

Wind Resource Assessment of a Site in Western Australia

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Abstract

This study estimates the long-term wind resource at a site on the north-western coast of Western Australia by means of the Wind Atlas and Measure-Correlate-Predict (MCP) methodologies, in order to determine its suitability as a site for a wind farm.

1. INTRODUCTION

A key factor in determining the economic viability of a candidate site for a wind farm is the long-term average wind speed. Year to year variability in the average wind speed requires that an on-site measurement campaign be conducted for at least five to ten years in order to establish the long-term wind resource at the site. As this technique is lengthy and costly, several alternative, cost-effective methods of estimating the long-term wind resource have been developed, such as those identified by Landberg *et al* (2003). Two of the most commonly used techniques for estimating the long-term wind resource at a potential site are the Wind Atlas methodology and the Measure-Correlate-Predict (MCP) methodology.

At the request of a mining company, the Research Institute for Sustainable Energy (RISE) initiated a 12-month measurement campaign at a potential wind farm site on the north-western coast of Western Australia. The wind data yielded a very promising short-term average wind speed. With the permission of the mining company and RISE, this data was made available to the authors for the purposes of this project. The project utilises the Wind Atlas and MCP methodologies to estimate the long-term wind resource at the candidate site, in order to evaluate the site's suitability for a wind farm.

2. COLLECTION OF WIND DATA

2.1. Short-term data from the candidate site

Wind data monitoring was undertaken by RISE between November 2002 and October 2003 at a candidate site, referred to as WA-Y, on the north-western coast of Western Australia. The resulting 12 months of half-hourly wind speed and direction data was subject to the validation processes described in the Wind Resource Assessment Handbook (NREL, 1997).

During the measurement period the wind speed averaged 10.7 ms^{-1} at 40 m height above ground level (a.g.l.). Extrapolated to 50 m a.g.l., this corresponds to a Class 7 resource according to the Wind Power Class rating system of the Wind Energy Resource Atlas of the United States (US Department of Energy, 1986). This rating system is used worldwide to classify wind sites and sites of Class 3 or above are generally held to be economically viable for wind power applications. Class 7 is the highest class of wind speed and encompasses average wind speeds of 8.8 ms^{-1} – 11.9 ms^{-1} at 50 m a.g.l..

The monitored data also revealed a highly directional wind resource, with almost 75 per cent of wind incident from the quadrant between SW and SE. Figure 1 displays the wind rose and wind speed distribution, as well as parameters derived from the Weibull fit to the wind speed distribution.

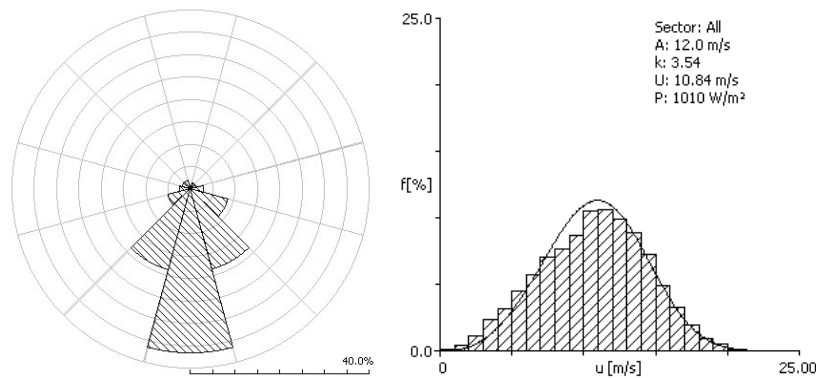


Figure 1 Wind rose and wind speed distribution for short-term data from WA-Y.

2.2. Long-term data from a reference site

In order to apply the Wind Atlas and MCP methodologies, a 10-year data set overlapping the 12-month measurement period at WA-Y was obtained from the nearest Bureau of Meteorology station. This reference site, referred to as WA-X, is some 80 km distant from the candidate site and located in a similar coastal situation to the WA-Y site. The data set, comprised of half-hourly wind speed and direction records was subjected to the Bureau's data quality control process prior to data validation by RISE in accordance with NREL guidelines; hence the data is believed to be of high quality.

Analysis of the WA-X dataset revealed an average long-term wind speed at the WA-X site of 6.1 ms^{-1} at 10m a.g.l.. Inter-annual variation in the average wind speed of up to nine per cent was observed over the 10-year period, while the annual average wind speed for the period concurrent to the duration of the WA-Y monitoring campaign was approximately three per cent greater than the long-term average wind speed.

The long-term wind direction frequency distribution and wind speed distribution for the WA-X site are shown in Figure 2. The parameters relating to the Weibull fit to the frequency distribution are also displayed.

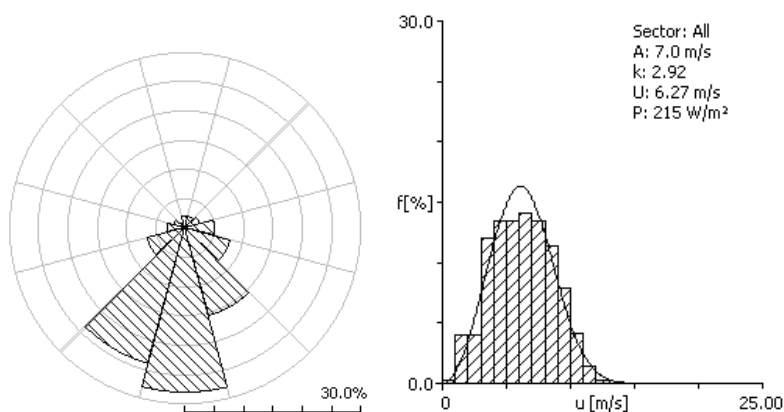


Figure 2 Wind rose and wind speed frequency distribution for long-term data from WA-X.

Figure 3 displays wind speed data from WA-Y plotted against concurrent wind speed data from WA-X. The graph reveals a distinct linear trend, with a correlation coefficient of 0.68. It also reveals a substantial amount of scatter in the data, particularly for wind speeds at WA-X of less than 6 ms^{-1} .

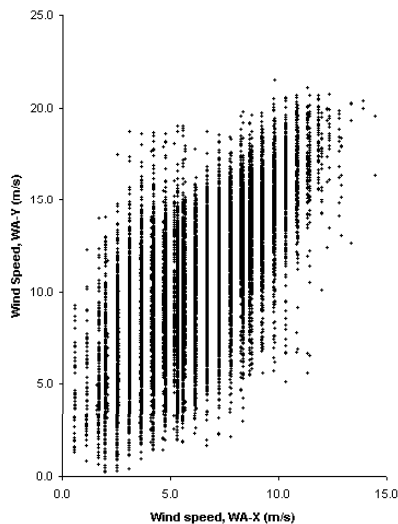


Figure 3 Correlation between wind speeds at WA-X and WA-Y.

3. WIND ATLAS METHODOLOGY

3.1. Summary of the Wind Atlas method

The Wind Atlas Analysis and Application Program (or WA^{SP}), described in detail by Mortensen *et al* (2003), is a widely used computer program that is able to generalize a set of surface wind observations into a regionally representative set of wind statistics by modeling the wind flow across the landscape.

In the *analysis* mode, the statistics derived from a set of long-term wind speed and direction data from a long-term reference site are used to create an Observed Wind Climate, or OWC. The OWC is then extrapolated to the top of the boundary layer by fitting to a Weibull distribution and modeling the effects due to obstacles, terrain roughness and orography at the reference site. The resulting set of wind speed and direction statistics representative of the geostrophic wind over the region is known as a *Wind Atlas*. In the *application* mode, a prediction of the wind resource at a candidate site is generated from the Wind Atlas data by extrapolating down from the top of the boundary layer, effectively applying the reverse of the *analysis* process.

The following conditions must be observed in order for WA^{SP} to provide accurate predictions of the wind regime at a candidate site:

1. The reference site (meteorological station) and predicted site (WTG [wind turbine generator] site or met. station) are subject to the same overall weather regime;
2. The prevailing weather conditions are close to being neutrally stable;
3. The reference wind data are reliable;
4. The surrounding terrain (of both sites) is sufficiently gentle and smooth to allow mostly attached flows; and,
5. The topographical model inputs are adequate and reliable.

(Mortensen & Petersen, 1997: 317)

3.2. Application of WA^{SP} to the WA-X data

An OWC was generated from the 10-year wind data set from the WA-X site. In order to generate the regional Wind Atlas from the OWC, descriptions of the obstacles, terrain roughness and orography at the WA-X site were created.

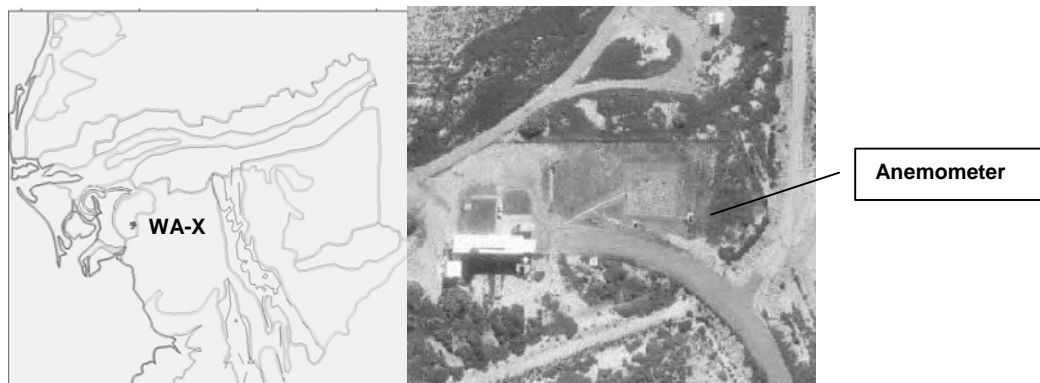


Figure 4 (left) Elevation and roughness contours in the area surrounding the WA-X site. (right) Detail of obstacles surrounding the reference anemometer obtained from SkyView WA.

The configuration and dimensions of obstacles at the reference site were calculated using the SkyView WA online digital aerial ortho-photography service (Skyview WA, 2000), in conjunction with digital photographs of the reference site. The SkyView WA service was used to calculate dimensions and displacements for obstacles located near the reference anemometer to a precision of ± 0.5 m, while heights of the obstacles were calculated from the obstacles' proportions, as determined from digital photographs of the site.

A map of height contours and terrain roughness encompassing the 100 km^2 region surrounding the WA-X site was constructed. The contour data was extracted from digitised 1:100 000 topographical maps. The roughness lengths of the terrain surrounding the WA-X site were ascertained from the same topographical maps, together with information from the SkyView WA service. Roughness length estimates were based on values suggested by Landberg *et al* (2004) and crosschecked with values used in the Western Australian Wind Atlas (Dear *et al*, 1990) to ensure consistency.

Identical procedures to those outlined above were used to generate descriptions of the obstacles, terrain roughness and orography at the candidate site.

3.3. Results

WA^SP predicted a long-term average wind speed of 9.2 ms^{-1} and a wind power density of 657 Wm^{-2} at 40 m a.g.l. at the WA-Y site (derived from a fitted Weibull curve). Figure 5 displays the predicted wind rose and wind speed frequency distribution.

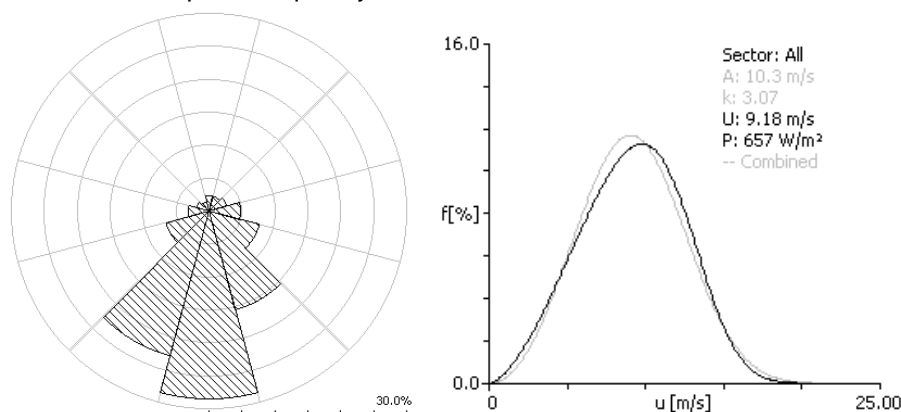


Figure 5 WA^SP predicted wind rose and wind speed frequency distribution for WA-Y.

3.4. Discussion

The average wind speed predicted by WA^SP was 14 per cent below the measured short-term average wind speed of 10.7 ms⁻¹. Extrapolating the predicted resource to 50 m a.g.l., this corresponds to a Class 6 wind power rating.

Aspliden *et al* (1986), as cited by Manwell *et al* (2002), propose that a one-year measurement campaign is sufficient to predict the long-term average wind speed to within 10 per cent, at a 90 per cent level of confidence, suggesting that the WA^SP predicted wind speed might be inaccurate. Some of the factors affecting the accuracy of WA^SP's prediction of the average wind speed are discussed below.

A high correlation between the weather regimes at the reference and candidate sites is considered essential to the accuracy of wind speed predictions made by WA^SP. The correlation coefficient for the 12 months of simultaneous data is 0.68, signifying that the two sites are subject to generally similar weather regimes. WA^SP assumes a correlation coefficient of one, so the accuracy of the prediction may be reduced, however the value of the correlation coefficient is indicative of neither the magnitude nor sign of the prediction error (Bowen & Mortensen, 1996).

WA^SP assumes that atmospheric conditions are neutrally stable. There is no information regarding atmospheric stability at either site, so this factor must be considered to add to the uncertainty of the wind speed prediction.

Differences between the complexity of the terrain at the reference and candidate sites can be a significant source of prediction error. A measure of the orographic complexity of terrain is the Ruggedness Index (RIX), described in detail by Bowen & Mortensen (1996). RIX describes the percentage of terrain with a slope greater than 0.3 and is thereby a coarse measure of the propensity for flow separation. A non-zero RIX is indicative of flow separation, a situation outside the performance envelope of WA^SP. Differences between the RIX at the reference and target sites can lead to large prediction errors, while sites of similar complexity may experience more accurate predictions due to a cancellation of the prediction errors resulting from flow separation at each site.

The two sites have dissimilar complexity: the reference site is flat, with a RIX of zero, while the target site has RIX ranging from 0 per cent to 2.2 per cent, primarily due to the cliff line seen in Figure 6. Consequently a prediction error is expected. As the target site is more complex than the reference site, however, the sign of this error would be expected to be positive (i.e. over prediction of the wind resource). A study of Portuguese and French sites by Mortensen and Petersen (1997) suggest that the magnitude of the wind speed prediction error due to a RIX difference in the above range could be expected to be in the order of ± 5 per cent.

The resolution of the available topographic data may reduce the accuracy of wind flow modelling over the terrain surrounding the target site. Landberg *et al* (2004) recommend topographic map data of 1:25 000 or 1:50 000 resolution, with a contour interval of less than 20 m for use with WA^SP. Due to the isolation of the target site, such detailed data was not available, requiring contour data at both the WA-X and WA-Y sites to be derived from manually digitised maps of the 1:100 000 National Topographic Map Series. This series of maps, constructed from aerial surveys conducted in 1974, have a contour interval of (20 ± 5) m and a horizontal resolution of 25 m. The uncertainty in the contour height is likely to have been further increased by the digitising process.

The study by Mortensen and Petersen (1997), mentioned previously, determined that wind speed prediction error is highly sensitive to the height contour interval of topographical input data above a threshold of ≈ 20 m. While the size and horizontal contour line accuracy of each of these maps is adequate according to their guidelines, the contour interval is on the threshold of recommended resolution and hence may not be sufficient to accurately model wind flow.

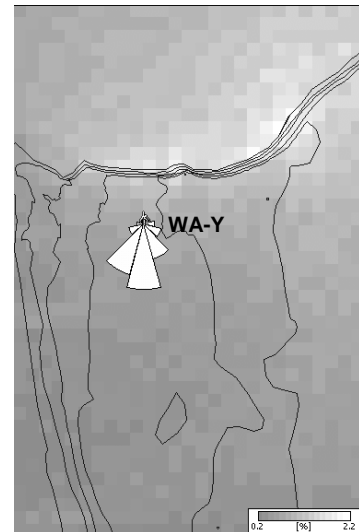


Figure 6 Terrain ruggedness at the WA-Y site (light areas are most rugged).

Dissimilarities between the wind direction frequencies derived from the short-term measurements at the candidate site, and those predicted by WA^sP may indicate that WA^sP has inaccurately modelled the flow. A comparison of the wind rose constructed from short term measurements at the candidate site (Figure 1), and the Wind Atlas rose derived from the long-term data from the reference site suggest that winds incident from the 150° and 210° sectors are being funnelled into the 180° sector at the candidate site, an effect not predicted by WA^sP (Figure 5). Bowen and Mortensen (1996) attribute this effect to steep oblique ridges, although there are no prominent ridges in the terrain between the WA-X and WA-Y sites.

The transformation applied to the reference wind data in order to generate the Wind Atlas can introduce prediction errors. In the *analysis* mode, the Wind Atlas is generated by forcing a Weibull fit to the measured reference wind speed frequency distribution. This transformation can introduce prediction errors, especially if there is a poor fit between the measured data and Weibull curve. WA^sP's *self-prediction* function revealed the wind speed prediction error resulting from the analysis process to be approximately -3%.

In predicting the wind regime at the WA-Y site it is apparent that the operational envelope of WA^sP has been violated; in particular, the correlation between the weather regimes at the WA-X and WA-Y sites has been shown to less than ideal. For this reason it is likely that the wind speed prediction made by WA^sP is inaccurate.

4. MEASURE-CORRELATE-PREDICT (MCP)

4.1. Summary of the MCP method

MCP is a statistical technique used for predicting the long-term wind resource at a candidate site by relating measurements from a short-term measurement campaign at the candidate site to long-term measurements at a reference site. The MCP method is described in detail by Derrick (1993) and Manwell (2002), but can be summarised as follows:

Wind speed and direction data are recorded simultaneously at both the reference and candidate sites over a recommended minimum period of one year. The concurrent data from the reference and candidate sites is binned according to the reference wind direction. For each direction bin a straight line is fitted to the data to relate the wind speed at the candidate site, y , to that at the reference site, x , and the coefficients m and c are determined through linear regression:

$$y = mx + c \quad (1)$$

To establish the goodness of fit, the standard deviation of each y estimate, corresponding to each x , is given by:

$$\sigma(y) = \sqrt{x^2 \sigma^2(m) + \sigma^2(c) + 2x \text{cov}(m, c)} \quad (2)$$

The long-term reference data are binned according to wind direction and for each direction bin the corresponding coefficients are used to adjust the wind speeds accordingly, producing predicted wind speed distributions for each sector. The predicted long-term average wind speed for each sector, \bar{y} , is determined by:

$$\bar{y} = \sum_i p_i y_i \quad (3)$$

In Equation 3, i is the wind speed bin index and p_i is the probability of y being in the i^{th} wind speed bin. The corresponding standard deviation of this estimate, $\sigma(\bar{y})$, is given by:

$$\sigma(\bar{y}) = \sqrt{\sum_i (p_i \sigma(y)_i)^2 + \sum_i \sum_j 2 p_i p_j \text{cov}(y_i, y_j)} \quad (4)$$

The long-term average wind speed at the candidate site, \bar{Y} , is derived from the average wind speed for each of the direction sectors:

$$\bar{Y} = \sum_k p_k \bar{Y}_k \quad (5)$$

In Equation 5, k is the sector index and p_k is the probability of \bar{y} being in the k^{th} sector. The overall standard deviation of the long term average wind speed, $\sigma(\bar{Y})$, is:

$$\sigma(\bar{Y}) = \sqrt{\sum_k p_k \sigma(\bar{Y}_k)} \quad (6)$$

4.2. Application of MCP to the data from WA-X and WA-Y

Prior to the application of the MCP procedure, the concurrent wind speed time series was filtered to improve correlation quality. The scatter observed in Figure 3 contributed to extremely poor correlations in some direction sectors when the MCP procedure was applied to the raw data. Much of this scatter is attributed to random, short-term wind speed variations caused by turbulence.

The filtering process employs a running average with a cut-off period of 17 hours. This process follows the suggestion of Derrick (1993) and is aimed at removing sub-diurnal effects while retaining the uncertainty associated with the long-term diurnal cycle at each site, thereby emphasising long-term wind speed relationships. The result, displayed in Figure 7, was a substantial reduction in scatter and a corresponding increase in the correlation coefficient to 0.88.

The filtered, concurrent wind data was subsequently binned into twelve 30° sectors and linear relationships generated to relate the wind speeds at the two sites.

The MCP procedure outlined above was executed using MS Excel. The procedure was checked in the manner suggested by Manwell *et al* (2001) by verifying that the mean wind speed for the concurrent period at WA-X (6.29 ms^{-1} at 10 m a.g.l.) could be predicted using the data from WA-Y. The average wind speed at WA-X was predicted to within 0.01 ms^{-1} . The predicted wind speed frequency distribution for the WA-X site was, however, substantially contracted, as can be seen in Figure 8. The contraction is consequence of regression line slopes of less than unity (average = 0.41) and intercepts greater than zero (average = 1.35).

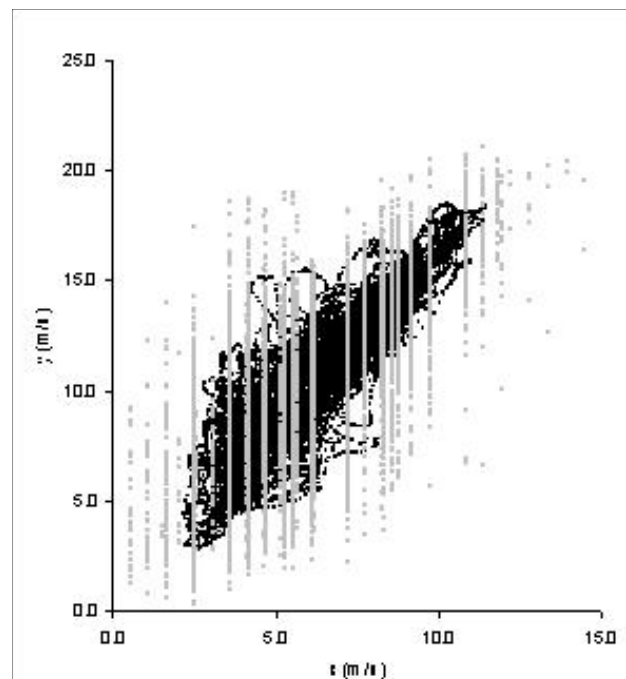


Figure 7 Comparison of the correlation between filtered, concurrent wind speed data (black) and the raw wind speed data (grey).

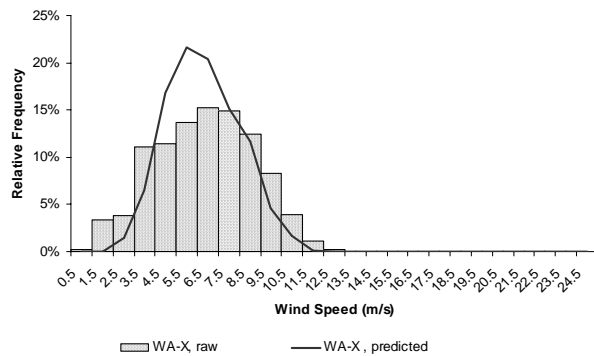


Figure 8 Comparison of the measured short-term wind speed frequency distribution for WA-X, and the distribution predicted from the short-term WA-Y data.

The linear relationships derived from the concurrent data were applied to the 10-year dataset from WA-X to predict the long-term wind speed and direction distributions at the WA-Y site.

4.3. Results

The long-term average wind speed at WA-Y was predicted to be 10.6 ms^{-1} , with a standard deviation of 0.4 ms^{-1} , at 40 m a.g.l.. Figure 9 compares the MCP predicted long-term wind speed frequency distribution with the short-term wind speed frequency distribution measured at WA-Y.

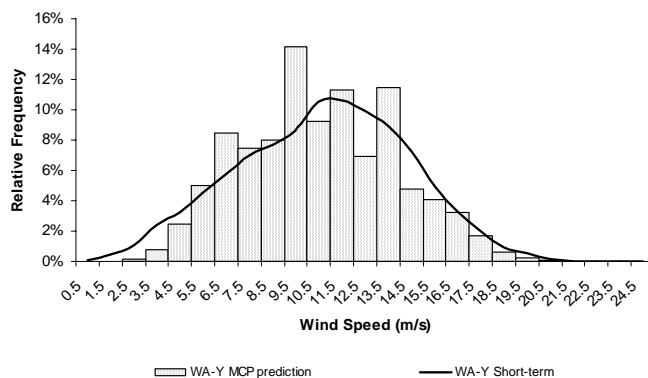


Figure 9 Comparison of measured short-term wind speed frequencies with the MCP predicted wind speed frequencies for WA-Y.

4.4. Discussion

The MCP predicted wind resource corresponds to a Class 7 wind power rating; however, the accuracy of this prediction is uncertain. Although the predicted long-term average wind speed at the WA-Y site is one per cent lower than the measured short-term average wind speed at WA-Y, comparisons between the MCP prediction and measured data are invalid, since the same measured short-term average was used in the prediction process. A discussion of the conditions required for accurate predictions and results of research regarding the accuracy of MCP predictions follows:

A prerequisite for obtaining accurate predictions with the MCP method is a high correlation coefficient between the wind speeds at the reference and prediction sites (Landberg & Mortensen, 1993). The correlation coefficient is indicative of the extent to which the two sites share the same weather regime. The correlation coefficient of the raw, short-term data is 0.68, while the filtered data has a coefficient of 0.88. As the neither coefficient is unity, this factor must be considered to add to the uncertainty in the wind speed prediction.

Several researchers have investigated the accuracy of MCP predictions by comparing MCP

predictions with long-term wind measurements at the prediction sites. Landberg and Mortensen (1993) report wind speed prediction errors averaging 10 per cent after a 12-month monitoring period. The prediction sites were located between 34 km to 45 km from the reference site in complex terrain, and had an average correlation coefficient of 0.60. Wind speed prediction errors of 2.4 per cent and 6.9 per cent are reported by Derrick (1993) for site separations of 40 km and 50 km, respectively, for 12 month monitoring periods, however no information regarding the correlation coefficients is provided for either site. Given that the correlation coefficient relating WA-X and WA-Y is greater than that for the sites studied by Landberg and Mortensen and that the terrain is relatively simple, it is conceivable that the prediction error for the wind speed prediction at WA-Y is also in the order of 10 per cent, despite a much greater separation between the reference and prediction sites.

The predicted wind direction frequencies at the WA-Y site are identical to those at the WA-X site, as conventional MCP assumes that the wind direction does not vary between the reference and prediction sites. As indicated in Section 3.4, inspection of the wind rose derived from WA-X (and its corresponding, more representative Wind Atlas) and the wind rose derived from short-term monitored data at WA-Y, suggest significant differences between the wind direction frequencies at each of the sites.

As the MCP analysis undertaken in this project is entirely dependent on the wind speed relationships derived from a single years' wind data, only further monitoring at the candidate site can verify the accuracy of the predictions that have been made. It is proposed to perform an MCP analysis on the second year's wind data gathered from the WA-Y site, to determine if there is convergence toward a stable value. The continued monitoring will also resolve the matter of the actual of wind direction frequencies at the WA-Y site.

5. CONCLUSIONS

The Wind Atlas and MCP methodologies have both been explored to predict the long-term wind resource at a potential wind farm site on the north-western coast of Western Australia. Short-term data from the potential site (WA-Y) and long-term data from the nearest meteorological station (WA-X) are used in the methods.

Initial wind data measurements at the WA-Y site indicate a Class 7 resource; the highest wind power rating.

The Wind Atlas method predicts a long-term average wind speed at the WA-Y site of 9.2 ms^{-1} at 40m a.g.l., corresponding to a Class 6 wind power rating. In predicting the wind regime at the WA-Y site, it is apparent that the operational envelope of WA^SP has been violated; in particular, the correlation between the weather regimes at the WA-X and WA-Y sites has been shown to less than ideal. For this reason it is likely that WA^SP has not predicted the long-term wind resource at the WA-Y site accurately.

The MCP method predicts a long-term average wind speed of 10.6 ms^{-1} at 40 m above ground level, corresponding to a Class 7 wind power rating. Studies concerning the accuracy of the MCP method suggest that the uncertainty in this estimate is in the order of 10 per cent.

The wind direction frequencies derived from both the Wind Atlas and MCP methods are significantly different to the wind rose derived from the short-term monitored data at the WA-Y site, suggesting that they are not accurate.

Further monitoring at the WA-Y site will enable a more accurate prediction of the long-term wind resource by the MCP method, and reveal the true nature of the wind direction frequencies.

Further investigation of the technical and economic feasibility of a wind farm at the WA-Y site is recommended on the basis of the Class 7 wind power rating predicted by the MCP method.

6. ACKNOWLEDGMENTS

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