Wind Tamer Turbine Performance Report 1kW – 15 kW Performance Predictions

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Executive Summary

The Wind Tamer is a wind turbine concept developed by Jerry Brock of Livonia, NY. Clarkson University has been asked to evaluate the performance of this concept by conducting full-scale tests of the turbine at the Clarkson Wind Turbine Test Site and analysis of full-scale tests in the Geneseo area.

The WindTamer concept utilizes a diffuser to increase the power produced by an open rotor wind turbine. The current configuration combines several concepts into a functionally attractive design that eliminates the need for furling and reduces the noise typically generated with smaller turbines. The WindTamer design concept has indicated an efficiency or power coefficient, Cp based on the rotor area, of approximately twice that of current small turbines, from recent experimental data and numerical predictions.

This report presents estimates for the proposed series of WindTamer platforms that span the generator range of 1 - 15 kW with respective rotor diameters of 52" - 172". The report includes power curves of each of the turbines and annual energy output (AEO) profiles based on standard Rayleigh wind distributions. Rated output powers are given at 11 m/s corresponding to the small wind turbine draft standard proposed by AWEA. The assumptions made in this report include an augmentation factor of 2 to account for the duct effect, no furling of the turbine, and a maximum continuous generator output at 33% above the stated generator value. In general, it was observed from the numerical estimations that the WindTamer turbine can produce approximately twice the annual energy output for a given swept rotor area than a conventional open rotor design.

It should be noted that the numerically predicted design performance presented in this report is in no way a guarantee of the final, full scale, real world performance.

Contents

Executive Summary	3
1. Wind Tamer Design Concept	5
2. Experimental Prototype Performance	6
3. Predicted Design Performance of 52" to 172" Rotor Designs	8
3.1. Geometries	9
3.2. Open Rotor Performance Estimates	9
3.3. Ducted Rotor Power Performance Estimates	12
3.4. Annual Energy Output Estimates	19
4. References	

Page

1. Wind Tamer Design

One proposed method of improving turbine efficiency is to put a duct around the turbine, often termed a Diffuser Augmented Wind Turbine (DAWT), as an improvement to the conventional open rotor Horizontal Axis Wind Turbine (HAWT). DAWTs employ a duct around the HAWT that increases in area as it extends aft. The purpose is to increase the mass flow through the blades and hence increase the power extracted for a given rotor size.

The Wind Tamer concept is a ducted rotor design. In contrast with of an open rotor, such as the Bergey Turbine illustrated in Figure 1a, the rotor is enclosed in a duct as shown in Figure 1b. The WindTamer also utilizes an increased blade number and does not need an additional tail to keep it aligned into the wind.





Figure 1: a) Bergey XL.1 b) Wind Tamer in Perry, NY, 78" design

DAWTs have been reported to have a greater efficiency than conventional HAWTs, based on the rotor area, even exceeding the theoretical limit of efficiency of extracting power from the wind, the so called Betz limit of 59.3%, based on the swept area of the rotor. Certain researchers indicate the efficiency increase is caused in part by the diffuser enabling a greater pressure drop across the rotor blade.¹ Others feel a larger stream tube is captured increasing the mass flow rate and hence the momentum exchange to the rotor. DAWTs offer additional advantages in addition to increased augmentation, including minimizing tip losses and being less yaw sensitive than HAWTs.

In addition to the above efficiency improvements, there are also several additional advantages of the WindTamer design that have been determined during the current developmental program at Clarkson University. First, the increased blade number reduces the tip speed ratio from a value of 5 to 6 for a typical open rotor 3-bladed design to approximately 2. This decreases the wear and fatigue, but most importantly, decreases noise levels, which increase as the fifth power of RPM, without a large compromise on efficiency. The presence of the diffuser also reduces the danger of ice throw from the blades when icing conditions occur. Lastly, it appears from the current test, that there is no need to furl the turbine in high winds as the design self regulates the power to the rated design output. The implications of this are that the turbine continues to output it's maximum power instead of decreasing it's output in higher winds, greatly increasing the amount of energy harvested from the wind.

2. Experimental Prototype Performance

Experimental data has been acquired on the WindTamer 52" and 77" rotor configurations. The 77" was a grid tied configuration and the 52" data was acquired using a resistive load. The most recent 52" data is summarized below and the 77" data can be found in Report #10 from WindTamer.

52" Rotor Data

In an effort to optimize the rotor geometry over a range, a mobile rig was designed with resistive loads by WindTamer to be used to both in a mobile mode and towed to locations to obtain parked data. Figure 2 illustrates the setup. The hub height is approximately 13 feet off the ground.



Figure 2: WindTamer Mobile Test Rig with 52" Rotor

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Data acquired with the rig parked is illustrated in Figure 3. The data was acquired every second and the Cp efficiency values are presented in red for the 1 second data. In order to get a more representative estimate of the efficiency, 1 minute averages were calculated and are illustrated in green. It can be seen that Cp, based on the rotor area, are above the Betz efficiency, from about 4 to 8 m/s (about 9 - 18 mph)



Figure 3: WindTamer Mobile Test Rig Data, Parked Configuration, 271 Ohm Resistance

These data above indicate that the WindTamer is capable of Cp values in the 0.6 to 0.8 range, well above that of small wind turbines on the market today by almost a factor of 2, and as has been shown, above the Betz level for an open rotor. As will be shown in the next section, these values are quite close to those predicted by the design code, *mRotor* used at Clarkson.

Several studies have been conducted in the past on the feasibility and potential efficiency gains that DAWTs could provide. ³⁻¹⁰ Gilbert and Foreman^{3,4} indicated that the overall Cp values could be greater than the Betz limit by a factor of 2.65. This is defined in terms of an augmentation ratio,

$$r = Cp / 0.593$$

namely the ratio of Cp obtained with the duct to the traditional, rotor Betz limit, obtained with an open rotor, which would translate as an equivalent Cp of about 1.57 for r = 2.65.

The above derivations are, of course, applied to ideal levels of power extraction, however *if the argument is used that the augmentation factor can be applied to a given turbine performance level*, this represents a potential to increase any rotor power extraction level by a factor of, say 2, leading to:

$$Cp_{Ducted Rotor} = r Cp_{Bare Rotor}$$

Based on the above literature, an augmentation factor of r = 2 seems the most realistic limit and will be used in the present predictions for the WindTamer rotors.

3. Predicted Design Performance of 52" to 172" Rotor Designs

In order to estimate the potential for the proposed series of WindTamer turbines, a numerical estimate was performed using *mRotor*, a blade element momentum code developed at Clarkson. The code was used to design the blades currently on the 77" and 52" turbines and can also analyze turbine performance.

Performance curves were estimated using an optimum design target tip speed ratio of $\lambda = 2$, based on previous studies. The wind speed of 11 m/s has been used to quantify the rated turbine output, as this is the proposed American Wind Energy Association (AWEA) velocity value at which the turbine would be rated. The open rotor estimates were then modified to obtain the WindTamer estimates, using the conclusions reached in Section 2 above, namely an augmentation factor of 2.

For the present annual energy output (AEO) estimates, a Weibull distribution of the wind for a given average wind speed and a shape factor of 2 was used. This is more commonly referred to as a Rayleigh distribution. An example with an average wind speed 16 mph (7.1 m/s) is shown in Figure 4. This wind velocity distribution is combined with the power curve to generate the AEO for a given average wind speed. The AEO was then determined for each rotor at average wind speed from 1 to 11 m/s, which covers most of the US continent.



Figure 4: Wind Probability Distribution Function (mean = 7.1 m/s, shape factor = 2)

3.1. Geometries

A total of 7 rotor diameters were examined. Table 1 lists the geometries that were used for the current performance estimates. Note that the rotor diameter, which is used for the performance estimates, is smaller than the shroud opening.

The generator values listed in Table 1 correspond to the generator size that will be used for the given turbine diameter.

Shroud (")	Rotor Diameter (")	Hub Diameter (")	Hub r/R	Generator (kW)
54	52	11	0.212	1
80	77	14	0.182	2.5
96	93	14	0.151	3.5
114	108	14	0.130	5
132	124	18	0.145	7.5
156	148	20	0.135	12
180	172	20	0.116	15

Table 1: WindTamer Geometry Setup

3.2. Open Rotor Performance Estimates

The rotor geometries were designed in *mRotor* and two examples of the calculated power curves are presented below in Figure 5. These results are for the un-ducted, open rotor, WindTamer geometries. The wind speed of 11 m/s has been identified in the figures, as this is the proposed American Wind Energy Association (AWEA) velocity value at which the turbine would be rated.

Figure 6 illustrates the plots of the Cp distributions for the plots of Figure 5 as a function of wind speed. It can be seen that Cp varies from 0.35 to about 0.36 for the 52" rotor, increasing over the range of wind speeds, and about 0.35 to 0.37 for the 93" rotor. It appears that as the rotor size increases the Cp does too, but not by much. Again, keep in mind that these plots are for the bare open rotor and do not account for a diffuser effect.



Figure 5: Optimized Un-ducted Rotor Power Production a) 53 inch b) 93 inch.



Figure 6: Optimized Un-ducted Rotor Cp Behavior a) 53 inch b) 93 inch.

3.3. Ducted Rotor Power Performance Estimates

Two things are surmised to occur once a diffuser is in place. First the tip losses are likely reduced which can improve the Cp up to 8-10%. Second, and more importantly, the diffuser augments the mass flow and this increases the power output by a substantial amount.

If the diffuser effect is now accounted for, by applying an augmentation factor of r = 2 as mentioned in the literature in the previous section, the optimum Cp would be predicted to approximately double. The *mRotor* analysis indicates Cp values on the order of 0.36 to 0.37 which would translate into WindTamer values of about 0.72 to 0.74. This compares favorably with what has being observed in the experimental measurements illustrated in Figure 3..

Figures 7-13 illustrate the predicted WindTamer power output for the 52" to 172" rotors respectively, along with the Betz limit and the total power available in the wind. Note that the turbine configurations are predicted to get Cp values greater than Betz, based on the rotor area, but lower than the total power in the wind. The figures also illustrate the output predicted to occur at 11 m/s and these values have been tabulated in Table 2. These are, however, still an estimate and further experimental data will be needed to verify this.

The projected generator limit for each turbine, based on the observed, self-limiting behavior of the WindTamer, is also illustrated in Figures 7-13 as a dotted line, corresponding to a 33% increase of the maximum generator output. This cutoff is used as the power curve to calculate the AEO in the following section.



Figure 7: WindTamer Power Curve Behavior, 52 inch rotor.



Figure 9: WindTamer Power Curve Behavior, 93 inch rotor.



Figure 10: WindTamer Power Curve Behavior, 108 inch rotor.





Figure 12: WindTamer Power Curve Behavior, 148 inch rotor.



Figure 13: WindTamer Power Curve Behavior, 172 inch rotor.

Shroud (")	Rotor Diameter (")	Generator (kW)	Unducted Rotor Output @ 11 m/s (W)	WindTamer Output @ 11 m/s (W)
54	52	1	395	790
80	77	2.5	865	1730
96	93	3.5	1293	2586
114	108	5	1772	3544
132	124	7.5	2314	4627
156	148	12	3372	6745
180	172	15	4637	9274

Table 2: WindTamer Power Output at 11 m/s

In order to gain an appreciation for the WindTamer behavior, as compared to that of a typical turbine, the estimated Cp behavior for a Bergey XL.1 rotor behavior, and the WindTamer are shown in Figure 14. In addition to an increased efficiency, the WindTamer has a relatively flat top estimated distribution until limited by the constant generator output. The open rotor Cp behavior of the Bergey decreases after a certain wind speed, because it's power is reduced by the furling of the turbine.



Figure 14: Cp Distribution Behavior

Two example estimated power curves for the 52 inch and 93 inch rotors, corresponding to the efficiencies in Figure 14, are shown in Figures 15 and 16 below. Not only does the WindTamer exhibit an increased output than a similar size open rotor design based on a Bergey Cp distribution because of the increased efficiency, but once it reaches it's peak power output, it continues to output at that level because it is not furled. The open rotor design is typically furled so that the generator does not overload, and this reduces the power output at higher wind speeds.

Figures 15 and 16 also contain the computed values of the AEO at an example average wind speed of 7.1 m/s (16 mph).. The 52 inch rotor WindTamer is estimated to generate about 3,030 kWh per year, roughly 2.5 times more energy than a comparable open rotor of the same diameter, which yields 1220 kWh per year. This is at an average wind speed of 7.1 m/s (16 mph). The 93 inch rotor WindTamer, in Figure 16, is estimated to generate about 10,000 kWh per year, again roughly 2.6 times more energy than a comparable open rotor of the same diameter, which yields 3870 kWh per year. As the average wind speed drops, however, so does the ratio falling to about 2:1 at 4 m/s (9 mph).



Figure 15: Estimated Power Curve and Annual Energy Output (AEO) for 52" Rotors



Figure 16: Estimated Power Curve and Annual Energy Output (AEO) for 93" Rotors

3.4. Annual Energy Output Estimates

As illustrated in Figures 15 and 16, the annual energy output (AEO) is calculated by combining the turbine power curve and a wind probability distribution curve, such as that shown in Figure 4 for a given average wind speed of 7.1 m/s. The AEO was calculated and plotted for a range of average wind speeds for all the rotor geometries and the results are presented in Figures 17-21.

As an indication of how effective the WindTamer can be, consider that a Bergey XL.1, with a rotor diameter of a little over 98", produces (according to the manufacturer at http://www.bergey.com/Products/XL1.Spec.pdf) about 1850 kWh per year for an average wind speed of 5 m/s. The 93" WindTamer, as shown in Figure 19, produces 3996 kWh, *more than twice the energy of the Bergey.*



Figure 17: Estimated Annual Energy Output (AEO) for 52" WindTamer Rotor



Figure 18: Estimated Annual Energy Output (AEO) for 77" WindTamer Rotor



Figure 19: Estimated Annual Energy Output (AEO) for 93" WindTamer Rotor



Figure 20: Estimated Annual Energy Output (AEO) for 108" WindTamer Rotor



Figure 21: Estimated Annual Energy Output (AEO) for 124" WindTamer Rotor



Figure 22: Estimated Annual Energy Output (AEO) for 148" WindTamer Rotor



Figure 23: Estimated Annual Energy Output (AEO) for 172" WindTamer Rotor

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