# ROKEM WIND FARM ENERGY YIELD ASSESSMENT

Report: 437_036_R_NPC_ASP_1D

Author: Diana Thomas

Issued: June 19, 2012

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| Client: | Anne Amanda Bangasser<br>Raoul Slavin<br>Aspenall Energies |

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This report contains 67 pages, including annexes and this cover page. It may only be distributed in its complete form.

## Revision History

| Issue | Date | Modification |
|---|---|---|
| A | February 1, 2012 | First issue |
| B | February 24, 2012 | Turbine layout and curtailment update |
| C | March 8, 2012 | Updates to Noise Assessment and Power Curve sections |
| D | June 15, 2012 | Update to energy yields using new layout for northern parcel and considering wake effects from southern parcel on northern parcel energy |

**DISCLAIMER OF LIABILITY**

1. This report is prepared by us, Natural Power Consultants, LLC ("NP"), for you, Aspenall Energies, LLC (the "Client") to assist the Client in assessing the potential energy yield of the proposed Rokem wind farm. It has been prepared to provide general information to assist the Client in its decision, and to outline some of the issues which should be considered by the Client. It is not a substitute for the Client's own investigation and analysis. No final decision should be taken based on the content of this report alone.

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3. Our advice is based on a full energy yield analysis, based on recorded wind data and various computer models. In compiling this report, we have relied on information supplied to us by the Client and by third parties. We accept no Liability for the completeness and/or veracity of the information supplied to us, nor for our conclusions or recommendations based on such information should it prove not to be complete or true.

4. We have been asked to comment on the projected energy yield of the Rokem wind farm and advise on the turbine layout, in accordance with the Client's instructions as to the scope of this report. We have not commented on any other matter and exclude all Liability for any matters out with the said scope of this report. If you feel there are any matters on which you require additional or more detailed advice, we shall be glad to assist.

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# 1. SUMMARY

This energy yield report presents the analysis used to predict the expected average annual energy production (AEP) for the proposed Rokem wind farm in Santa Isabel County, Puerto Rico. The wind farm is divided into a northern parcel and a southern parcel. The northern parcel turbine layout used in this analysis was supplied by the client, while the southern parcel layout was designed by Natural Power (NP) and based on the constraints supplied by the client. An energy production assessment was performed for each of the layouts independently. In addition, the energy production was assessed for the northern parcel taking into account the wake effects from the southern parcel. Each layout had 6 turbines, but different rotor diameters and hub heights, as follows:

- Northern parcel: Vestas V100 1.8MW (95 m hub height); 6 turbine layout
- Southern parcel: Vestas V90 1.8MW (67 m hub height); 6 turbine layout

Site measurements have been collected at a single mast approximately 1.6 km (1 mi) southeast of the city of Santa Isabel. The 60m mast has provided wind speed measurements at 60 m, 50 m and 40 m AGL (above ground level) for 29 months. The mast is located in a coastal region on flat terrain with towns to the north-east and north-west and a mountainous terrain around 10km to the north of the mast location.

The site wind speeds were correlated to a reference data set from a meso-scale model and adjusted to the long term. Wind speeds were extrapolated to hub height using average shear computed on a monthly and hourly basis. The WAsP flow model was used to extrapolate the long term wind climate at the mast location to each turbine location. Energy yields were computed using WindFarmer 4.2.20.0.

Expected net AEP figures are given in Table 1-1 below. This report contains an uncertainty analysis of P50 and P90 exceedance estimates.

| Turbine (hub height) | P50 Net AEP GWh/ year | P50 Net Capacity Factor % | 10-year P90 Net AEP GWh/ year | 10-year P90 Net Capacity Factor % | 1-year P90 Net AEP GWh/ year | 1-year P90 Net Capacity Factor % |
|---|---|---|---|---|---|---|
| Vestas V100 (95 m) | 24.9 | 26.3 | 20.5 | 21.7 | 18.7 | 19.8 |
| Vestas V90 (67 m) | 18.0 | 19.0 | 15.2 | 16.0 | 13.5 | 14.3 |
| Vestas V100 (95 m) with V90 wake effects | 24.7 | 26.1 | 20.3 | 21.5 | 18.5 | 19.6 |

**Table 1-1 Summary of site production and efficiency for the northern parcel, southern parcel and the northern parcel including wake losses from the southern parcel.**

These production figures take into account modeled wake losses, and estimated losses due to turbine availability, blade degradation, control, turbulence, the site electrical system and curtailment.

Throughout this report direction sectors are often referred to by number. All analysis has been carried out using 12 30° sectors, with the center of sector 1 at 0°.

This report contains an uncertainty analysis. Comment has been made on any sources of uncertainty and these have been quantified to provide 90% probability of exceedance figures.

# 2. SITE DESCRIPTION

The site is 2 km southeast of the town of Santa Isabel on the southern coast of Puerto Rico. The site boundary was provided by the client. The land is split over two parcels, with a total of 2.85km$^2$ (1.1 square miles) available. The mast is located to the south of the southern land parcel, around 1km from the coast. The altitude of the site ranges from 2-10 m AMSL. The surrounding terrain is flat with a coastal marshy area to the south and east with the open ocean beyond. To the northwest of the mast there is the large town of Santa Isabel and further to the north, approximately 10 km (6 mi) from the site, there is a range of hills reaching up to 300 m above mean sea level (AMSL). Further north the terrain becomes quite mountainous and the elevation reaches up to 800 m AMSL.

All information about the site surroundings are based on information from the client and aerial imagery. A site visit has not been conducted by NP. Therefore, terrain, vegetation, and surroundings of neither the mast nor the turbines have been confirmed.

The layout for the northern parcel was provided by the client but also optimized to ensure the southern parcel would not affect the energy yields should it be developed in the future. The southern parcel was optimized in the previous analysis. The layouts for both the northern and southern parcels contain 6 turbines each. The northern parcel turbines are between 8 m and 11 m (AMSL) while the southern parcel turbines are between 1 m and 7 m (AMSL).

A regional context map of the project is included in Figure A-5. A detailed map showing the turbine layouts and the anemometry mast position is given in Figure A-1 and A-2.

## *2.1. Roughness map*

A roughness map of the site was digitized from freely available topographic maps and aerial imagery. This roughness map designated all areas within 10 km (6 mi) of the turbine locations with one of four roughness values.

Open areas were attributed a roughness length of 0.03 m. Forested areas were attributed a roughness length of 0.8 m. A roughness length of 1.0 m was attributed to the surrounding towns and industrial buildings. Open water features were designated with a roughness value of 0.000 m.

| Surface description | Roughness value (m) |
|---|---|
| Open water | 0.000 |
| Open farmland, grassland | 0.03 |
| Small trees, shrubs | 0.5 |
| Closed canopy forest | 0.8 |
| Villages and towns | 1.0 |

**Table 2-1 Surface roughness designations used**

## *2.2. Topography*

Digital terrain maps (DTM) data was obtained from the SRTM database (NASA) and converted into 10m contour data for an area at least 10 km (6 mi) in all directions from the site boundaries. The zero contour at the coast line was manually digitized using the image from Google Earth®. No obstacles have been modeled as part of this study.

## *2.3. Forestry*

There is no mature forestry close to the site. From the available aerial imagery, areas of scrubby trees have been identified along the coastline. It is not anticipated that they will contribute significant detrimental flow conditions across the site area.

## *2.4. Obstacles*

There are a number of large towns and smaller villages in close proximity to the site. The town of Santa Isabel lies approximately 2 km (1 mi) west of the site and there are smaller villages along the coast to the south west and the town of Jauca to the east. While these developments will contribute to the overall roughness around the site, they are expected to be located at a sufficient distance from any turbine as not to contribute any specific flow effects. The proximity of potential structures requires the careful consideration of turbine noise which is discussed later.

## *2.5. Layout*

Layouts were designed taking into account wind flow constraints and technical constraints. There are FAA height restrictions for the southern parcel of the Rokem wind farm limiting these 6 turbines to a hub height of 67 m. The northern portion of the Rokem wind farm is not limited by FAA restrictions; therefore these 6 turbines have a proposed hub height of 95 m.

A turbine layout for the southern parcel was designed by NP within site boundaries supplied by the client considering several constraints and setbacks, shown. The turbine layout for the northern region was provided by the client and is shown in Figure A-1**.** Per client request, NP optimized the northern parcel in order to address potential wake losses from the southern parcel turbines**.** The change in wake losses from the two layouts was minimal as the losses due to the southern parcel turbines decreased only 0.3% in the optimized layout. As such, the optimized layout was not used and the layout provided by the client for the northern parcel was used for the energy yield analysis.

Vestas V100 1.8MW turbines were used for the energy yield analysis for the northern region and the coordinates are given in Table A-1. Vestas V90-1.8MW turbines were used for the southern parcel and the layout can be found in Figure A-2 and Table A-2. Structures 2 and 4 within Figure A-2 were deemed farm buildings by the client. No buffer was applied to these two structures during optimization of the southern parcel. The client was unaware of any pipelines or microwave paths through the site; therefore it was assumed none exist..

The layout was designed to have a minimum elliptical separation distance of 4 rotor diameters (RD) in the predominant wind direction (90 degrees) and 2 RD in the direction perpendicular to the predominant wind direction. These cross-wind and down-wind spacing recognize the unidirectional nature of the site wind climate. The spacing is slightly less between some turbines in order to maximize capacity within the site boundaries in the northern region. All turbines are greater than 2 RD apart. It is recommended that turbine manufacturers are consulted to ensure the suitability of the layout with regards to IEC guidelines. Natural Power makes no claim to the suitability of the supplied layout with regard to specific turbine models.

It is recommended that all local regulations regarding turbine siting are confirmed and that the site is visited to ensure that all potential constraints have been considered.

## *2.6. Noise Assessment*

A noise assessment was carried out for the Vestas V100 and the Vestas V90 turbines using the simple noise model in Windfarmer 4.2.20.0. The noise limit used in the assessment

was 55 dB, provided by the client. A reference sound power level of 105 dB (A) was used with an attenuation of 2 dB/km.

The site designs from the previous analyses were constrained by several potential noise sensitive properties close to and within each site boundary. A minimum setback distance of 500 m from each structure has been maintained for properties within the southern parcel. In order to maintain the turbine layout for the northern parcel, building 10 required a setback of 400 m while building 9 required a setback of 350 m. These setbacks were in compliance with the noise limit specified by the client.

Structure locations have been identified using Google Earth images and the status of these properties should be confirmed. Two noise sensitive structures considered in the previous report (776947m E, 1987128m N and 776239m E, 1987424m N) were deemed farm buildings by the client and buffers have been removed to include additional turbines in the southern parcel of Rokem wind farm.

The turbine layouts and constraints as well as noise contours are shown in Annex A. Turbine coordinates are also given in Annex A.

## *2.7. Coordinate System*

Unless otherwise indicated, all coordinates in this report are given in UTM Zone 19, WGS84.

# 3. SITE DATA

One 60 m meteorological mast (Rokem) was installed in the vicinity of the site to collect wind data. The client provided an installation document detailing the mast configuration and the surroundings. Calibration certificates were not provided but were obtained through NRG online resources from the provided serial numbers. No site visit was carried out as part of this analysis; as such NP has not been able to visually check that the 60 m mast is configured as detailed in the documents provided by the client. Photos of the mast and immediate surroundings have been provided by the client. Table 3-1 shows a wind speed data summary for the 60m mast.

| | |
|---|---|
| Coordinates | 17° 57' 6.12" N, 66° 23' 25.82" W<br>UTM: 776400.9E, 1986782.9N |
| Data Start | 07/03/2009 |
| Data End | 11/03/2011 |
| Base height (in m AMSL) | 3 |
| Anemometer heights (in m AGL) | 60m E, 60m S, 50m E, 50m S, 40m N, 40m S |
| Mean measured wind speeds (m/s) | 5.8, 5.7, 5.6, 5.6, 5.4 5.3 |
| Mean measured wind shear exponent (all instruments) | 0.27 |
| Mean turbulence intensity > 3m/s | 12% |
| Data capture – raw data | 100% |
| Data capture – post QC | 82% |

**Table 3-1 Summary of data recorded at the 60m anemometry mast**

## *3.1. Mast and Instrumentation*

| Sensor | Channel | Type | Brand/Model | Height m (AGL) | Orientation |
|---|---|---|---|---|---|
| A1 | 1 | Anemometer | NRG #40 | 60 | 180° |
| A2 | 2 | Anemometer | NRG #40 | 60 | 90° |
| V1 | 7 | Wind Vane | NRG #200P | 60 | 0° |
| A3 | 13 | Anemometer | NRG #40 | 50 | 180° |
| A4 | 3 | Anemometer | NRG #40 | 50 | 90° |
| V2 | 8 | Wind Vane | NRG #200P | 50 | 0° |
| A5 | 14 | Anemometer | NRG #40 | 40 | 180° |
| A6 | 15 | Anemometer | NRG #40 | 40 | 0° |

**Table 3-2 Onsite anemometry equipment**

Based on information supplied by the client, the instruments were mounted on booms approximately 7.5 times the mast diameter in length and on stalks greater than 10 times the mast diameter in length. IEC recommendation 61400-12 (IEC, 1999) recommends that the booms should be longer than 8.5 times the mast diameter to ensure the instruments experience minimal flow distortion from the mast. On inspection of the data, the lower instruments were observed to experience noticeable mast shadowing effects. The effects on the top pair of instruments was less noticeable as the instruments were mounted proud of the top of the mast. However, flow distortion was visible and this would need to be accounted for in a detailed uncertainty analysis. The two 60m sensors were used to predict the long-term mean wind speed. The two wind speeds were averaged when neither was shadowed. If one sensor was affected by tower shadow, the wind speed from the other sensor was used.

The inspection of the mast shadow effects showed that some of the logger channels were incorrectly labeled. According to the tower shadow observed, the 60 m and 40 m sensors have been switched such that channel 1 was oriented 180° but the installation document noted the sensor oriented 90°. Channel 2 was actually oriented 90°, channel 14 180° and channel 15 0° while the installation document stated orientation 180°, 0°, and 180°. The orientations shown in Table 3-2 are correct. Annex B contains the full mast logger information with photos of the mast and surrounding terrain.

## *3.2. Raw data verification*

Raw mast data was provided by the client in the form of *.RWD files from an NRG Symphonie data logger. Raw data coverage and monthly mean speeds are reported in Annex C.

### 3.2.1. Rokem Mast

The Rokem mast's instruments recorded data in ten-minute intervals, using an NRG Symphonie logger. Calibration values were not provided in the commissioning document, but were obtained from NRG online resources using the sensor serial numbers. These documents listed NRG instruments and the corresponding transfer functions, and these transfer functions were applied to the raw data.

Correlations were performed between wind speed data from the average of the two 60m anemometers (A1/A2) and each other anemometer on the mast to validate the wind speed measurements at all heights. Only data from the sectors not affected by tower shadow were used in these correlations.

The correlation between wind speeds measured at A1 and A2 is excellent ($R^2$ = 0.997).

The correlation between wind speeds measured at A1/A2 and A3 is excellent ($R^2$ = 0.991).

The correlation between wind speeds measured at A1/A2 and A4 is excellent ($R^2$ = 0.992).

The correlation between wind speeds measured at A1/A2 and A5 is fair ($R^2$ = 0.976).

The correlation between wind speeds measured at A1/A2 and A6 is fair ($R^2$ = 0.972).

The correlation between wind speeds measured at A3 and A4 is excellent ($R^2$ = 0.995).

The correlation between wind speeds measured at A5 and A6 is excellent ($R^2$ = 0.994).

When the wind blows from the opposite direction from which the anemometer booms are oriented, the flow is obstructed by the mast and leads to a reduction in the wind speed recorded. This occurrence is known as "tower shading". If multiple anemometers are mounted at the same height, when one anemometer is shaded, the wind speed can be replaced with the wind speed recorded at the non-shaded anemometer.

At the 60-m level, the anemometer booms were mounted at the top of the mast, and there was minimal tower shadow effect on the wind speeds recorded at that height. When wind speeds from both anemometers were valid, the wind speeds from both were averaged to obtain a representative 60-m wind speed. At the 50-m level, data from wind directions between 255 to 285 degrees were affected at anemometer A3 and data from wind directions between 0 and 30 degrees were affected at anemometer A4. When one anemometer was affected, the wind speed from the other anemometer was used. When both anemometers had valid data, the wind speeds from both were averaged to obtain a representative 50-m wind speed. At the 40-m level, data from wind directions between 5 to 35 degrees were affected at anemometer A5 and data from wind directions between

170 and 200 degrees were affected at anemometer A6. When one anemometer was affected, the wind speed from the other anemometer was used. When both anemometers had valid data, the wind speeds from both were averaged to obtain a representative 40-m wind speed.

Winds flowing over the top of the mast are also likely to experience flow distortion effects. Because the 60-m anemometer booms are mounted at the top of the mast, it is possible that the wind speeds have been over-reported from those anemometers. The data available cannot provide sufficient information about the magnitude of any speed-up effect experienced at these anemometers. Given the length of the booms of upon which these instruments are mounted, it has been concluded that mast speed up at 60m is negligible; therefore, no correction has been applied to the wind speed data to account for these effects.

### *3.3. Dry Friction Whip*

Dry friction whip is a mechanical malfunction prevalent in NRG #40 anemometers manufactured between 2006 and 2008. Instruments affected by DFW occasionally enter a vibratory mode which causes a slow-down and underreporting of wind speeds. The problem often worsens over time after sensor deployment.

The best way to assess data potentially affected by DFW is to compare it to concurrent data from a properly functioning anemometer mounted at the same height on the same mast. NRG has suggested some statistical tests that can be used to detect instances of DFW, listed in Table 3-3. Often a relationship between wind speeds from the two sensors can be used to derive a correction for the DFW-affected data.

| Statistic | Expected normal performance |
|---|---|
| Mean bias | ≤ ±0.2 m/s |
| Ratio | Within 0.98-1.02 |
| Pearson's correlation coefficient | ≥ 0.995 |
| Standard deviation of the wind speed ratio | ≤ 0.02 |
| Test 1: Exceedance of the mean bias threshold for 3 out of 5 consecutive weeks | |
| Test 2: Exceedance of any 2 or more threshold statistics for 4 consecutive weeks | |

**Table 3-3 Statistical tests for detecting DFW (Clark, 2009)**

Natural Power ran the suggested tests on wind speed data from the pair of anemometers at each height. The sensors used at the Rokem mast are outside the known time period of affected sensors. The series of tests for each sensor was still applied and minimal bias was observed, but is within the standard magnitude of error for NRG anemometers and not believed to be a result of DFW.

# 4. LONG-TERM ADJUSTMENT

In order to determine the average energy production over the wind farm project lifetime, it is necessary to correlate the site-measured data, typically measured over a short period such as one year, with longer-term data usually measured at a meteorological (reference) station for a consistent period assumed to be representative of the long term.

To determine the estimated long-term site wind climate, the onsite data was corrected using a monthly measure-correlate-predict (MCP) method. This method involved setting up a statistical relationship between the monthly averages of the concurrent data sets at the site and reference station. The relationship was then used to project the short term data measured on site into the longer term. It should be noted that a "prediction" in the MCP sense is in fact an extrapolation into the past, and assumes that the next *n* years will be equal to the past *n* years.

## *4.1. Selection of Reference Station*

The search for a suitable reference station is the first step of the MCP method. The reference station should have a similar climatology to the site and not have been subject to any changes which would affect the consistency of the historic period. Stations surrounding the site and within 80 km (50 mi) from the site center were considered for use. Two reference long-term data sets with concurrent data to the measured site data was assessed, which is an Automated Surface Observation Stations (ASOS) operated by the National Climatic Data Center (NCDC) and data from the Vortex mesoscale model

All ASOS stations were originally equipped with cup anemometers that have subsequently been replaced with sonic ice-free wind (IFW) sensors. This sensor change creates an inconsistency within the data set and only data sets with consistent instrumentation are considered suitable as a long-term reference.

The San Juan L M Marin Airport (SJU) ASOS station is located in San Juan, approximately 52 km (33 mi) north of the site, on the north coast of Puerto Rico. Data is available from July 1996 to present. The wind speed sensor was changed in January 2009. Data from San Juan L M Marin Airport was only used after January 2009.

The Roosevelt Road (NRR) ASOS station is located in Ceiba County, approximately 61 km (38 mi) northeast of the site, on the east coast of Puerto Rico. Data is available from December 2005 to present, but is missing from December 2008 to September 2010. The wind speed sensor was changed in June 2009.

Data from the Vortex meteorological model (Vortex) was obtained for the site. Vortex is a site-specific meteorological model that is seeded with NCEP/NCAR reanalysis data and downscaled from macro-scale to meso-scale and micro-scale by running the Weather Research and Forecasting (WRF) model on nested domains. The model outputs a time series of hourly wind speed and direction data at a 3-km spatial resolution at 60 m AGL. Vortex modeled data for the site was available from 2002 to present.

Correlations were performed between monthly mean wind speeds from each of the masts to each of the potential references. The reference data sets were evaluated based on the resulting correlation coefficients, as well as consistency of data (absence of trends or step changes), length of data set, and similarity of wind distributions to the site.

Using monthly correlations, the long-term mean wind speed predicted from the site using 10 years of data from Vortex was 5.33 m/s and using 2.75 years of data from SJU was 5.15 m/s. The long-term mean wind speeds at each hub height was extrapolated from the long-term mean wind speed at the height of the mast (60m) by using a factor of 1.05.

The strongest correlations were observed to the Vortex model data set, which also had a significantly longer period of consistency than any of the empirical reference data sets. The Vortex data was used for the subsequent analysis and the monthly correlations are found in Figure C-8.

It should be noted that the previous assessment of the Rokem mast correlated the site mast data to the Magueyes Islands as well as the San Juan airport. This assessment also correlated the updated Rokem site data to the San Juan airport, but additionally correlated with Roosevelt Roads ASOS and Vortex model output. Correlating site data with Vortex output was not in practice when the previous report was released and has since become a common resource for wind speed correlations and reference station data.

Test correlations were run with both reference stations. The data from the San Juan L M Marin airport met station did not correlate with the site data with an r-value of 0.75. The data from the Vortex model showed a strong correlation with the site wind speed data with an r-value of 0.80 thus this reference source was used for a long term correction.

The wind regimes at the reference stations and the site both show a strong diurnal pattern, due to the coastal locations of the measurement points. Because the reference stations are on the north and east coast while the site is on the south coast, the wind roses of the site versus those from the reference stations show variations in the observed direction distributions. All of the wind roses show a strong easterly predominance, consistent with expectations of this location. The San Juan L M Marin airport and Roosevelt Roads reference stations are mostly in sectors 3 and 4 while the site's wind rose is more spread across sectors 3, 4 and 5, with the majority of the energy in the wind coming from sectors 3 and 5. Vortex wind frequency is mainly in sector 3 with a moderate amount in sectors 4 and 5. There is little data in any of the westerly sectors at either the site or the reference station and vortex.

The wind roses for the site, the San Juan L M Marin airport, Roosevelt Roads reference stations and Vortex model data are shown in Figure C-9, Figure C-10, Figure C-11 and Figure C-12.

A validation of the use of the Vortex modeled data in Puerto Rico was performed by obtaining a meso-scaled modeled time series for Rokem, including 60m and 80m. Additionally, the modeled data from Guayama was used at 60m as well as 80m. Each modeled data set was compared to the long term trends of the reference ASOS stations previously mentioned. Figure C-7 contains the long term trends of both Vortex modeled data sets and each ASOS station.

The meso-scale modeled data provided the strongest monthly and daily correlations with the on-site dataset than the San Juan LM Marin airport and Roosevelt Roads ASOS stations.

A regional context map showing the position at which the meso-scale dataset, each NOAA ASOS station as well as the Rokem mast is included in Figure A-5.

## 4.2. MCP

To correct the on-site measurements for the long-term, the measure-correlate-predict (MCP) methodology was applied using monthly wind speed averages over a concurrent period between the site mast and the Vortex model data set.

Monthly 60-m mean wind speeds from the on-site mast were correlated to Vortex over the concurrent period of record. The monthly wind speed correlation had an $R^2$ value of 0.80. A linear regression function was applied to the long-term mean annual wind speed from Vortex to predict the long-term mean wind speed at the Rokem mast at 60 m AGL, as detailed in Table 3-1. The correlation is shown graphically in Annex C, Figure C-8.

The overall correlation coefficient ($R^2$ value) between the mast and the reference station was 0.80. This is considered acceptable in MCP best practice, i.e. over 0.70. The results are shown, together with details of the correlation, in Table 4-1. The correlation can be seen graphically in Figure C-8. The average wind speed of the two 60m instruments was used to predict the long term site wind speed as detailed in Section 3.1.

| | |
|---|---|
| Gradient | 0.96 |
| Intercept | 0.23 |
| Mean of long-term reference data (60 m) | 5.3 m/s |
| **Mean of long-term prediction (60m)** | **5.3 m/s** |

**Table 4-1 Monthly MCP results for Rokem site and Vortex modeled data**

## 4.3. Windiness Index

A windiness index for the site was also calculated to provide an additional estimation on the long term site wind speed. The windiness index is the ratio of the reference long-term mean wind speed to the reference mean wind speed over a concurrent period. The concurrent period used in this analysis was July 2009 through November 2011. Details of the windiness index are given below in Table 4-2.

| | |
|---|---|
| Mean of concurrent site data (60 m) | 5.1 m/s |
| Mean of concurrent reference data (60m) | 5.0 m/s |
| **Mean of long-term prediction (60 m)** | **5.3 m/s** |

**Table 4-2 Windiness index results from Rokem mast**

## 4.4. MCP results

The results of the monthly correlations performed with the Vortex data validate the use of this reference data set in the analysis. The long-term mean wind speeds at the mast location used in this analysis were the values given in Table 4-1.

# 5. TURBINE SELECTION

NP has been asked to estimate the power production for two Vestas turbine models and two hub heights provided by the client.

- Vestas V100, 1.8MW, with a rotor diameter of 100m and a hub height of 95m.
- Vestas V90, 1.8MW, with a rotor diameter of 90m and a hub height of 67m.

The client is advised to ensure that the selected turbine meets the manufacturer's criteria for site compliance. Natural Power has not been asked to assess, and makes no claims about the suitability of the selected turbine with respect to the site conditions, IEC class, or any other criteria. Due to the location of this site in a potential hurricane region, it is recommended that the client commissions a site classification report.

## *5.1. Turbine Selection*

Natural Power was asked to estimate the power production for two turbine types provided by the client, the Vestas V100-1.8 MW (northern parcel) and Vestas V90-1.8MW (southern parcel).

Summary of the turbine power curve is given in the following tables. Further details of the power curves are given in Annex D.

| | |
|---|---|
| Type of power curve | Calculated |
| Source of power curve | From Client |
| Power curve density | 1.225 kg/m$^3$ |
| Rotor diameter | 100 m |
| Cut in-out wind speed | 3-20 m/s |
| Turbulence Intensity | 8% - 12% |
| Power and thrust curve in detail | Figures D-1 and D-2 |

**Table 5-1 Summary of the Vestas V100-1.8 MW data**

| | |
|---|---|
| Type of power curve | Calculated |
| Source of power curve | From Client |
| Power curve density | 1.225 kg/m$^3$ |
| Rotor diameter | 90 m |
| Cut in-out wind speed | 4-25 m/s |
| Turbulence Intensity | 6% - 12% |
| Power and thrust curve in detail | Figures D-3 and D-4 |

**Table 5-2 Summary of the Vestas V90-1.8 MW data**

## *5.2. Site Climatic Conditions*

The Vestas V100-1.8 MW is a class IEC S turbine. It is designed for class IEC IIIA average conditions and class IEC IIA extreme conditions. This classification is practical for a site with this type of climate, with low average wind speeds, high turbulence, and the potential for high extreme winds. NPC examined the site climate in relation to the turbine design parameters. Based on this initial analysis, it is expected the site average wind speed is within turbine design limits, the turbulence intensity and extreme winds are near the limits, and the shear exceeds the limits. However, a detailed site suitability analysis was not performed, and it is recommended that the client have discussions with the turbine manufacturer to ensure this turbine model would be suitable for this site, especially in relation to the high shear and extreme winds.

The Vestas V90-1.8 MW is a class IEC IIA designed for class IEC IIA average conditions. This classification is practical for a site with this type of climate, with low average wind speeds, high turbulence, and the potential for high extreme winds. NPC examined the site climate in relation to the turbine design parameters. Based on this initial analysis, it is expected the site average wind speed is within turbine design limits, the turbulence intensity and extreme winds are near the limits, and the shear exceeds the limits. However, a detailed site suitability analysis was not performed, and it is recommended that the client have discussions with the turbine manufacturer to ensure this turbine model would be suitable for this site, especially in relation to the high shear and extreme winds.

### 5.2.1. Average Wind Speed

The V100 is designed for an average hub-height wind speed of up to 7.5 m/s. The predicted long-term mean hub-height wind speed for all turbines is less than 7.5 m/s.

The V90 is designed for an average hub-height wind speed of up to 8.5 m/s. The predicted long-term mean hub-height wind speed for all turbines is less than 8.5 m/s.

### 5.2.2. Turbulence Intensity

The documentation for the V100 and V90 (Vestas Wind Systems A/S, 2010) states that it is designed for a 90% quantile TI of 18% at 15 m/s. The IEC standard for a class A turbine is for a mean TI of up to 16% at 15 m/s. The TI for this site has been measured at 60 m AGL at the mast location. There is significant uncertainty in the extrapolation of the mast TI to the turbine locations due to the difference in mast height and hub height, and the shortage of data records for wind speeds of 15 m/s. At the mast, the mean TI at 15 m/s is projected to be approximately 11%, while the 90% quantile TI at 15 m/s is projected to be approximately 15%. It can be expected that the TI will decrease with height above the ground. However, the TI at some, if not all, turbine locations will be increased due to wake-added turbulence.

### 5.2.3. Wind Shear

The V100 and V90 are designed for an average wind shear across the rotor (45 m to 145 m AGL) of up to 0.20. The measured shear between 40 m, 50 m and 60 m AGL at the mast location is significantly higher than this limit, particularly through the night, when the atmospheric conditions become stable. It's possible that the shear at greater heights and at the turbine locations is lower. This issue should be investigated further, and would be best assessed with the use of a remote sensing device at or near the mast/turbine locations with measurements up to tip height. If shear is found to exceed the turbine design limits, then the turbine manufacturer will need to decide if these conditions will be detrimental to the machine, and another turbine model, likely with a smaller rotor, may need to be considered.

### 5.2.4. Extreme Winds

The V100 and V90 are designed to withstand extreme wind speeds up to a 10-min average of 42.5 m/s or a 3-second gust of 59.5 m/s. The extreme wind is defined as a 50-year maximum, or the wind speed that has a probability of occurring once every 50 years. There are several statistical methods, and variations within each method, to estimate this value based on a shorter data set. This site's tropical location, and therefore susceptibility to hurricanes, must also be considered.

The period of site data collection was not sufficient for extreme value analysis, so data from the San Juan ASOS station was used and extrapolated to the site location. Extreme wind speeds were estimated using a Gumbel distribution applied to annual wind speed maxima, a General Pareto Distribution (GPD) applied to daily maxima, an extended method of independent storms (XIMIS), and the European Wind Turbine Standard (EWTS). These methods, and variations within each, yielded values ranging from 16 m/s to 39 m/s, with the most confident estimates falling in the range of 20 to 25 m/s. The most confident estimates yield the upper wind speed at 30 m/s, which is well within the 50-year, maximum 10-min average extreme wind speed for both V100 and V90. However, with the upper end at 39 m/s, the hub height 50- year maximum 10-min average wind speed is above the wind speeds for both the V100 and V90. Based on the data and the statistical analysis, it is unlikely that wind speeds at this site will be observed exceeding the maximum 10-min wind speed limits for either the V100 or V90.

The effect of tropical storms and hurricanes must also be considered. Based on records from NCDC and the National Hurricane Center (NHC) from the past 16 years, tropical cyclones (including tropical storms and hurricanes) make landfall in Puerto Rico an average of just less than once every 2 years. The number of hurricanes hitting Puerto Rico is less. A hurricane is defined as having a 1-min average wind speed of at least 33 m/s.

The highest 1-min average wind speed recorded at San Juan in 20 years was 35 m/s. The highest officially recorded wind speeds anywhere on the island in recent history were associated with Hurricane Georges (1998) and Hurricane Hugo (1989). Georges saw maximum 1-min average wind speeds up to 40 m/s and maximum 5-sec gusts up to 48 m/s. Hugo brought maximum 10-min average wind speeds up to 40 m/s, maximum 1-min average wind speeds up to 44 m/s, and maximum 5-sec gusts up to 54 m/s. When considering these values, it should be noted that official observations are generally taken at 10 m AGL, and that wind speed can be expected to increase with height, and that 1-min averages will generally be higher than 10-min averages. Also, extreme winds are a localized phenomenon, meaning that the wind could be 40 m/s in San Juan and only 20 m/s in Rokem, or vice versa.

Given the information on hurricane winds, it could be reasonably assumed that the 50-year extreme winds at the site would be of a similar magnitude to those highest wind speeds cited above. If that conclusion is made, then the extreme site climate would fall just within the design limits of the V100 and V90.

A more thorough analysis of hurricanes and extreme winds is recommended to better ascertain whether the V100 and V90 are suitable for this site, and these conditions should be further discussed with the turbine manufacturer.