Report on Experimental Performance and Up-Scaled Performance Prediction of the ART Turbine

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EXECUTIVE SUMMARY

A conservative analysis of the test data from February 3rd 2012 indicates that the 8 ft ART Turbine rotor has a power coefficient of 0.31 for wind speeds above 10 m/s. That this number was derived using a conservative analysis approach on non-optimized tests means the peak efficiency of the rotor could be even higher. A methodology for using the power coefficient curve from the experimental results to predict the performance of up-scaled ART Turbines in various wind climates was developed. This methodology incorporates Reynolds number scaling of the power coefficient curve, wind speed adjustments for various hub heights using the power law, and techniques for accepting either raw or statistical wind speed data. The methodology has been packaged into a spreadsheet-based tool that allows fast and flexible estimation of energy production potential. Annual energy production estimates were produced for a selection of locations in Canada and elsewhere, for five different sizes of ART Turbine. These estimates can be combined with cost estimates to calculate the cost of energy of various sizes of ART Turbines at each of these locations.

ANALYSIS OF TEST DATA

An analysis of the data from the February 3rd, 2012 tests on Cowichan Valley Highway has been performed to provide a second opinion on the power curves provided by ART Turbine. This analysis relies on two-dimensional binning of the complete set of test data, to provide a complete summary of the correlations between wind speed and turbine power in the February 3rd data. This approach ignores the time sequence of the data points and allows neither cherry-picking of optimally-tuned data points nor exclusion of poor data points. Because the torque of the rotor would not be optimally tuned for maximum power during much of the testing, constructing the power curve through the most populated bins provides a *conservative* estimation of the power potential of the turbine.

The full February 3rd data set consisted of 156 687 data points. The recorded wind speed, rotor rotation speed, and brake force from each data point were taken, and the corresponding rotor mechanical power and power coefficient were calculated. These calculations used a force measurement moment arm of 1.05 m, a rotor swept area of 1.85 m^2, and an air density of 1.225 kg/m^3. The resulting data set was binned according to wind speed and either power coefficient or power. Figures 1 and 2 are two-dimensional histograms with the vertical axis representing the number of data points taken within each bin. The bin sizes are 0.5 m/s by either 0.01 (for power coefficient) or 20 W (for power). Figures 3 and 4 show the same data on colour-coded two-dimensional plots with the colour indicating the number of data points within each bin. Overlaid on the respective plots are the power coefficient and power curves provided by ART Turbine for the same data set. These curves can be clearly seen to fall within the highly-populated bins, indicating that the power curve provided by ART Turbine is well-supported by the experimental data, even according to this conservative analysis approach. This power curve and the corresponding power coefficient curve are therefore be used for the energy yield estimations done in later sections.

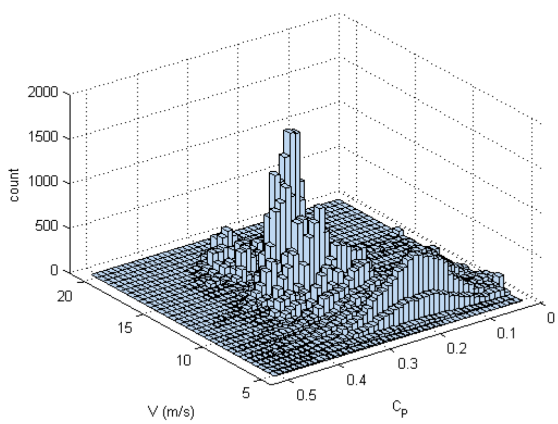

Figure 1: Histogram of power coefficient vs. wind speed

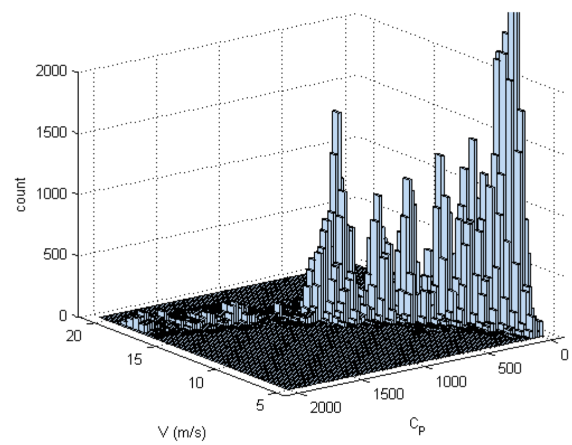

Figure 2: Histogram of power vs. wind speed

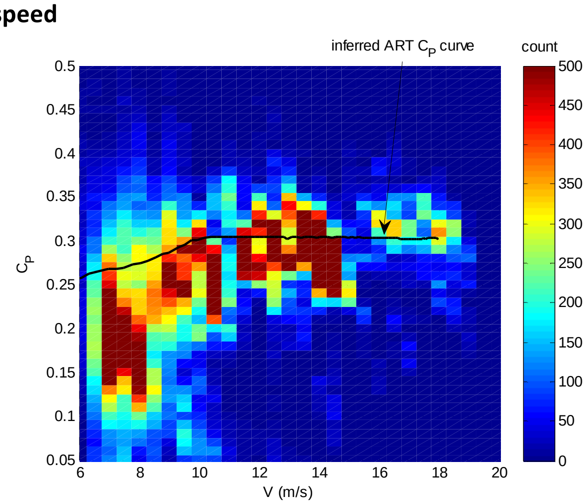

Figure 3: Colour-histogram of power coefficient vs. wind speed

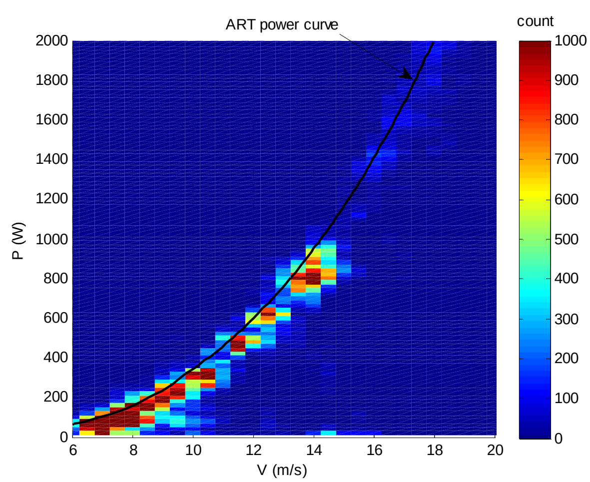

Figure 1: Colour-histogram of power vs. wind speed

The power coefficient curve (the black line in Figure 3) is the most useful performance indicator for estimating the behaviour of scaled-up turbines. The flatness of this curve from 10 m/s to 18 m/s suggests a lack of Reynolds number dependence over the corresponding Reynolds number range of 760,000 to 1,200,000. The noticeable decline in CP for wind speeds less than 10 m/s could be a result of Reynolds number effects or possibly other factors that become more significant at the lower torques and rotation speeds at this wind level, such as bearing friction. Assuming this decline below 10 m/s occurs from Reynolds number effects (where laminar flow conditions create increased levels of drag from increased flow separation) is the most conservative explanation, so it is therefore used in the following analysis work.

METHODOLOGY FOR PERFORMANCE PREDICTION OF UP-SCALED ART TURBINES

Generating performance predictions for larger turbines in different wind conditions involves a number of steps: processing wind data for the location in question, adjusting this wind data to account for any difference between anemometer height and hypothetical rotor height, scaling the size and the power coefficient curve of the experimental turbine to the desired size, and applying the scaled power curve to the adjusted wind data to predict the energy produced by the hypothetical turbine at the desired location.

Wind data

The wind data for the desired location may come in one of several forms. If the wind speed data comes in the form of a time series of wind speeds or a list of hours at each wind speed, a histogram of hours at each wind speed is generated at the desired wind speed resolution of the analysis. If only an average wind speed is available for the site, the distribution of wind speeds can be approximated; the standard method for doing this is with a Weibull distribution. The Weibull probability distribution is:

$$P(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left(-\left(\frac{V}{c}\right)^{k}\right)$$

where k is the shape factor and c is the scale factor [1]. The scale factor is related to the mean value of the distribution and is calculated using the Gamma function. The shape factor relates to the variance of the distribution, or the variability of wind speeds, and is therefore site-specific. A value of two is often a good guess for shape factor if other data isn't available.

Wind height scaling

Wind speed measurements are rarely at the height of a wind turbine rotor, and the atmospheric boundary layer results in a gradient in wind speed with height from the ground. The power law is an approach to approximate the wind profile. It takes the form

$$\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^{\alpha}$$

where α relates to the shape of the profile; 0.14 is common for over land and 0.11 is common over water [2].

Turbine performance scaling

The aerodynamic performance of the turbine rotor is represented by the non-dimensional power coefficient, C_P. This is a function of both tip speed ratio and Reynolds number. For the ART Turbine, where constant and optimal tip speed ratio operation is assumed due to the inexpensive nature of the generator (no power limiting is expected), the power coefficient is treated as a function of Reynolds number only. Once this functional relationship has been determined experimentally, the power output of a scaled rotor can be estimated using the rotor power equation:

$$P = \frac{1}{2}\rho C_P(R_e)AV^3$$

where ρ is air density, R_e is Reynolds number, A is swept area, and V is wind speed.

For each wind speed considered in the analysis, this equation can be applied at the corresponding Reynolds number and multiplied by the number of hours at this wind speed to predict the energy output of the turbine for this wind speed. The wind speed would have already been adjusted using the power law to the height of the aerodynamic center of the rotor. The aerodynamic center is taken to be at 40% of the rotor height. Summing the result over the full range of wind speeds gives an estimate of the total energy production for the duration of data. For the span of a year, this is referred to as annual energy production (AEP).

SPREADSHEET

The methodology described in the previous section has been implemented into an Excel-based spreadsheet tool, which will allow quick and efficient calculation of AEP for turbines of different sizes under different wind conditions. This tool is set up to allow easy adjustment of all input parameters, including the power curve of the turbine. This will allow fast updating of energy production estimates as the performance data for the ART Turbine evolves. A screenshot of the spreadsheet tool is given in Figure 5.

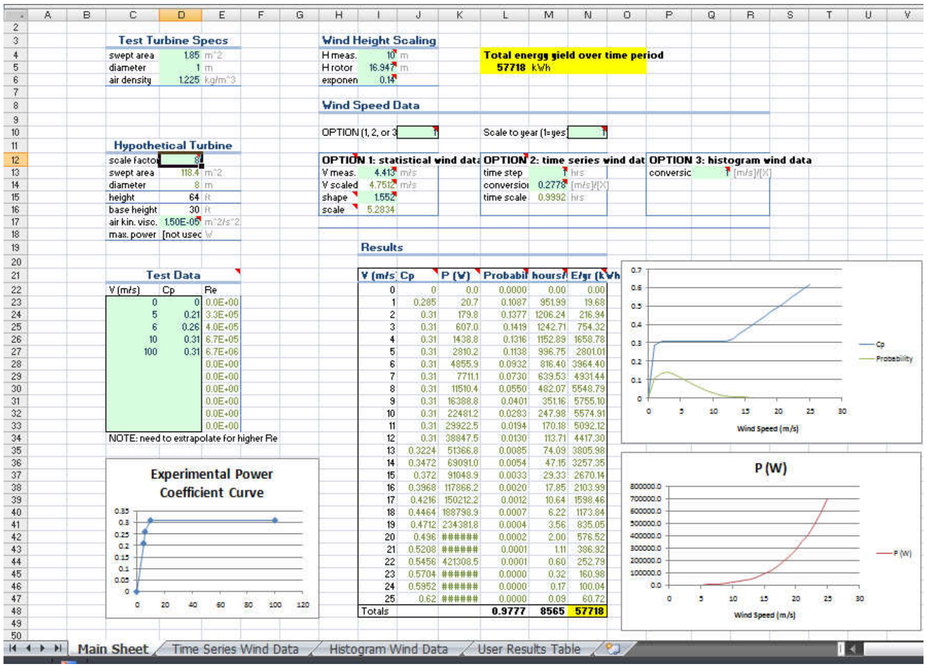

Figure 5: Screenshot of Excel-based AEP prediction tool

Annual Energy Production Estimates for Sample Locations

AEP estimates for a selection of cities have been prepared using the above approach. Different methods for the wind speed data inputs were used according to the availability of different data sets for different locations. These details are summarized in Table 1 below. North Cape, PEI was selected because it has some of the strongest winds in the country and is the test site for the Wind Energy Institute of Canada.

Table 1: Wind Data Sources

Location	*Data type*	*Year(s)*	*Mean Speed (m/s)*	*Meas. Height (m)*	*Ref.*
Victoria Int. Airport	time series	2012	2.56	10	[3]
North Cape, PEI	time series	2012	6.66	10	[3]
Izmir, Turkey	Statistical	1995-1999	2.90	15	[4]
Ibadan, Nigeria	Statistical	1995-2004	1.95	10	[5]
Kudat, Malaysia	Statistical	2006	3.38	10	[6]
Dhahran, Saudi Arabia	Statistical	1970-1990	4.41	10	[7]

Five different ART Turbine sizes are considered: 8 ft, 16 ft, 24 ft, 32 ft, and 64 ft, each with a base height of 30 m. Each size experiences different wind speeds as a results of the change in the height of the turbine's aerodynamic center. The cut-out speed is taken to be 25 m/s and full power output up to that point is assumed. A cut-in wind speed is not specified as this contribution to energy production is negligible. The AEP estimates are provided in Table 2.

Table 2: Annual Energy Production Estimates (kWh/year)

Location	ART 8 ft	ART 16 ft	ART 24 ft	ART 32 ft	ART 64 ft
Victoria Int. Airport	196	948	2259	4091	19336
North Cape, PEI	1767	7609	18009	32762	169091
Izmir, Turkey	147	779	1870	3454	15505
Ibadan, Nigeria	33	216	552	1036	4694
Kudat, Malaysia	253	1256	2980	5491	24791
Dhahran, Saudi Arabia	623	2834	6651	12230	57718

Conclusions and Recommendations

The test results from Feb 3rd 2012 show a very good power coefficient of approximately 0.31. This was produced using a relatively conservative analysis on data from tests that include non-optimal operating points. It is therefore reasonable to expect that slightly higher power coefficients could be realized experimentally if optimal torque control is introduced. It is reasonable to expect that aerodynamic shape optimization of the rotor could further increase the power coefficient. Over a wind speed of 10 m/s, corresponding to a Reynolds number of 760,000, the power coefficient appears to be constant. This suggests that Reynolds-related performance gains from up-scaling would only benefit the low-speed performance of the turbine.

Determining the tip speed ratio that maximizes power production is a logical next step. While it may be possible to extract this from the Feb 3rd data set, the ideal scenario would be to run additional experiments in which the wind speed is constant and the torque (and thus tip speed ratio) is varied sequentially. Such a test, conducted at several wind speeds, should provide conclusions about the optimal tip speed ratio, which can then be used as the basis for optimal torque control of the rotor.

A verification of the Reynolds number performance of the rotor could be done by running two identical tests with different-sized rotors. While this may be interesting from a technical perspective, the performance of the rotor is already good enough that studying these Reynolds number effects may not be justifiable from a cost perspective.

Aerodynamic shape optimization of the rotor could be performed either through continuing the iterative experimental approach, or switching over to a computer simulation-based approach. The complexity of the physics involved would make the computational approach extremely challenging and resource intensive. And the existing iterative experimental approach has already shown extremely good aerodynamic performance. Continuing the current approach seems to be the logical choice.

Aside from the aerodynamic design of the rotor, an important consideration that needs to be solidified is the upper end of the operational envelope of the turbine. Continuing to operate the rotor at the optimal tip speed ratio to maximize power output at high wind speeds is constrained by both structural limits and generator power limits. Reducing the tip speed ratio at higher wind speeds and stopping the rotor at extreme wind speeds are common approaches to for these constraints. As ART Turbine designs are scaled up and exposed to more severe wind conditions, these considerations will become important.

The state of ART Turbine development is now such that annual energy production estimates can be made for different turbine sizes. If the remaining unknowns about the operating envelope of the turbine can be decided upon, and if cost estimates can be developed, then it will be possible to generate cost of energy estimates. These cost of energy estimates will be invaluable in indicating the commercial potential of the technology.

References

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