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# WHALEPOWER WENVOR BLADE

## A REPORT ON THE EFFICIENCY OF A WHALEPOWER CORP. 5 METER PROTOTYPE WIND TURBINE BLADE

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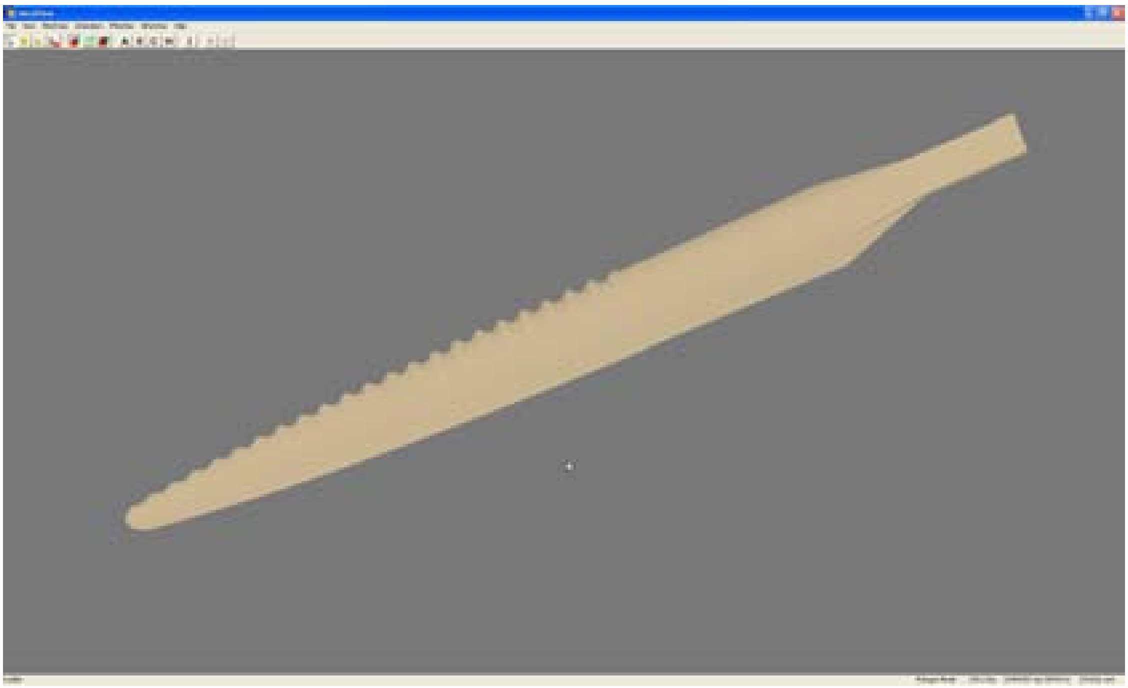
# A REPORT ON THE EFFICIENCY OF A WHALEPOWER CORP. 5 METER PROTOTYPE WIND TURBINE BLADE

## EXECUTIVE SUMMARY


In this report, we examine the performance of prototype 5 meter Whalepower wind turbine blades as measured by the Wind Energy Institute of Canada (WEICan) at North Cape, Prince Edward Island. The blades were installed on a Wenvor 25kW wind turbine and all measurements were taken with this wind turbine. The results are corrected to ISO standard air density. The electro-mechanical efficiency of the transmission-generator combination is quantified as a function of relative electrical power output. The efficiency of the transmission-generator combination is approximately 80% for relative power of 22% and increases to approximately 90% for 100% relative power output. The electrical power output is shown as a function of wind speed and is compared to the published power curve for the standard Wenvor turbine. We find that the Whalepower blades produce a power curve with a greater slope than the published data for the Wenvor blades. We also study the coefficient of power with and without correction for transmission and generator losses and these are compared to the Betz limit. The mean corrected coefficient of power attains a maximum of 0.4 at a wind speed of 7.5m/s while the electrical power coefficient peaks at 9m/s. An analysis of tip speed ratio suggests that refinements in the inertial pitch change mechanism could result in additional improvements in performance. Generator cut-in, rated power, and generator cut-out occur for approximate respective tip speed ratios of 13, 4, and 2.5. Our final set of results shows the yearly power production assuming a Rayleigh-distributed wind of varying mean speed.

## METHODS

A prototype wind turbine blade incorporating tubercles along the outer portion of the blade was fabricated by Whalepower Corp. and tested on a Wenvor 25kW wind turbine by the Wind Energy Institute of Canada at their testing site located at North Cape, Prince Edward Island. The data used for the analysis contained in this report were supplied by Lee Downer and Paul Dockrill of WEICan in five separate spreadsheets, Whalepower Test Data (Feb. 7, 2008), Whalepower Test Data (March 7, 2008), Whalepower Test Data (March 17, 2008), Whalepower Test Data (March 20, 2008), and Whale Power Days 122-148 (May 30, 2008). It should be noted that the test date logged in this last data file, Whale Power Days 122-148, shows the year 2003 rather than 2008. However, in an email to WhalePower, Paul Dockrill indicates that the year is incorrectly logged and that the data are from the current, 2008, testing [Dockrill]. The data contain one-minute interval measurements of the wind speed from two anemometers, barometric pressure, temperature, electrical power produced, and wind direction. All measurements were reported in the form of mean, standard deviation, minimum and maximum.

Each data file included at least two worksheets containing the raw data and valid test data. Validity of the measurements was determined by WEICan using data standards as specified by the IEC [IEC]. For the analysis reported herein, the valid test data from each of the five files were consolidated onto one data set. For calculation of wind speed, the readings from both anemometers were averaged. Air density was calculated using Boltzmann's barometric equation [Hau, p.509, corrected]. The tip speed ratio, $\lambda$, was calculated using the published rotor rotational rate of 120 rpm [Wenvor], a 5 meter blade radius, and the measured average wind speed. Corrections to the electrical power output to account for electrical and mechanical power losses were made, where appropriate, using corrections provided by Wilf Moll of Renewable Energy Solutions [Moll].

Power curve data for the 25kW Wenvor wind turbine were obtained directly from the Wenvor web site [Wenvor]. In comparing the Wenvor power curve to the Whalepower-Wenvor power curve, the test data were corrected to a standard ISO air density of $\rho = 1.225 kg/m^3$, in accordance with IEC standards [IEC]. The data were sorted into bins of $0.5 m/s$ width and the power was averaged for all data contained in each bin. Power averages, standard deviation, maximum, minimum and number of data points in each bin are tabulated in the appendix. All calculations use an actuator disk swept area of $78.54 m^2$.

For comparing the power curve of the Whalepower and Wenvor blades, the published data for the Wenvor turbine and the measured dada from the WEICan testing were compared. . Wind data for annual power production cases were produced from a Weibull distribution with a shape factor of 2 (Rayleigh distribution) and corrected to standard air density. A cut-in wind speed of $5 m/s$ and a cut-out wind speed of $25 m/s$ were used for all annual power production calculations.

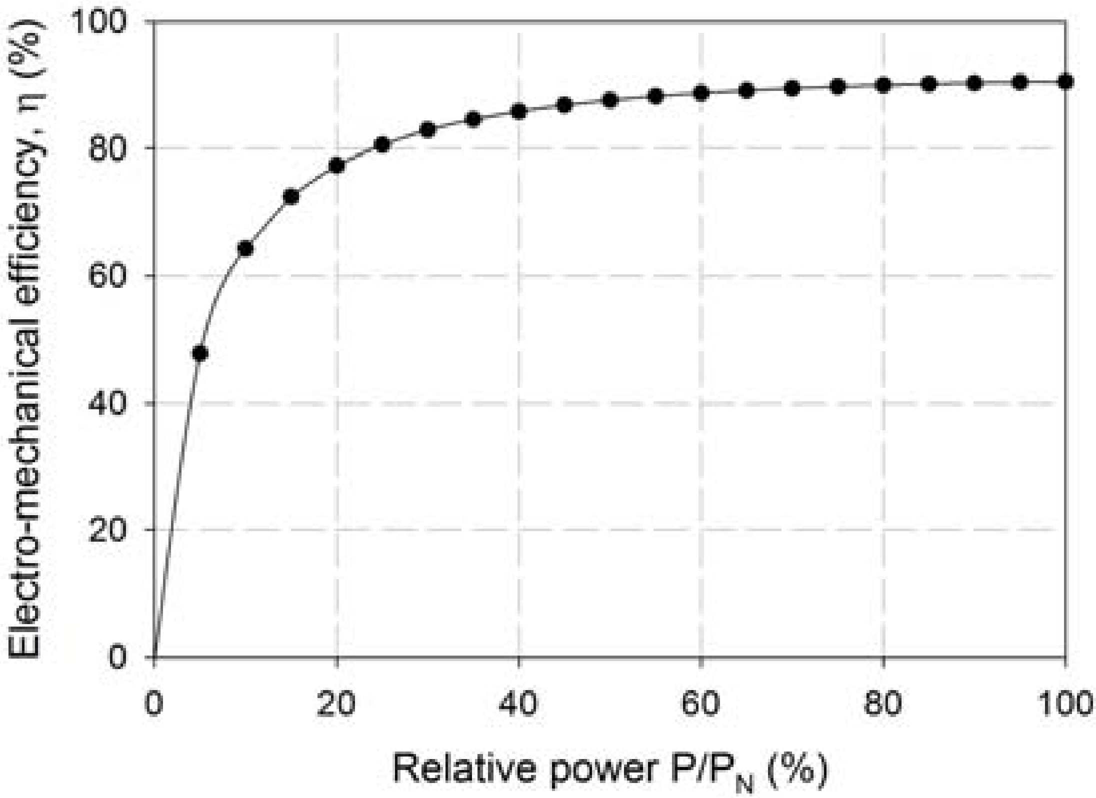



*Figure 1. Electro-mechanical efficiency of the Wenvor wind generator as a function of relative power. For these results, we assumed a rated power of Pn = 30kW.*

Power losses in the transmissions and generators of wind turbines reduce the input power (aerodynamic power) so that measured power (output power) need correction for studies of aerodynamic efficiency. The electro-mechanical loss for the Wenvor transmission/generator were supplied by Wilf Moll [Moll] as a function of electrical output power and is shown in Figure 1. The coefficient of power

$$C_p = \frac{P}{\frac{1}{2}\rho U^3 A}$$

where $P$ is the aerodynamic power (electrical power corrected for electro-mechanical loss), $\rho$ is the air density, $U$ is the hub-height wind speed, and $A$ is the actuator disk (blade swept) area is displayed graphically in Figure 2. In analyzing the performance of a wind turbine, the power coefficient is usually corrected to standard ISO air density and to the site average air density. The maximum available wind power is given by the Betz limit

$$C_{p,\max} = 16/27 \quad .$$

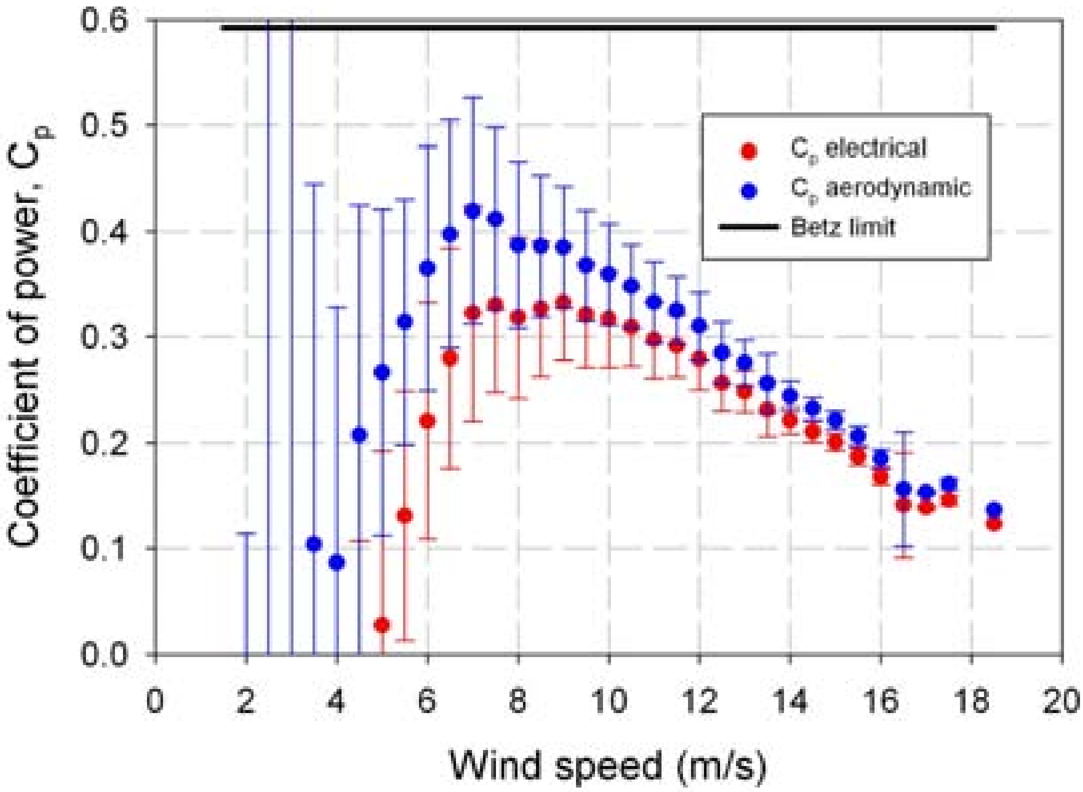



*Figure 2 Power coefficient vs. hub-height wind speed. Both the electrical and aerodynamic power coefficients are shown. The bars represent the measured mean ± standard deviation for each $0.5m/s$ wide data bin.*

With a maximum power coefficient slightly greater than $0.4$, produced at a wind speed of $7.5m/s$, it is likely that an improvement could be realized by better tuning of the inertial pitch change mechanism. However, smaller (10s of kW) turbines are typically less efficient than larger (MW) turbines so the power coefficient gains earned by tuning the pitch change device will likely be modest.

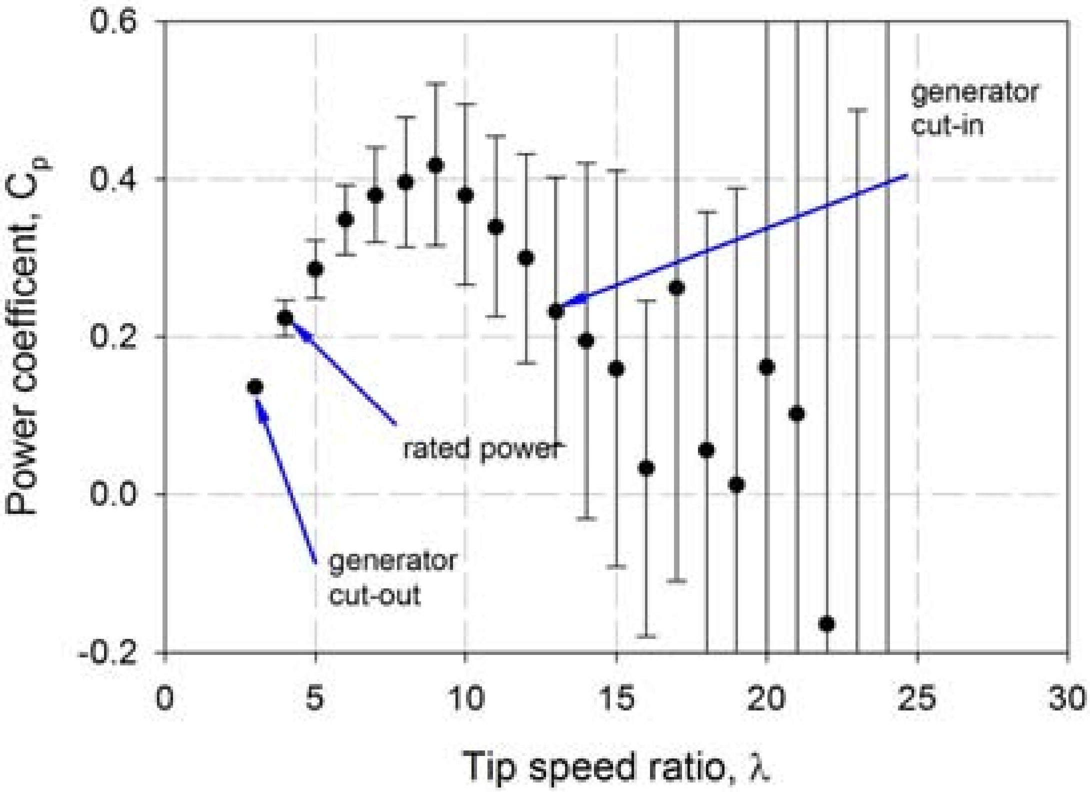



*Figure 3. Tip speed ratio, $\lambda$, vs. standard air density power coefficient. The error bars show the mean ± standard deviation for all data in each data bin. Wind speed increases with decreasing tip speed ratio. The approximate generator cut-in, rated power, and generator cut-out points are indicated in the figure.*

The tip speed ratio, defined as

$$\lambda = \frac{\omega R}{U}$$

where $\omega$ is the blade angular speed and $R$ is the blade radius, is used in tuning the blade pitch controller for optimal power coefficient with varying tip speed ratios [Hanson, p. 43, Hau, p. 487, Burton, p. 65]. Note that the Wenvor turbine uses a constant rotational speed of $120 rpm$ [Wenvor] so that an increase in wind speed results in a decrease in tip speed ratio. The peak power coefficient at a given tip speed is a function of blade pitch, $\beta$. A locus of power coefficient maxima defines the optimum blade pitch as a function of tip speed ratio. Pitch controllers are programmed to match the optimum blade pitch to the tip speed ratio. In further tuning of the pitch controller for the Whalepower blades, it is recommend that a $\lambda, C_p, \beta$ calculation be performed so that the target blade pitch $\beta$ vs. $\lambda$ schedule is known. A tuned pitch controller would seek to match this $\beta$ vs. $\lambda$ schedule.

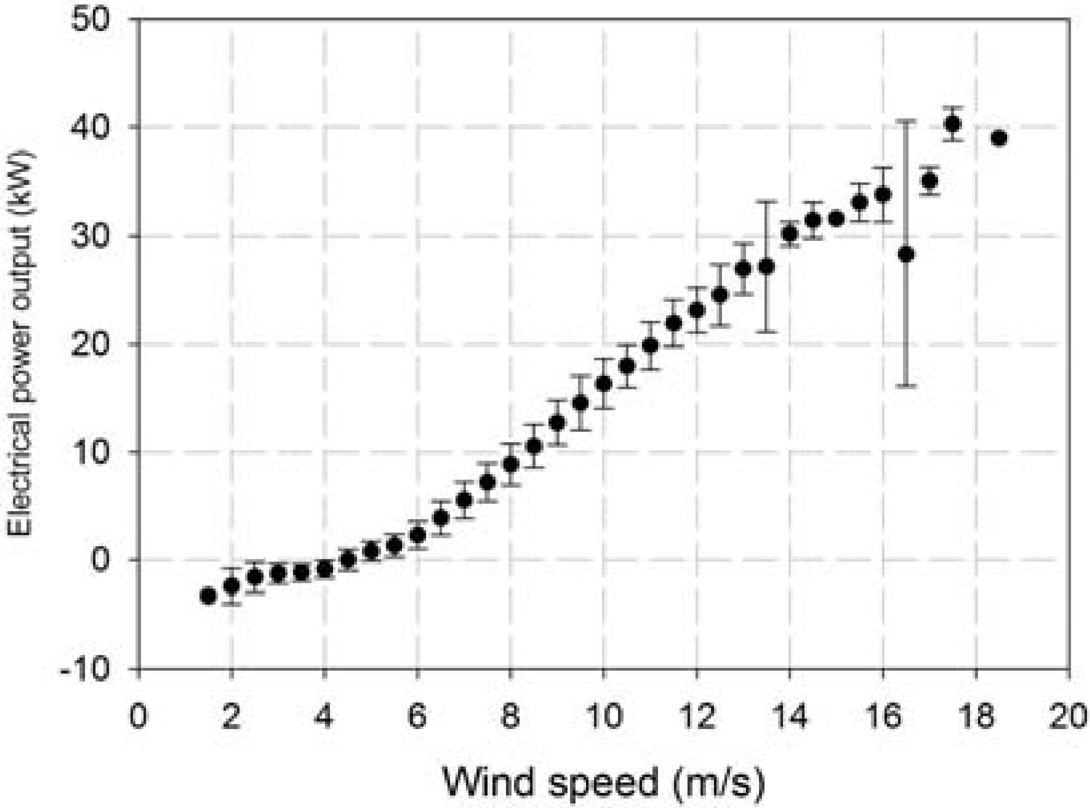



*Figure 4. Electrical power output corrected to ISO standard air density* $\rho = 1.225 kg/m^3$ *vs. wind speed at hub height. The error bars show the mean ± standard deviation for each 0.5m/s wide data bin.*

In Figure 4, we show the electrical output power plotted against hub-height wind speed. The data are shown as mean ± standard deviation for all data in each data bin. The data are also tabulated in the appendix. Note that the tabular data show a scarcity of data for higher wind. In comparing these measurements to the published Wenvor power curve , a generator cut-in wind speed of $5m/s$ and a power limit of $35kW$ were used. The comparison is shown in Figure 5. Note that the Whalepower blade has a greater slope than the Wenvor published data and that the power output is reached at a lower wind speed.

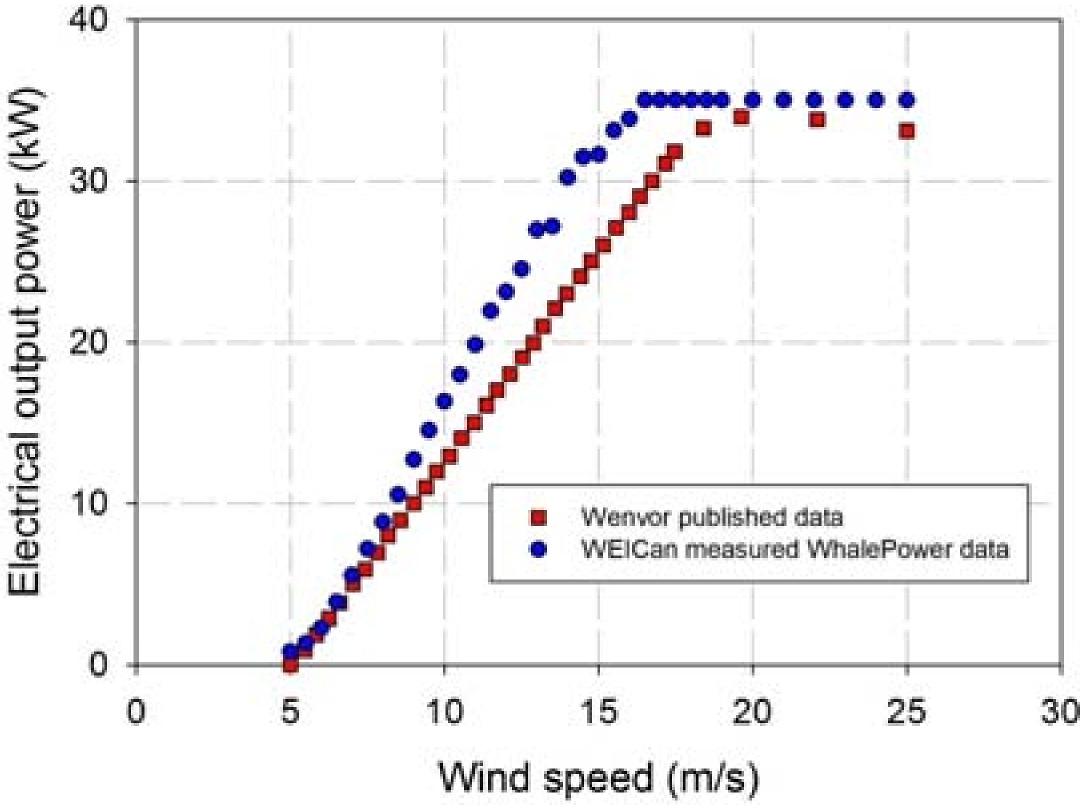



*Figure 5. Measured electrical power produced by the Whalepower blades corrected to standard air density* $\rho = 1.225 kg/m^3$ *as a function of wind speed at hub height. For this comparison, the published Wenvor data are shown. For these results, power output levels above 35kW are not shown due to the scarsity of data for wind speeds greater than approximately 15m/s.*

Our final analysis focuses on annual power production. For these calculations, we used the measured Whalepower electrical power curve (Figure 2, blue circles) and assumed a Weibull-distributed hub-height wind field. The Weibull distribution is given by

$$f(x;k,\beta) = \frac{k}{\beta}\left(\frac{x}{\beta}\right)^{k-1} e^{-\left(\frac{x}{\beta}\right)^k}$$

where $k$ is the shape factor ($k > 0$, real), $\beta$ is scale factor ($\beta > 0$, real), $x$ is the random variate (in this case, wind speed), and $f$ is the probability distribution. Typically, wind data are correlated with a shape factor of $k = 2$ in which case the Weibull probability distribution becomes the Rayleigh probability distribution

$$f(x;\sigma) = \frac{x}{\sigma^2} e^{\left(\frac{-x^2}{2\sigma^2}\right)} \quad .$$

In writing the Rayleigh distribution, we used the substitution $\beta = \sqrt{2}\sigma$. The Rayleigh scale factor, $\sigma$, is related to the mean of the random variate by

$$\mu(x) = \sigma\sqrt{\frac{\pi}{2}} \quad .$$

For an energy production study, we specify the mean wind speed, $\mu = (x)$, calculate the Rayleigh scale factor, $\sigma$, construct the wind speed probability density function, $f(x;\sigma)$, and use the measured power curve to predict the annual energy production.

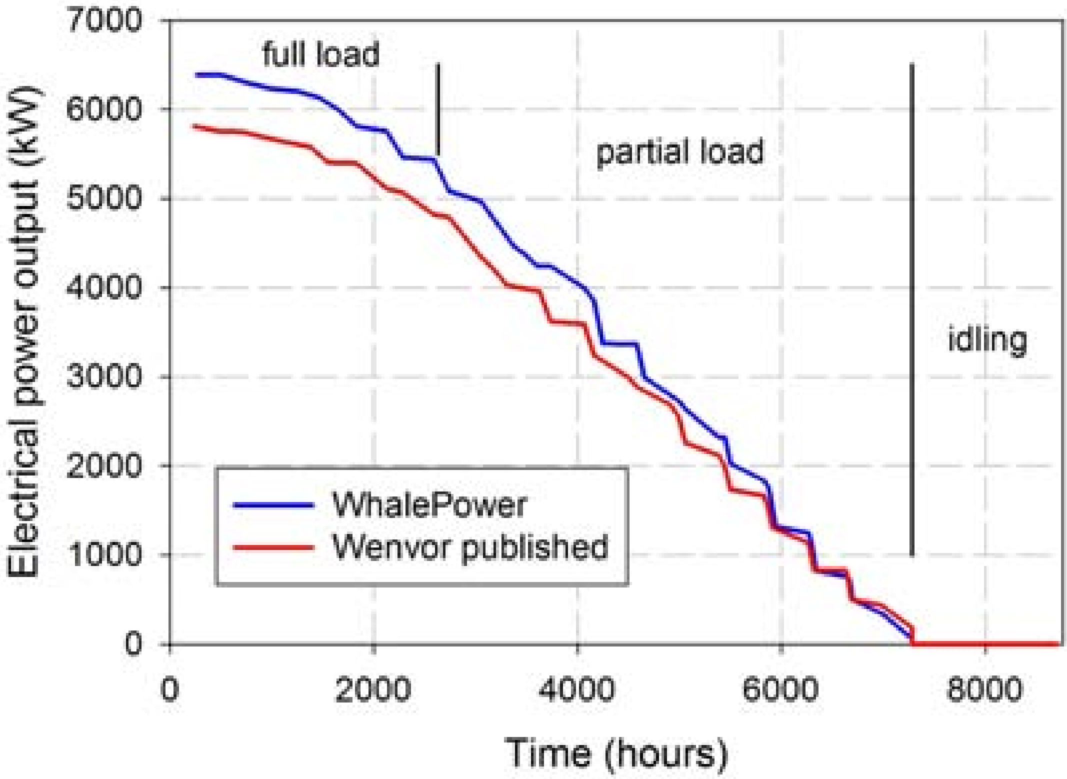



*Figure 6. Power output on an annual graded basis for a site with a Rayleigh-distributed 10m/s mean wind field. A standard year of 8760 hours was used together with the measured power curve to generate these results.*

In Figure 6, we show the annual graded power production for a Rayleigh-distributed hub-height wind distribution. A technical availability of 100% is used for these calculations along with a standard year consisting of 8760 hours. The figure shows the duration, in hours, of operation at full load and the portions of the year at partial load and idling. The annual energy production is found by integrating this annual graded electrical power output curve.

By changing the mean wind speed, we can create a plot of annual energy production as a function of mean wind speed, as shown in Figure 7. Here we show the yearly production in MegaWatt-hours, $MWh$ for the WhalePower blades (blue curve) and the Wenvor published data (red curve).

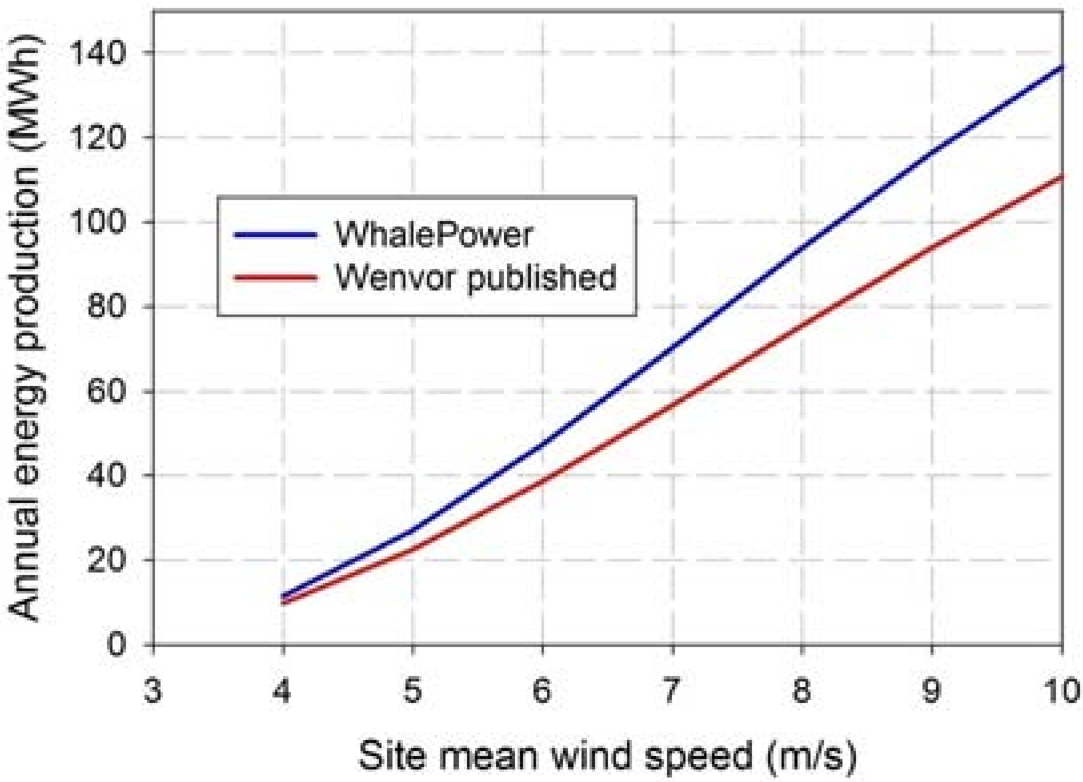



*Figure 7. Yearly energy production in MegaWatt-hours (MWh) for the WhalePower blades (blue curve), the WEICan measured Wenvor blades (green curve) and the Wenvor published data (red curve) vs. site Rayleigh-distributed mean wind speed for ISO standard air density* $\rho = 1.225 kg/m^3$.

For further investigation of the Annual Energy Production (AEP) of the Whalepower blade-equipped turbine, we selected a class 5 wind zone for analysis. A class 5 wind zone is characterized by a mean wind speed of $6.0 - 6.4 m/s$ at an elevation of $10m$ and a mean wind speed of $7.0 - 8.0 m/s$ at an elevation of $50m$ [Hau, p 457]. A Rayleigh distribution was used to generate the AEP results shown in Figure 8. The black curve shows the number of hours (right vertical axis) the wind spends at the indicated speed. The blue curve shows the power produced (kWh - left vertical axis) by the Whalepower blade-equipped wind turbine at the speed indicated on the horizontal axis while the red curve shows the power that would be produced by a wind turbine with the Wenvor published power curve.

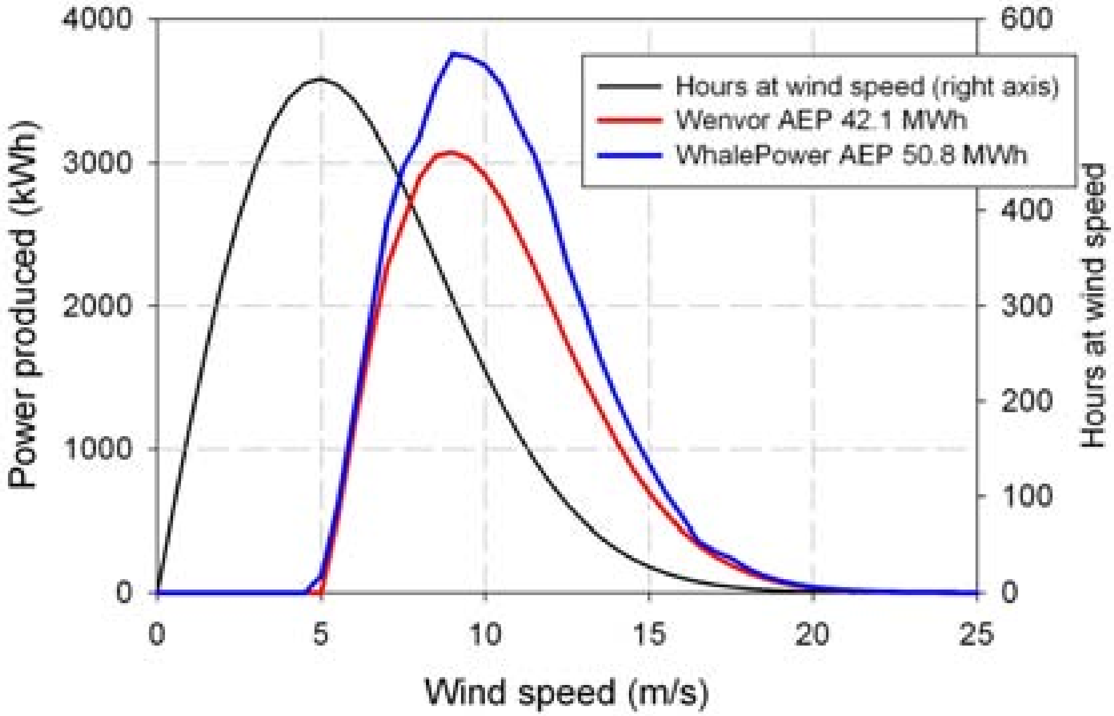



*Figure 8. Annual Energy Production (AEP) for a class 5 wind zone. The black curve (right vertical axis) shows the number of hours the wind spends at the indicated speed. The blue curve (left vertical axis) corresponds to the WhalePower AEP and the red curve (left vertical axis) corresponds to the Wenvor AEP. The measurend Whalepower and published Wenvor power curves were used in combination with a Rayleigh-distributed class 5 wind to genreate these results.*

## SUMMARY

The analysis in this report compared the measured performance of prototype Whalepower wind turbine blades to performance data previously published by Wenvor using their standard blades. The measurements collected for the Whalepower blade-equipped turbine were collected by the Wind Energy Institute of Canada (WEICan) and were controlled to IEC standards. The comparison between the two turbines in this report is not a controlled comparison as both sets of performance data would need to be controlled to IEC standards and collected, ideally, at the same location using the same wind turbine generator and transmission. The results contained in this report show that the Whalepower and Wenvor blades have the same start-up wind speed, approximately $5m/s$. The Whalepower blades have a greater power curve slope and reach rated power at approximately $12.5m/s$ whereas the Wenvor blades reach rated power at approximately $15m/s$. For the Whalepower blade-equiped turbine, the peak aerodynamic power coefficient of approximately $C_p = 0.4$ is achieved at approximately $7m/s$.

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*Table 1. Power output data corrected to ISO standard air density.*

| Speed (m/s) | Mean Pwr. (kW) | Std. Dev. | Min. | Max. | Bin Samples |
|---|---|---|---|---|---|
| 1.5 | -3.283 | | -3.283 | -3.283 | 1 |
| 2.0 | -2.788 | 1.332 | -3.576 | -1.249 | 3 |
| 2.5 | -2.126 | 1.365 | -3.852 | 0.715 | 15 |
| 3.0 | -1.484 | 1.095 | -3.904 | 0.560 | 29 |
| 3.5 | -1.201 | 0.787 | -2.587 | 0.433 | 30 |
| 4.0 | -1.185 | 0.818 | -2.614 | 1.486 | 49 |
| 4.5 | -0.529 | 1.028 | -2.852 | 1.745 | 103 |
| 5.0 | 0.222 | 1.059 | -2.667 | 3.268 | 214 |
| 5.5 | 1.127 | 1.026 | -1.850 | 4.665 | 261 |
| 6.0 | 2.433 | 1.251 | -0.920 | 6.812 | 385 |
| 6.5 | 3.891 | 1.496 | -0.060 | 8.144 | 394 |
| 7.0 | 5.606 | 1.775 | 0.131 | 12.305 | 415 |
| 7.5 | 6.988 | 1.763 | 1.543 | 13.470 | 459 |
| 8.0 | 8.204 | 2.031 | 0.598 | 14.439 | 440 |
| 8.5 | 10.155 | 2.036 | 2.888 | 18.539 | 381 |
| 9.0 | 12.198 | 1.987 | 5.801 | 20.448 | 446 |
| 9.5 | 13.878 | 2.195 | 0.082 | 21.696 | 399 |
| 10.0 | 15.842 | 2.283 | 5.269 | 28.368 | 399 |
| 10.5 | 17.893 | 2.100 | 12.385 | 30.152 | 277 |
| 11.0 | 19.666 | 2.324 | 13.087 | 30.303 | 211 |
| 11.5 | 22.142 | 2.195 | 14.934 | 30.309 | 172 |
| 12.0 | 23.981 | 2.000 | 18.894 | 30.410 | 122 |
| 12.5 | 24.979 | 2.461 | 17.225 | 30.955 | 143 |
| 13.0 | 26.916 | 1.994 | 19.843 | 32.432 | 157 |
| 13.5 | 28.091 | 3.052 | 0.111 | 33.070 | 137 |
| 14.0 | 29.676 | 1.622 | 23.937 | 34.486 | 90 |
| 14.5 | 31.316 | 1.558 | 25.206 | 34.744 | 58 |
| 15.0 | 32.955 | 1.310 | 30.337 | 36.020 | 38 |
| 15.5 | 33.793 | 1.266 | 31.823 | 36.346 | 24 |
| 16.0 | 34.498 | 1.565 | 32.044 | 35.900 | 5 |
| 16.5 | 31.690 | 10.424 | 19.683 | 38.424 | 3 |
| 17.0 | 35.115 | 1.279 | 34.211 | 36.020 | 2 |
| 17.5 | 40.276 | 1.536 | 39.049 | 41.998 | 3 |
| 18.0 | | | | | |
| 18.5 | 38.958 | | 38.958 | 38.958 | 1 |

*Table 2 Electrical power coefficient corrrected to ISO standard air density.*

| Speed (m/s) | Mean Cp - ele | Std. Dev. | Min. | Max. | Bin Samples |
|---|---|---|---|---|---|
| 1.5 | -12.218 | | -12.218 | -12.218 | 1 |
| 2.0 | -5.427 | 1.899 | -6.828 | -3.265 | 3 |
| 2.5 | -2.436 | 1.587 | -4.380 | 0.747 | 15 |
| 3.0 | -1.151 | 0.961 | -3.508 | 0.379 | 29 |
| 3.5 | -0.552 | 0.375 | -1.489 | 0.166 | 30 |
| 4.0 | -0.364 | 0.261 | -0.884 | 0.370 | 49 |
| 4.5 | -0.117 | 0.224 | -0.659 | 0.416 | 103 |
| 5.0 | 0.027 | 0.165 | -0.500 | 0.428 | 214 |
| 5.5 | 0.131 | 0.118 | -0.233 | 0.497 | 261 |
| 6.0 | 0.221 | 0.112 | -0.088 | 0.639 | 385 |
| 6.5 | 0.280 | 0.104 | -0.004 | 0.578 | 394 |
| 7.0 | 0.322 | 0.102 | 0.007 | 0.785 | 415 |
| 7.5 | 0.330 | 0.082 | 0.077 | 0.649 | 459 |
| 8.0 | 0.318 | 0.076 | 0.025 | 0.520 | 440 |
| 8.5 | 0.327 | 0.064 | 0.103 | 0.619 | 381 |
| 9.0 | 0.332 | 0.054 | 0.164 | 0.550 | 446 |
| 9.5 | 0.321 | 0.050 | 0.002 | 0.505 | 399 |
| 10.0 | 0.317 | 0.045 | 0.099 | 0.544 | 399 |
| 10.5 | 0.309 | 0.037 | 0.207 | 0.520 | 277 |
| 11.0 | 0.297 | 0.036 | 0.190 | 0.502 | 211 |
| 11.5 | 0.292 | 0.030 | 0.207 | 0.409 | 172 |
| 12.0 | 0.279 | 0.029 | 0.211 | 0.377 | 122 |
| 12.5 | 0.257 | 0.027 | 0.163 | 0.319 | 143 |
| 13.0 | 0.249 | 0.020 | 0.164 | 0.298 | 157 |
| 13.5 | 0.232 | 0.026 | 0.001 | 0.269 | 137 |
| 14.0 | 0.221 | 0.013 | 0.176 | 0.259 | 90 |
| 14.5 | 0.211 | 0.010 | 0.177 | 0.237 | 58 |
| 15.0 | 0.201 | 0.008 | 0.185 | 0.225 | 38 |
| 15.5 | 0.187 | 0.008 | 0.161 | 0.203 | 24 |
| 16.0 | 0.168 | 0.008 | 0.157 | 0.177 | 5 |
| 16.5 | 0.141 | 0.050 | 0.084 | 0.176 | 3 |
| 17.0 | 0.139 | 0.001 | 0.138 | 0.139 | 2 |
| 17.5 | 0.146 | 0.005 | 0.140 | 0.149 | 3 |
| 18.0 | | | | | |
| 18.5 | 0.123 | | 0.123 | 0.123 | 1 |

*Table 3. Aerodynamic power coefficient corrected to ISO standard air density – corrected for transmission and generator losses.*

| Speed (m/s) | Mean Cp | Std. Dev. | Min. | Max. | Bin Samples |
|---|---|---|---|---|---|
| 1.5 | -6.962 | | -6.962 | -6.962 | 1 |
| 2.0 | -2.363 | 2.477 | -3.863 | 0.496 | 3 |
| 2.5 | -0.784 | 1.483 | -2.616 | 2.287 | 15 |
| 3.0 | -0.074 | 0.855 | -2.116 | 1.464 | 29 |
| 3.5 | 0.104 | 0.341 | -0.547 | 0.757 | 30 |
| 4.0 | 0.086 | 0.242 | -0.352 | 0.854 | 49 |
| 4.5 | 0.207 | 0.218 | -0.294 | 0.774 | 103 |
| 5.0 | 0.267 | 0.154 | -0.203 | 0.635 | 214 |
| 5.5 | 0.314 | 0.116 | -0.038 | 0.692 | 261 |
| 6.0 | 0.365 | 0.116 | 0.056 | 0.803 | 385 |
| 6.5 | 0.397 | 0.108 | 0.102 | 0.708 | 394 |
| 7.0 | 0.419 | 0.107 | 0.091 | 0.911 | 415 |
| 7.5 | 0.412 | 0.086 | 0.152 | 0.747 | 459 |
| 8.0 | 0.387 | 0.079 | 0.092 | 0.595 | 440 |
| 8.5 | 0.386 | 0.067 | 0.161 | 0.696 | 381 |
| 9.0 | 0.385 | 0.058 | 0.213 | 0.615 | 446 |
| 9.5 | 0.368 | 0.053 | 0.037 | 0.563 | 399 |
| 10.0 | 0.359 | 0.048 | 0.130 | 0.602 | 399 |
| 10.5 | 0.348 | 0.040 | 0.239 | 0.574 | 277 |
| 11.0 | 0.333 | 0.039 | 0.220 | 0.555 | 211 |
| 11.5 | 0.325 | 0.032 | 0.236 | 0.451 | 172 |
| 12.0 | 0.310 | 0.032 | 0.235 | 0.416 | 122 |
| 12.5 | 0.285 | 0.029 | 0.183 | 0.352 | 143 |
| 13.0 | 0.275 | 0.021 | 0.183 | 0.329 | 157 |
| 13.5 | 0.256 | 0.028 | 0.011 | 0.298 | 137 |
| 14.0 | 0.244 | 0.014 | 0.195 | 0.285 | 90 |
| 14.5 | 0.232 | 0.011 | 0.197 | 0.261 | 58 |
| 15.0 | 0.221 | 0.009 | 0.205 | 0.248 | 38 |
| 15.5 | 0.206 | 0.009 | 0.177 | 0.224 | 24 |
| 16.0 | 0.185 | 0.008 | 0.173 | 0.195 | 5 |
| 16.5 | 0.156 | 0.054 | 0.094 | 0.194 | 3 |
| 17.0 | 0.153 | 0.001 | 0.152 | 0.154 | 2 |
| 17.5 | 0.161 | 0.005 | 0.155 | 0.165 | 3 |
| 18.0 | | | | | |
| 18.5 | 0.136 | | 0.136 | 0.136 | 1 |

*Table 4. WhalePower annual energy production (AEP) as a function of site average wind speed.*

| Mean Wind Speed (m/s) | AEP (MWh) |
|---|---|
| 4 | 1.75 |
| 5 | 6.46 |
| 6 | 14.73 |
| 7 | 26.15 |
| 8 | 40.01 |
| 9 | 55.51 |
| 10 | 71.93 |
| 11 | 88.62 |
| 12 | 104.99 |
| 13 | 120.52 |
| 14 | 134.74 |
| 15 | 147.30 |