with the min, max and the actual scale factor of the Chouet met mast at 10m AGL. Chouet best represents how the resource varies as it is the most exposed to the winds that the offshore site will be exposed to.

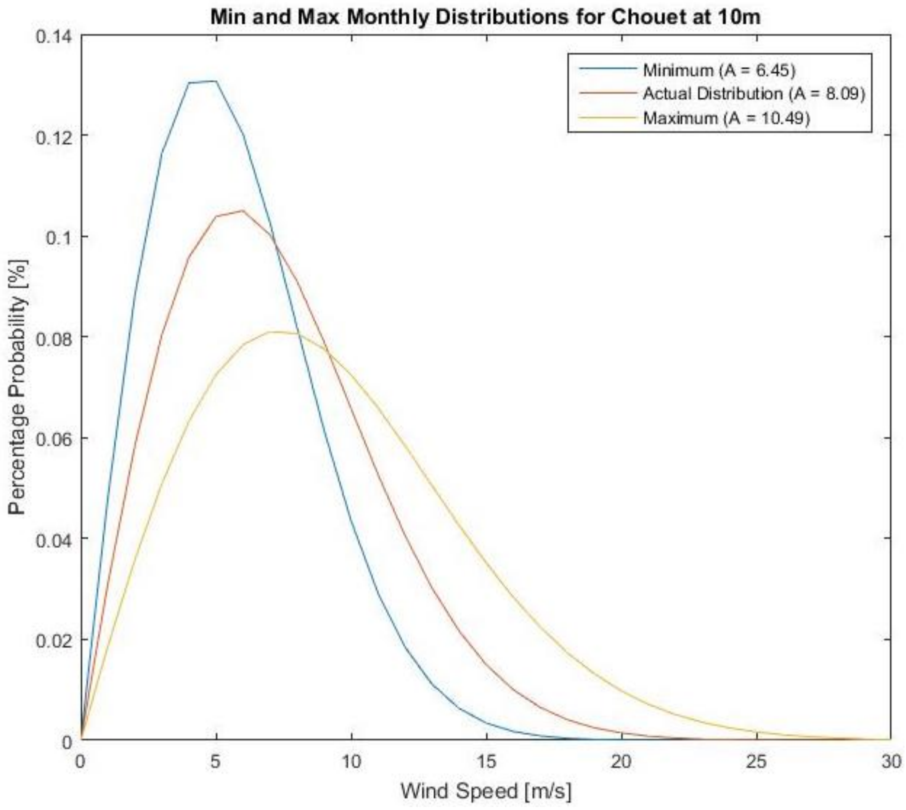


Figure 6-7: Min and max distributions of the monthly variations against the actual distribution

These distributions are all plotted using values generated by a probability density function in MATLAB. Tables of these values can then be used in later calculations against power curves of turbines with similar bins to produce energy yields for all the varied scenarios.

7. Measure Correlate Predict

Figure 6-2 shows that the Alderney met mast has the strongest resemblance to the mast data from Chouet. The Principal Component Analysis (PCA) method was used in WindFarmer to produce the predicted long-term results.

Being based on the correlation between the reference and target sites, the Pearson's correlation coefficient (r) for each direction of the wind speed are as follows.

Direction (^{O})	r
0	0.91
30	0.86
60	0.70
90	0.70
120	0.69
150	0.88
180	0.91
210	0.86
240	0.92
270	0.92
300	0.92
330	0.92

Table 7-1: Pearson's correlation coefficient results from the MCP analysis of wind speeds from each direction

The results show a large lack of correlation between the wind direction sectors of 60^{O}, 90^{O} and 120^{O}. These sectors could have the least correlation because of the vast difference in terrain and topography in those direction sectors, from flat sea and land at Chouet to the elevated land leading to Alderney's met mast in the same respective sectors. Likewise the correlation might be higher than expected in the sectors from 150^{O} to 210^{O} as the more gradual gradient across the larger landmass of Guernsey may produce similar effects on the wind to the respective Alderney sectors that cross open sea and then a much smaller distance across a more elevated land mass.

Although there are substantial correlations between the 2 masts there are gaps in the predictions where there wasn't data from Alderney for 12 hours of the day. 37,203 records of the 87,609 produced by the MCP function were represented by NaN values (999) and so the data recovery rate from the MCP was 57.5%.

The data produced by the MCP function put through the same process as in the Wind Resource Assessment produces similar characteristics that were plotted as the following

Weibull distribution. This can also be used in the same models used later to represent the resources offshore.

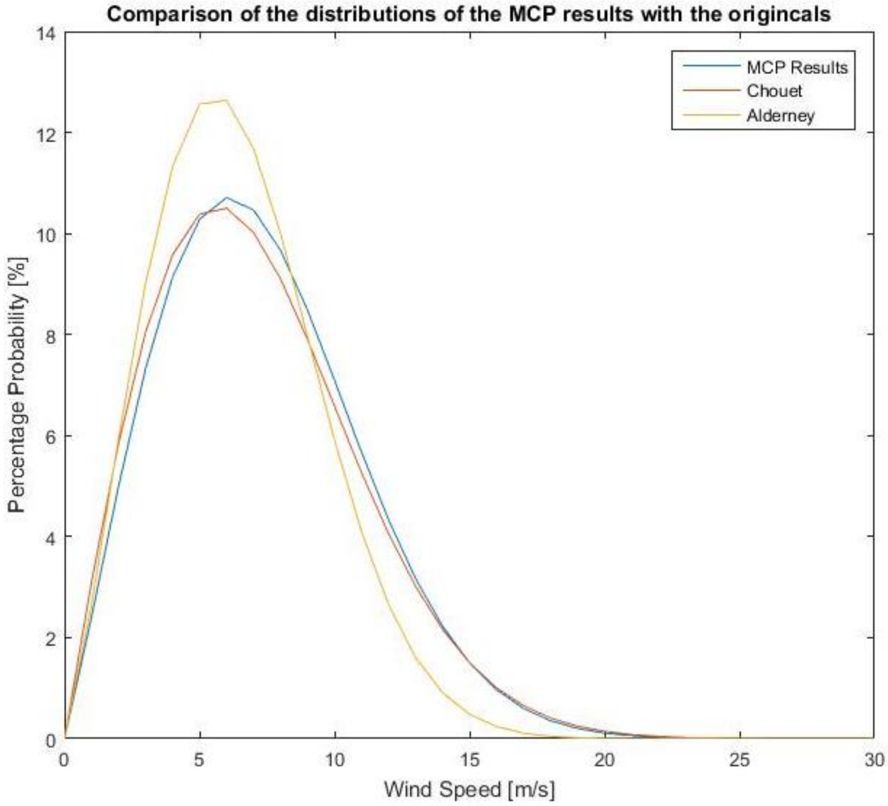


Figure 7-1: Comparing distributions of Alderney and Chouet with the MCP results.

8. Wind Flow Modelling

8.1 WindFarmer

WindFarmer is software developed for the wind industry to design wind farms, 'to achieve maximum energy production'. Data and outcomes from previous parts of the assessment were used as the input for WindFarmer. The same shear exponent values calculated for each met mast site and given in table 9 are applied to the plotted met mast entities. The met mast entities consist of the validated data sets from the four original met masts. They are positioned on a map at their real locations, along with boundaries marked out for the proposed offshore wind sites. Elevation data with geographical coordinates are placed on top of the map to provide the key part in calculating the wind flow model.

The minimum requirements for the simple wind flow model are a frequency distribution in a .tab file, generated in the inbuilt Measure Correlate Predict function, and terrain data (SRTM1). The validated data sets were processed through the function to achieve the distribution format required by WindFarmer and were paired with their corresponding met masts.

The terrain data used in the modelling was from the Shuttle Radar Topography Mission (SRTM), giving elevation data to a resolution of 1 arc-second (30m). This was imported from the United States Geological Survey's, an online GIS tool for downloading a variety of data from selected areas. This was an increase in precision of elevation data from the 3 arc-second data (90m) resolution provided by the online database in WindFarmer.

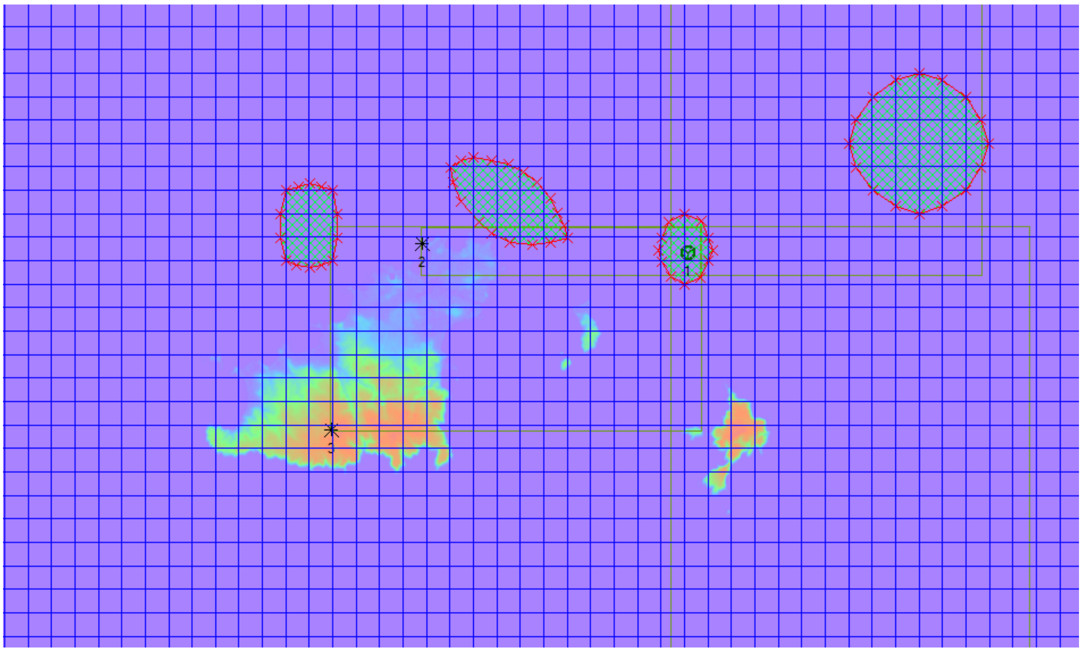


Figure 8-1: WindFarmer interface, showing the elevation data from SRTM 1, anemometer positions, farm boundaries and 1 turbine in the proposed North Herm farm.

Wind Resource Grids (WRG's) are calculated from each met mast, at a certain elevation with a certain resolution, to cover areas consisting of the offshore sites. Included in the generation of the WRGs was also the association method, available in WindFarmer, where the data for each met mast is 'scaled to the turbine locations using the predictions of the wind flow model' (Hassan, 2009). The simple flow model is then run, giving the distribution of wind energy over the area in question.

8.2 Conceptual Model

A conceptual model is defined as 'A set of relationships between factors that are believed to impact or lead to a target condition'. The factors in this conceptual model are the elevation of the met masts and their wind speeds, producing a conceptual value of the wind speed at sea level from both the 10m mast height data and the 90m and 100m extrapolated values. Below a table shows the data used in comparing the elevation to the wind speeds.

		Met masts			
		Alderney	Chouet	Guernsey	Jersey
Elevation [m]		88	6	102	84
AMWS at height, [m]	10	6.42	7.16	6.15	6.13
	90	10.69	11.46	10.25	10.78
	100	10.96	11.72	10.50	11.08

Table 8-1: Altitiudes of the met masts and their AMWSs at 10m, 90m and 100m.

This model overall tries to encompasses a somewhat similar approach given in figure 3 where the overall terrain and topography has been modelled on the input wind data, which has been done in the extrapolation of all 4 met masts. Afterwards this conceptual model based on the correlation between the stated factors estimates the offshore wind resource. Both of the paths taken to model the offshore resource don't specifically model a location but in general the offshore climate around the Channel Islands.

Plotting the met mast averages at 10m produces a graph with strong correlation, with the forecast trend line crossing the x axis at 7.27m/s. Extrapolating using the same method as in the WRA (power law), with an exponent representing the value of open water (α = 0.15), produces 10.10m/s at 90m, and with further extrapolation, 10.27m/s at 100m. The values of the shear exponent could vary due to the variation of the sea state, having a varying turbulent effect on the ABL and the extrapolation.

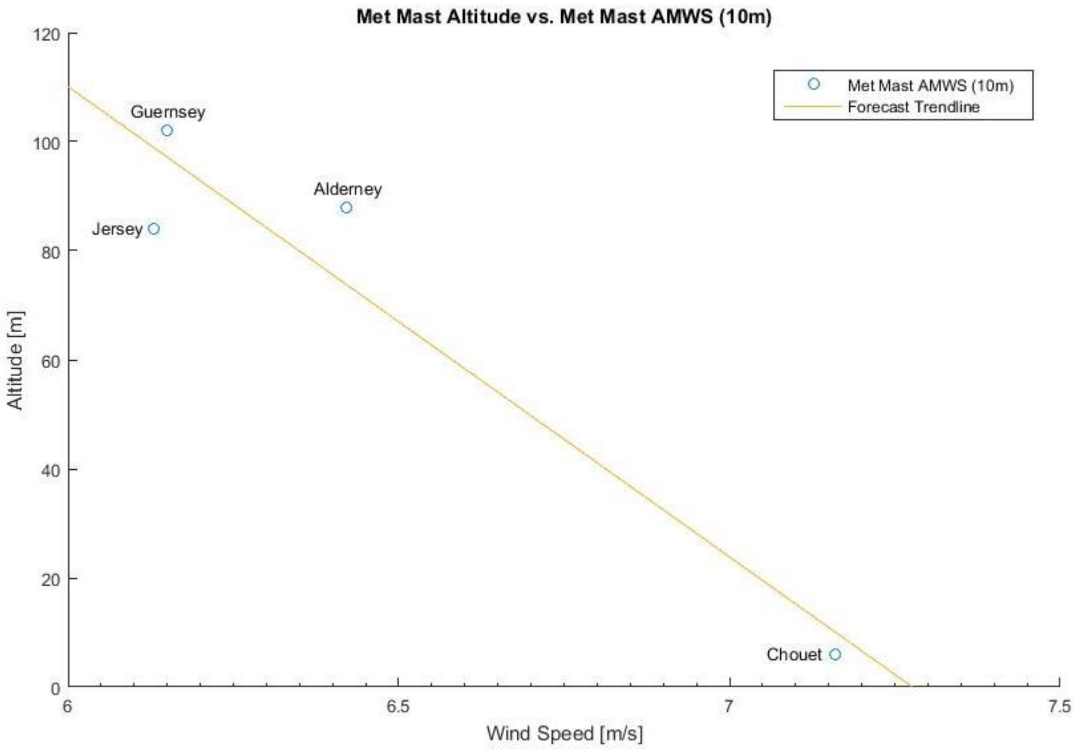


Figure 8-2: 10m conceptual model

A similar conceptual model based on the average of the extrapolated wind speeds at each met mast, at an extrapolated 90m and 100m, predicts a wind speed of 11.64m/s and 11.92m/s offshore at their respective heights. Their plots are below and on the next page.

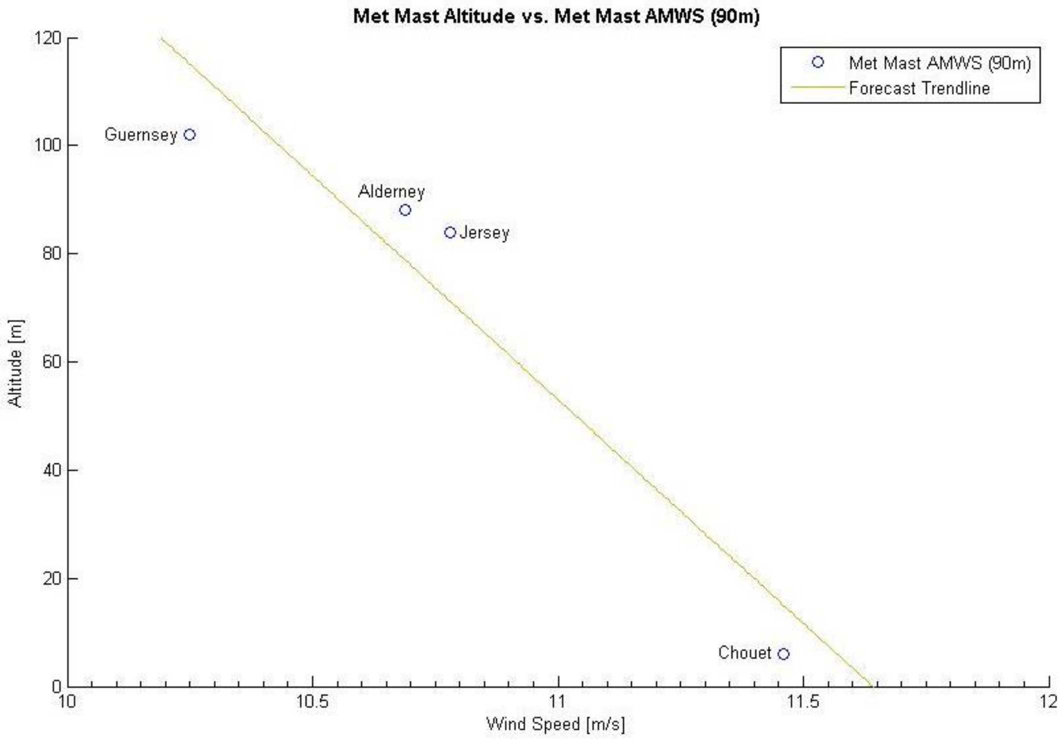


Figure 8-3: 90m conceptual model

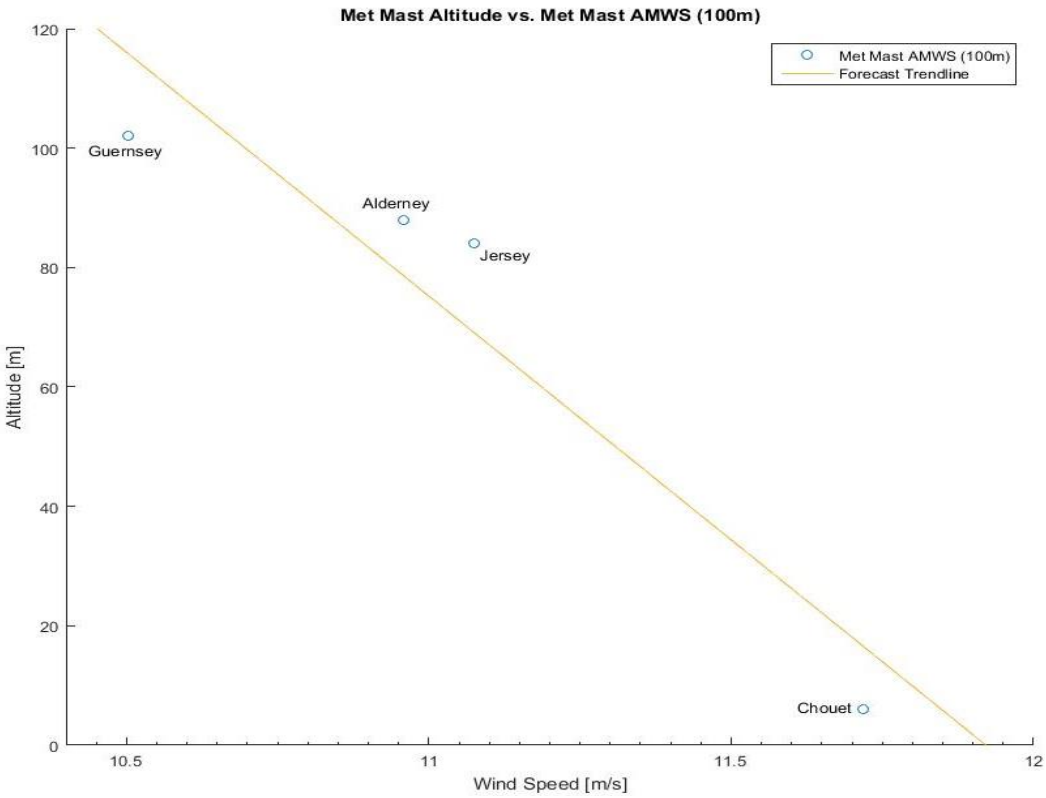


Figure 8-4: 100m conceptual model

The difference in the results of these two models is that first has compensated for the terrain and topography offshore whilst the second that encompasses the latter two plots compensates at the met masts. The results from the last two can be used in the power law equation to produce a model shear exponent, α = 0.2256.

$$\frac{v}{v_0} = \left(\frac{H}{H_0}\right)^{\alpha}$$

$$\frac{11.92}{11.64} = \frac{100^{\alpha}}{90}$$

$$\alpha = \frac{ln(^{11.92}/_{11.64})}{ln(^{100}/_{90})}$$

9. Predicted Energy Yields

The predicted energy yields come from the distribution of the wind speeds found throughout this wind resource assessment against the rated power of industry offshore turbines at those wind speeds. There are many predicted yields from the met mast sites to the proposed offshore sites.

9.1 Turbine Model

The rated power of offshore turbines at certain wind speeds isn't easily available and so a power curve model based on the little information available is built to give an estimate of their capabilities. The most readily available information relating to the generation is the cut-in and nominal wind speeds, shown below for the 2 turbines chosen to be modelled. All information for the wind turbines were recorded from 4coffshore.com and wind-turbine-models.com.

Turbine Model	Rated Power (kW)	Cut-in speed (m/s)	Rated Wind Speed (m/s)
SWT-4.0-130	4000	5	11
SWT-6.0-154	6000	3	12

Table 9-1: Turbine model values

The 2 models represent the main line of Siemens turbines. The SWT-4.0-130 is the next generation of workhorse turbine, replacing the most widely used offshore turbine, the SWT-3.6-120. The SWT-6.0-154 is a turbine used in the floating offshore turbine prototype, Hywind, developed for depths of up to 220m. Over the page two power curves show the similarity between an actual power curve of the Vestas V112-3.0MW, provided by Vestas, against an SWT-4.0-130 turbine. This gives confidence in the modelling of the range of turbines, that they will accurately portray the power curves and the AEP's that will be associated.

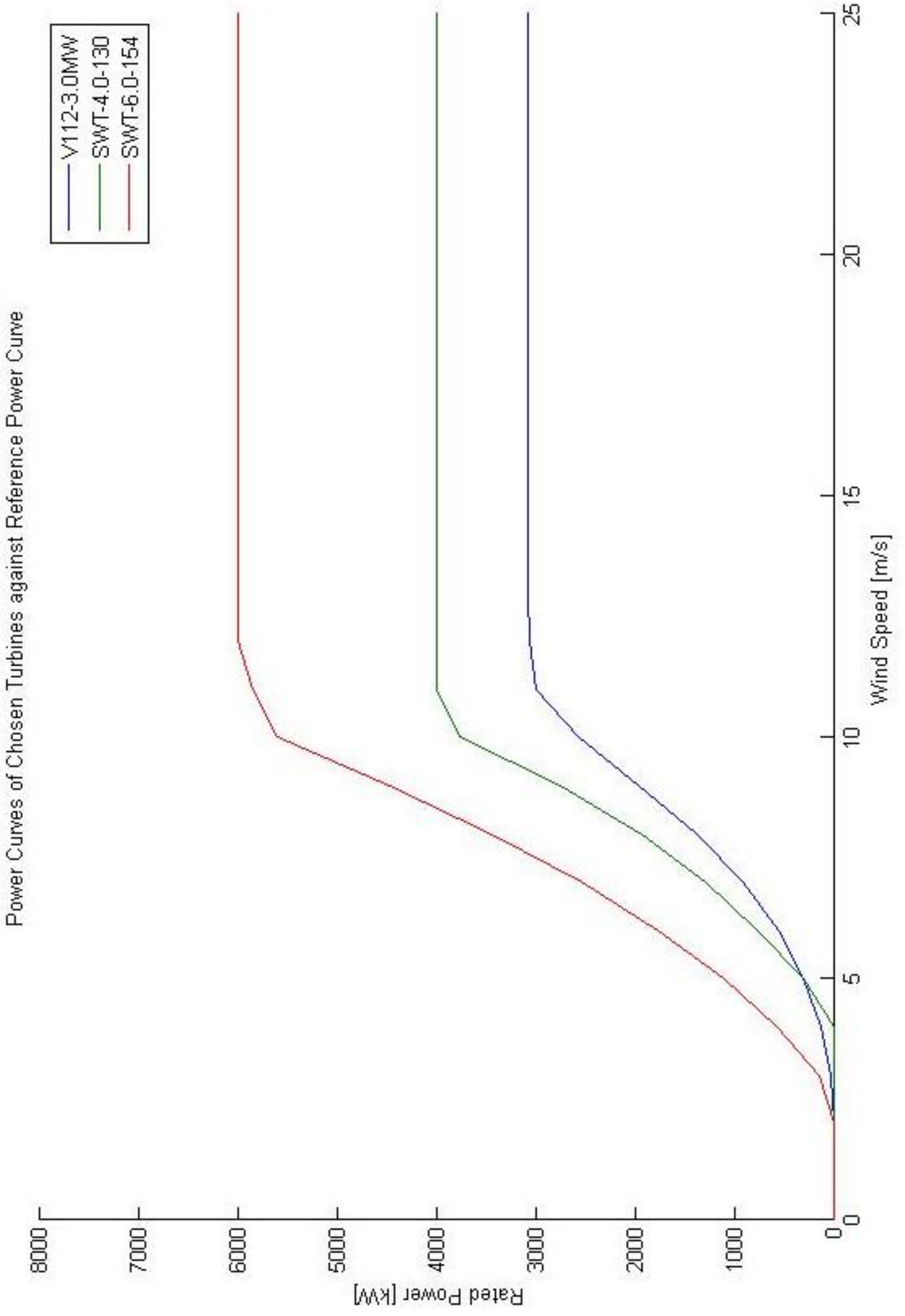


Figure 9-1: Comparison of the imported V112-3.0MW power curve and the modelled SWT-4.0-120 power curve

9.2 Met Sites

The energy yields at each site were calculated by producing a Weibull distribution with the same shape parameter from the 10m distribution but with a new scale parameter based on their extrapolated average wind speed. Although not a realistic scenario, it should show how each area the met masts are in differ in actual available resource at hub –height, and be compared with the outcome of the models.

Below are the results of the predicted energy yields, of the two Siemens turbines, at the four sites. Showing an expected generation of 1800MWh and 2900MWh per month on average.

Net Yield at Met Mast (MWh)				
	Alderney	Chouet	Guernsey	Jersey
SWT-4.0-130	21190	21630	20350	21740
SWT-6.0-154	34650	34860	33560	35530

Table 9-2: Met mast net yields

The monthly variation from table 5-3 also produces minimum and maximum distributions. The key assumption here is that the shape factor would remain constant with seasonal variations, which it would not. Combined are the percentage deviations from the average monthly net yield. The results of the monthly net yields show actually a very small shift from the expected monthly amounts stated previously, with larger percentage losses in production from the larger turbine.

	Min, Max and Average Monthly Net Yield [MWh]		
	Min	Max	Average
SWT-4.0-130	1620	2010	1800
SWT-6.0-154	2660	3080	2900

Table 9-3: Monthly yield variations

9.3 Measure Correlate Predict

Utilizing the results from the MCP function will give a long-term AEP prediction from the Chouet site. The predicted outcome of the MCP function had a shape parameter, k, of 2.10 and an average of 7.33m/s, up from the initial site values of 1.98 and 7.16m/s. At the 90m and 100m elevations marked as hub heights of generation the average speeds are 11.74m/s and 12.00m/s, using the same average exponent value assessed for the site in table 5-2. These averages then produce scale factors, 13.24 and 13.54, that can create more distributions of the resource at this elevation range.

The product of the distributions and the power curves of the turbines produces a very optimistic yield, with the results below.

	Net Yield [MWh]	Capacity Factor [%]
SWT-4.0-130	24350	69.5
SWT-6.0-154	38360	73.0

Table 9-4: Yields and capacity factors of the MCP resource at Chouet

Imposing the same monthly variation from the previous section, an estimate the monthly min and max can be produced below.

	Min, Max and Average Monthly Net Yield [MWh]		
	Min	Max	Average
SWT-4.0-130	1830	2270	2030
SWT-6.0-154	2930	3400	3200

Table 9-5: Monthly yield variations of the MCP resource

9.4 Wind Flow Modelling – Numerical and Conceptual

Two sets of annual energy yields can be produced from the two models produced, one of which was the direct outcome of using the WindFarmer software. Below, the values of the turbine models imported into WindFarmer and run against the wind energy map created, show the final annual net yield figures that were generated from the entire process.

Turbine	Rated Power	Annual Net Yield (MWh)	Capacity Factor (%)
SWT-4.0-130	4000	23280	66
SWT-6.0-154	6000	34100	65

Table 9-6: Net Yield of the simple wind flow model produced by WindFarmer

The conceptual model produced a value that can be used as a rough estimate for the wind resource in an offshore climate in the Channel Islands. The produced averages varied from 10.27m/s to 11.92m/s at 100m, depending at which point the surroundings were accounted for. The 11.92m/s is favoured as the linear correlation is plotted from points that represent the 'actual' wind resource with a rough extrapolation taking account for the effect of the surroundings. Whereas the averages produced from the values given at 10m AGL are forecasting a low lying wind speed without taking immediate account.

Any assessment of the energy yield from the conceptual model is variable as there is no derived shape parameter for the offshore site, and so any distribution produced will be an inaccurate representation. Two shape parameters could be incorporated to provide a lower end and higher end of what could potentially be produced. For this, k =2 and 2.20.

	Conc10		Conc100	
Shape Parameter, k	2	2.2	2	2.2
SWT-4.0-130 [MWh]	21620	22420	23670	24790
SWT-6.0-154 [MWh]	34740	35990	37380	39080

Table 9-7: Largely varied resources from the two conceptual models with derived shape parameters

10. Discussion

Throughout this assessment there have been statements and assumptions based on the surroundings for the met masts. Although, with the observations all being taken through the same method and so having the same handicap, the observed surroundings could perhaps be better estimated by eye. The shear exponents all affect the final yield greatly and reduced or increased yields could have been produced with exponents being incorrect. The same potential error affects all of the produced results and should be a key part of improving any wind resource estimate.

The monthly averages produced by the Chouet met mast were less smooth in comparison to the rest. One concern is that this could be from seasonal variation in the wind direction in the climate and that the island is sheltering the mast from the seasonal direction changes. Figure 5-3 potentially shows this in the transition between the summer and winter months, showing large variations. However, this could just be due to the reduced amount of data available from the Chouet met mast in comparison to the others. At this time, another complete year of data would be available to add onto this analysis.

A useful tool would be the use of the association method with another met mast on the island in a position where it's exposed to the offshore environment where the current met mast isn't. This may be difficult largely due to most of the rest of the island being at a higher elevation than the current met mast and so may also produce poor correlations with the Chouet met mast, as there was with the Alderney met mast in the results of the MCP function.

The varied results of the net yields produce yields for the wind resource at Chouet and the offshore that have capacity factors between 61.7% and 70.7%, 64.9% and 74.4% for the respective 4MW and 6MW turbines at their respective heights of 90 and 100m. The unusually higher generation points towards either a turbine model that generates more than it should or a wind resource much larger than there actual is. However, the average wind speeds produced by the conceptual models should be taken as a discretionary range of possible values for the offshore site, with which the numerical model lies in, reaffirming an actual average in that range.

10.1 Recommendations

The use of WAsP software could greatly increase the accuracy of the numerical and conceptual wind flow models. It's a well proven method that would require a much more specific value of the surface roughness and produce a modelled wind speed at site that could prove to be much more accurate than WindFarmer.

Reducing the need for a wind flow model completely and obtaining a closer measurement of the resource would be of obvious use. A LiDAR installation could increase the accuracy of all the variables produced in the WRA, by utilizing its function to measure the resource horizontally out at sea. Guernsey is in a unique scenario in which it can do this, measuring a close offshore resource from onshore.

Another suggestion is to improve the Chouet met mast site with another anemometer placed on top of the existing one, ideally by 20m. This would alleviate concerns over the assessment of the surface surrounding the met mast by directly calculating an exponent from the two measurement points for each direction. To remove concerns over wind shadowing on Chouet, and presenting a more accurate resource around the island, another met mast could be placed along the south of the island. This additional mast could even be placed on Herm, favouring its low-lying features that could measure the resource reliably from most directions.

References

Guernsey Electricity (2016), Combined leaflet and accounts for website Available at: https://www.electricity.gg/media/51675/combined-leaflet-and-accounts-for-website.pdf (Accessed: 17 March 2016).
(Combined leaflet and accounts for website, 2016)

Guernsey facts and figures (2015), Available at: http://www.gov.gg/CHttpHandler.ashx?id=97608&p=0 (Accessed: 17 March 2016).
(Guernsey facts and figures, 2015)

Guernsey Electricity, Annual report and accounts (2016) Available at: https://www.electricity.gg/about/annual-reports/ (Accessed: 17 March 2016).
(Guernsey Electricity, 2016)

Policy Council (2014), GUERNSEY ELECTRICITY SUPPLY -FUTURE STRATEGY Available at: http://theoldsite.gov.gg/CHttpHandler.ashx?id=86677&p=0 (Accessed: 17 March 2016).
(Policy Council, 2014)

Guernsey electricity company history (2016) Available at: http://www.electricity.gg/about/our-history/ (Accessed: 17 March 2016).
(Guernsey Electricity History, 2016)

Jersey electricity (nd) Plc - jersey electricity signs major deal with Guernsey on power cable links Available at: https://www.jec.co.uk/about-us/latest-news/jersey-electricity-signs-major-new-deal-with-guernsey-on-power-cable-links/ (Accessed: 24 April 2016).
(Jersey electricity, no date)

HM Government (2015) Contracts for difference (CFD) allocation round One outcome. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/407059/Contracts_for_Difference_-_Auction_Results_-_Official_Statistics.pdf (Accessed: 24 April 2016).
(HM Government, 2015)

Renewable Energy Students (2013) Guernsey energy analysis and strategy recommendations to 2050 in co-operation with the Guernsey renewable energy team. Available at: http://www.guernseyrenewableenergy.com/documents/managed/FINISHED%20Master%20Report%20Part%201.pdf (Accessed: 24 April 2016).
(Renewable Energy Students, 2013)

OWEC (2013) Owec tower Beatrice. Available at: http://www.owectower.no/references/beatrice/ (Accessed: 18 April 2016).
(OWEC, 2013)

Office, M., Road, F., Exeter, PB, E. 1 3 and Kingdom, U. (2010) The atmospheric boundary layer. Available at: http://www.metoffice.gov.uk/research/foundation/parametrizations/boundary-layer (Accessed: 6 April 2016).
(Met Office, 2010)

Michael Brower (2012) Wind resource assessment: a practical guide to developing a wind project, Hoboken, N.J: Wiley. Available from Penryn Library (Accessed: December to April 2015-2016)

Bañuelos-Ruedas, F., Angeles-Camacho, C. and Rios-Marcuello, S. (2011) Wind farm - technical regulations, potential estimation and siting assessment. Available at: http://www.intechopen.com/books/wind-farm-technical-regulations-potential-estimation-and-siting-%20assessment/methodologies-used-in-the-extrapolation-of-wind-speed-data-at-different-heights-and-its-impact-in-th (Accessed: 7 April 2016).
(Bañuelos-Ruedas, Angeles-Camacho, and Rios-Marcuello, 2011)

IEC (2005) Wind turbines – part 1: Design requirements. Available at: http://homes.civil.aau.dk/rrp/BM/BM8/r.pdf (Accessed: 18 April 2016).
(IEC, 2005)

Bhattacharya, P. (2011) Wind energy management. Available at: http://www.intechopen.com/books/wind-energy-management/weibull-distribution-for-estimating-the-parameters (Accessed: 20 April 2016).
(Bhattacharya, 2011)

Hassan, G. (2009) GH WindFarmer wind farm design software 4.0 wind energy experts worldwide. Available at: http://www.ccpo.odu.edu/~klinck/Reprints/PDF/garradhassan09.pdf (Accessed: 19 April 2016).
(Hassan, 2009)

Carta, J.A., Velázquez, S. and Cabrera, P. (2013) ‘A review of measure-correlate-predict (MCP) methods used to estimate long-term wind characteristics at a target site’, Renewable and Sustainable Energy Reviews, 27, pp. 362–400. doi: 10.1016/j.rser.2013.07.004.
(Carta, Velázquez, and Cabrera, 2013)

Probst, O. and Cárdenas, D. (2010) State of the art and trends in wind resource assessment. Available at: http://www.mdpi.com/1996-1073/3/6/1087/htm (Accessed: 19 April 2016).
(Probst and Cárdenas, 2010)

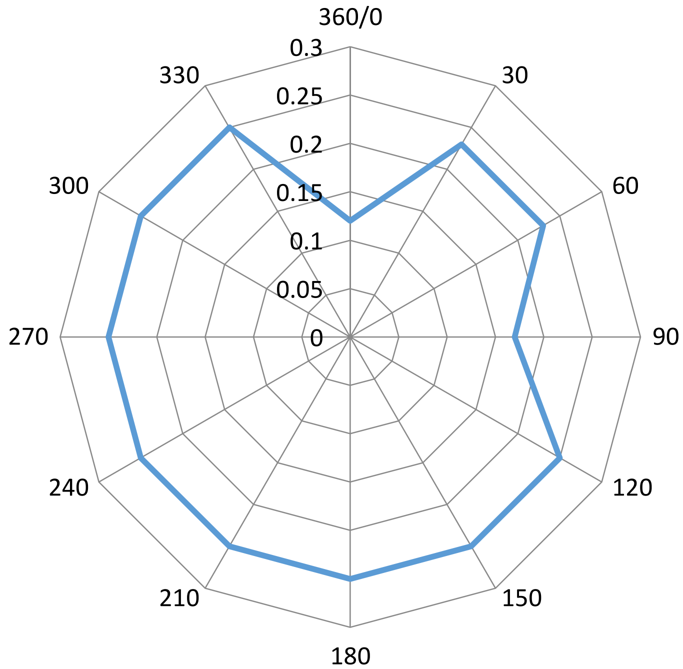
Krueger, S.K. (2014) Wind flow modeling. Available at: http://www.inscc.utah.edu/~krueger/5270/wind_flow_modeling.pdf (Accessed: 11 April 2016).
(Krueger, 2014)

Brower, M.C., Vidal, J. and Beaucage, P. (2011) Evaluation of four numerical wind flow models. Available at: http://www.ewea.org/events/workshops/wp-content/uploads/2013/06/EWEA-RA2013-Dublin-2-1-Michael-Brower-AWS-Truepower.pdf (Accessed: 6 April 2016).
(Brower, Vidal, and Beaucage, 2011)

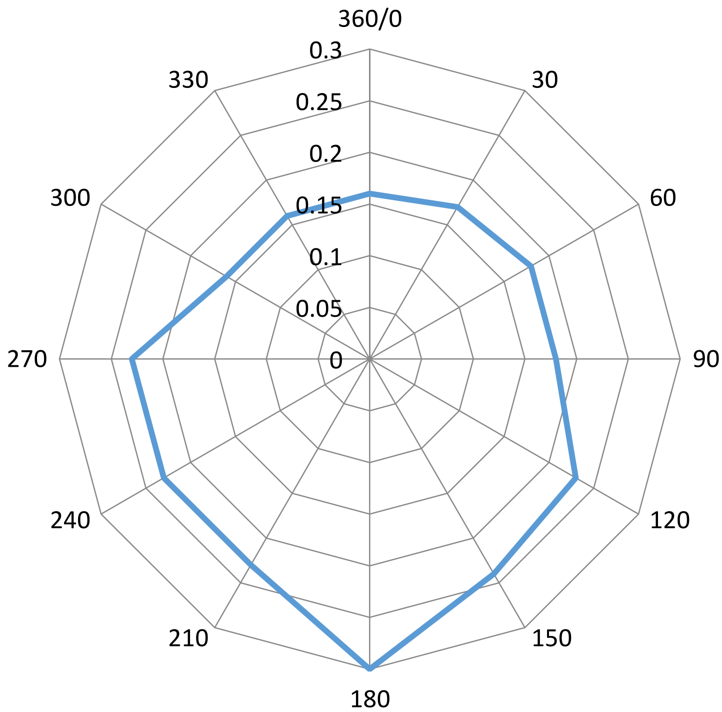
11. Appendix

11.1 Roughness Roses

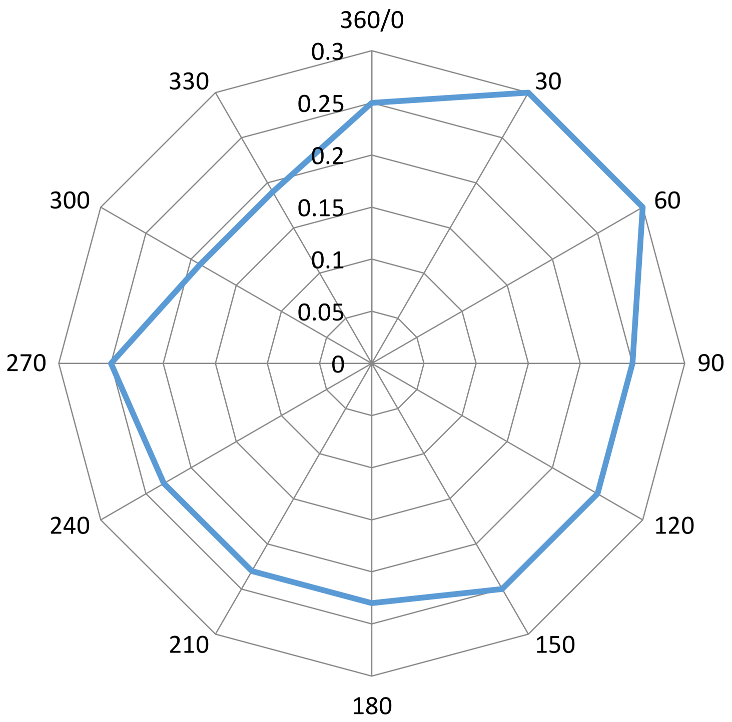
Alderney



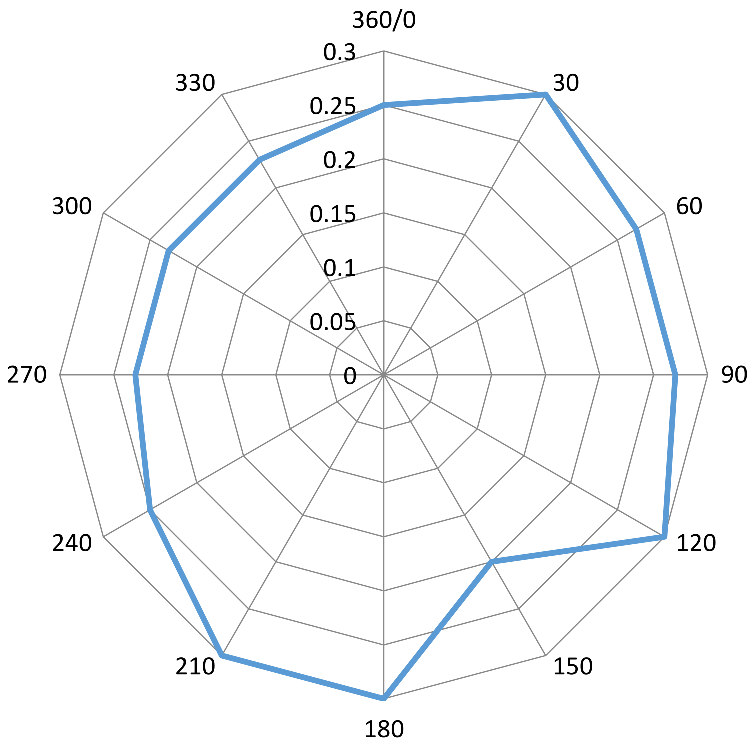
Chouet



Guernsey


360/0
30
60
90
120
150
180
210
240
270
300
330
0.3
0.25
0.2
0.15
0.1
0.05
0

Jersey


360/0
30
60
90
120
150
180
210
240
270
300
330
0.3
0.25
0.2
0.15
0.1
0.05
0

11.2 Monthly data

	Wind Speed at Met Mast			
Months	Alderney	Chouet	Guernsey	Jersey
Jan	7.46	8.45	7.09	6.93
Feb	7.23	8.81	6.83	6.68
Mar	6.77	6.35	6.38	6.33
Apr	5.86	7.36	5.54	5.63
May	5.92	6.38	5.82	5.76
Jun	5.34	6.08	5.34	5.36
Jul	5.40	5.72	5.44	5.37
Aug	5.41	5.97	5.26	5.32
Sep	5.84	5.95	5.44	5.60
Oct	6.56	7.92	6.11	6.22
Nov	7.80	7.70	6.99	7.00
Dec	7.99	9.30	7.55	7.37

11.3 Turbulence Intensity and shear average calculations

Alderney

	360/0	30	60	90	120	150	180	210	240	270	300	330
STDEV	3.01	2.41	2.43	2.64	2.17	2.37	3.48	3.38	3.32	2.95	2.84	2.87
Mean	4.76	5.54	6.49	7.06	4.83	4.85	6.72	7.33	7.32	6.57	6.26	5.84
Frequency	4725	4810	6636	6458	2155	3178	6743	7049	11067	10089	7618	4876
TI	0.632	0.436	0.375	0.374	0.449	0.488	0.518	0.461	0.454	0.449	0.453	0.492
10m weight	22472	26633	43051	45607	10405	15408	45300	51651	80987	66335	47710	28474
Exponent	0.12	0.23	0.23	0.17	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
E weight	567	1106.3	1526.28	1097.86	538.75	794.5	1685.75	1762.25	2766.75	2522.25	1904.5	1219
90m	6.19	9.18	10.75	10.26	8.36	8.40	11.64	12.69	12.67	11.39	10.85	10.11
90m weight	29252	44146	71361	66260	18023	26688	78461	89463	140274	114895	82636	49318

Chouet

	0/360	30	60	90	120	150	180	210	240	270	300	330
STDEV	3.43	4.15	3.50	2.76	2.00	2.73	3.82	3.78	3.85	3.93	3.96	3.77
Mean	7.52	7.36	6.66	5.65	4.40	4.95	6.79	7.48	8.38	8.20	7.59	7.10
Frequency	890	1101	2280	2015	1441	1140	1932	2836	3385	4443	2840	2001
TI	0.456	0.563	0.525	0.489	0.454	0.552	0.562	0.506	0.460	0.479	0.522	0.531
10m weight	6692	8107	15185	11377	6346	5638	13117	21223	28376	36445	21543	14204
Exponent	0.16	0.17	0.18	0.18	0.23	0.23	0.28	0.3	0.3	0.17	0.16	0.16
EWeight	142	187	410	363	331	262	541	851	1016	755	454	320
90m mean	10.69	10.70	9.89	8.39	7.30	8.20	12.56	14.47	16.21	11.92	10.78	10.09
90m weight	9511	11779	22552	16897	10519	9346	24268	41029	54856	52949	30619	20188

Guernsey

	360/0	30	60	90	120	150	180	210	240	270	300	330
STDEV	2.40	2.22	2.70	2.35	1.70	2.21	2.72	2.69	2.95	3.16	2.82	2.52
Mean	4.18	4.84	6.33	5.53	4.53	5.00	5.97	6.51	7.36	7.50	6.36	5.23
Frequency	8933	9570	14266	9204	5605	8699	11441	14372	21191	22166	17003	10540
TI	0.574	0.458	0.426	0.425	0.376	0.442	0.455	0.413	0.401	0.422	0.444	0.482
10m weight	37320	46316	90307	50882	25374	43507	68297	93581	155929	166216	108179	55104
Exponent	0.2	0.23	0.25	0.23	0.25	0.25	0.23	0.25	0.25	0.25	0.19	0.19
E weight	1787	2201	3567	2117	1401	2175	2631	3593	5298	5542	3231	2003
90m mean	6.48	8.02	10.96	9.16	7.84	8.66	9.89	11.28	12.74	12.99	9.66	7.94
90m weight	57915	76772	156416	84341	43950	75356	113208	162087	270077	287895	164229	83654

Jersey

	360/0	30	60	90	120	150	180	210	240	270	300	330
Frequency	9251	10426	12338	12177	6987	9288	11754	12970	13932	20166	20167	11506
Average	4.59	5.16	5.73	5.61	4.93	5.86	6.46	6.90	7.23	6.95	6.44	5.60
ST.dev	2.56	2.13	2.26	2.16	1.93	2.47	2.48	2.61	2.98	3.18	2.97	2.75
TI	0.557	0.413	0.395	0.385	0.391	0.422	0.384	0.378	0.413	0.458	0.462	0.490
10m weight	42472	53770	70678	68296	34447	54428	75888	89544	100671	140133	129880	64399
Exponent	0.25	0.3	0.27	0.27	0.3	0.2	0.3	0.3	0.25	0.23	0.23	0.23
Eweight	2313	3128	3331	3288	2096	1858	3526	3891	3483	4638	4638	2646
90m mean	7.95	9.97	10.37	10.15	9.53	9.09	12.48	13.35	12.52	11.52	10.68	9.28
90m weight	73564	103946	127918	123607	66592	84464	146705	173104	174368	232282	215287	106748

11.4 Turbine Power Curve Values

	SWT-4-130	SWT-6-154
0	0	0
1	0	0
2	0	0
3	0	140
4	0	560
5	300	1100
6	770	1760
7	1290	2540
8	1920	3440
9	2740	4460
10	3760	5600
11	4000	5850
12	4000	6000
13	4000	6000
14	4000	6000
15	4000	6000
16	4000	6000
17	4000	6000
18	4000	6000
19	4000	6000
20	4000	6000
21	4000	6000
22	4000	6000
23	4000	6000
24	4000	6000
25	4000	6000