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Balancing Performance, Noise, Cost, and Aesthetics in the Southwest Windpower "Storm" Wind Turbine

Preprint

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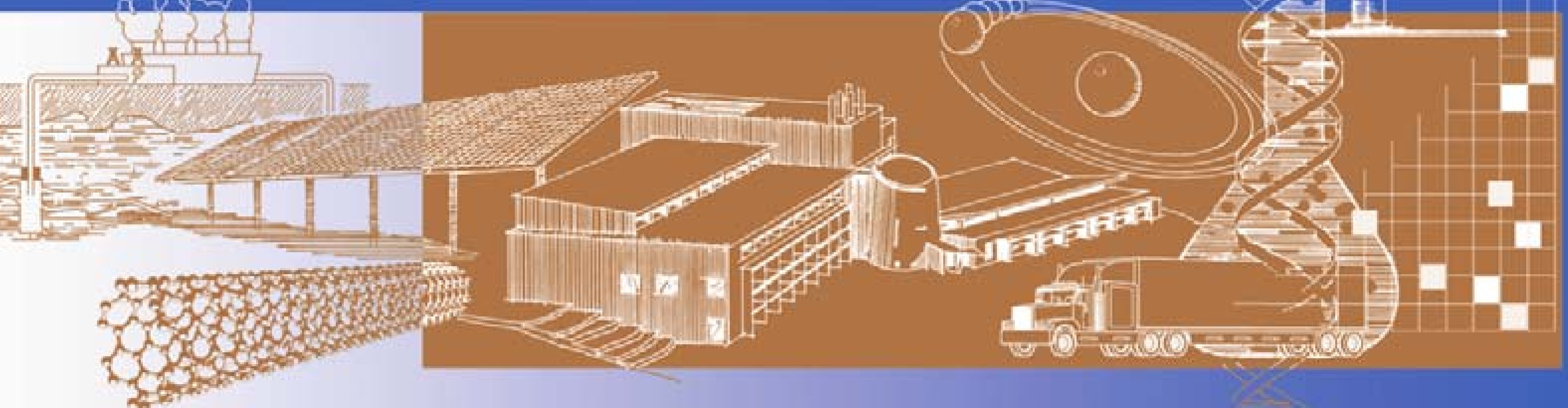
Prepared for WindPower 2005
Denver, Colorado
May 15–18, 2005

Conference Paper
NREL/CP-500-38157
August 2005



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BALANCING PERFORMANCE, NOISE, COST AND AESTHETICS IN THE SOUTHWEST WINDPOWER "STORM" WIND TURBINE

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ABSTRACT

This paper describes the design, fabrication, and testing of an 1800-watt innovative small wind turbine and discusses the importance of idiosyncratic aerodynamic and aeroacoustic airfoil characteristics for clean airfoils at low Reynolds numbers. The wind turbine has three blades, downwind orientation, and no tail vane. It does not use furling, or blade flutter for control. Primary design goals for the turbine were unobtrusiveness, low noise, and high energy capture at low wind speed sites. Preliminary field-test data indicate these goals are achievable. The turbine has an exceptional rotor efficiency of approximately 45% compared to 59% that is theoretically possible. A patented electronic stall control method effectively regulates power and RPM. The project was a cost-shared public/private partnership between Southwest Windpower of Flagstaff, Arizona, and the U.S. Department of Energy. Technical support was provided by the National Renewable Energy Laboratory and Sandia National Laboratories.

INTRODUCTION

The U.S. Department of Energy (DOE) Wind and Hydropower Technologies Program is working through the National Renewable Energy Laboratory (NREL) in Golden, Colorado, and the Sandia National Laboratories in Albuquerque, New Mexico, to advance distributed wind technology (DWT) systems of 100 kilowatts (kW) and less.

The goal of the DWT project is to reduce the life-cycle cost of energy (COE) to 10–15 cents/kilowatt-hour (kWh) in Class 3 wind resources by 2007. Class 3 sites are characterized by a power density of 150–200 watts/meter^2 (m^2) of rotor swept area. Alternatively, they are defined by an annual average wind speed of 5.35 meters per second (m/s) measured at a height of 10 m. To achieve this COE goal, the project is addressing a variety of technical issues, including wind turbine reliability and cost, power electronics for grid connection, aerodynamics and rotor design, blade structural design and manufacturing methods, advanced control techniques, and noise reduction. A detailed discussion of technology barriers identified by the U.S. small wind turbine industry can be found in the industry roadmap released in 2002 by the American Wind Energy Association[1] (AWEA).

One approach DOE uses to pursue its DWT goals is to engage industry members in partnerships for the development of advanced distributed wind technologies. Cost-shared grants and subcontracts are issued to companies with promising concepts, components, or complete turbine systems through a series of competitive solicitations. Grantees and subcontractors are asked to develop multiple-phase project plans having preliminary, detailed, and final design along with iterative design, analysis, hardware fabrication, and testing. NREL staff members support these projects by providing periodic design reviews and direct technical assistance that compliments the capabilities of the industry

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participant. The assistance includes laboratory and field tests of components and the complete "pre-prototype" turbine. NREL evaluates the consequent production "prototype" at its National Wind Technology Center (NWTC) in rigorous tests that comply with International Electrotechnical Commission (IEC) standards. In addition, NREL supports research on topics[2] of interest to the wind industry as a whole. For example, NREL provided supporting research, including wind tunnel tests, on the aerodynamics and aeroacoustics of airfoils at low Reynolds numbers (Re), for the project discussed in this paper.

Southwest Windpower (Southwest) of Flagstaff, Arizona, has been a DOE DWT project partner since 2000. The company has sold more than 60,000 small wind turbines. This extensive experience, coupled with its corporate vision, was brought to bear in defining the goals and objectives of its next-generation ***Storm*** turbine.

To gain widespread public acceptance, Southwest believes small wind turbines must fit into the urban (or suburban) environment. To do so, it is of utmost importance for them to be quiet. This means no annoyance from flutter, furling, drivetrain, or "tower thump" noise. Tower thump is a periodic fluctuation created when the blades pass behind the tower. The turbine must be unobtrusive and have a scale and appearance like other objects, such as light poles, encountered in residential areas. To meet this goal, the turbine will be installed on a tapered, tubular tower approximately 10 m tall. This will place the maximum vertical extremity of the blades at a height consistent with many zoning regulations.

The vast majority of potential small wind turbine customers reside in low wind sites. Therefore, to maximize the market potential, good low-wind performance is essential. Southwest's research indicates there are many regions where the average annual electricity consumption is surprisingly low. Therefore, the turbine had to be carefully sized. If the turbine were too large, it would jeopardize potential sales to consumers not wishing to purchase excess capacity. If the turbine is too small, it might not produce enough electricity to meet the customer's needs. Southwest settled on a goal of 400 kWh per month (average) with the perspective that a customer could always buy *two* turbines (if *one* was too small for an application), but could not buy *one-half* of a turbine (if *one* was too large for a particular application).

Southwest set a 10 ¢/kWh COE goal for the new turbine, which is slightly greater than the average residential utility rate. In addition, the company set an aggressive goal for a 5-year payback of installed cost, an attractive measure of merit for a machine expected to satisfy a substantial portion of electricity demand for at least 20 years. The company recognized, though, that this goal could only be achieved if the mature, value-engineered Storm turbine sold in large quantities.

To achieve extensive deployment and fully exploit the potential wind energy in the U.S. and elsewhere, small wind turbines must be accepted as "appliances." To be considered an appliance, the turbine must be easy to purchase and install, versatile, and highly reliable. To achieve versatility, Southwest wanted to design a turbine suitable for on- or off-grid applications at either 120 or 240 volts alternating current (AC). AC transmission minimizes power losses in the wires and allows the turbine to be placed a large distance from the interconnect point. Thus, an owner can optimize the energy capture of its turbine by seeking the best wind location on its site. To help achieve high reliability, Southwest wanted to minimize the number of parts. Therefore, the Storm turbine has a simple design with no tail, guy wires, or mechanical brake.

As is the case with all system-optimization, Southwest knew it might need to compromise some of its many objectives and that it might not achieve all its goals in the first generation Storm. The following report describes the balance Southwest struck among its performance, noise, cost, and aesthetics objectives.

AESTHETICS

Southwest's first aesthetic goal – for the turbine to be unobtrusive – resulted in several important configuration decisions. The Storm would have a downwind rotor and no tail so there would be less to see. The turbine would also have a tubular tower, which is visually familiar in the urban environment. This choice eliminates guy wires that might cause avian, safety, and maintenance concerns and are thought by some to be unsightly. Southwest also wanted to design the nacelle and blades to be similar in scale to light fixtures and their support arms. They carefully selected colors, textures, and shapes for their anticipated appeal. Figure 1, an early depiction of the turbine, exemplifies some of the aesthetic goals.

Although unobtrusiveness is an important goal, Southwest also wanted the turbine be seen as serving its intended purpose – extracting wind energy. Therefore, Southwest engineers wanted blade rotation to be the first indication (to an observer) of any wind. This would be achieved through high blade torque and low resistance from friction and cogging so that the blades would turn at very low wind speeds. Southwest summarizes their aesthetic goals for the ***Storm*** by saying their wish is that when somebody installs it, "If a neighbor notices it, they will want to buy one!"

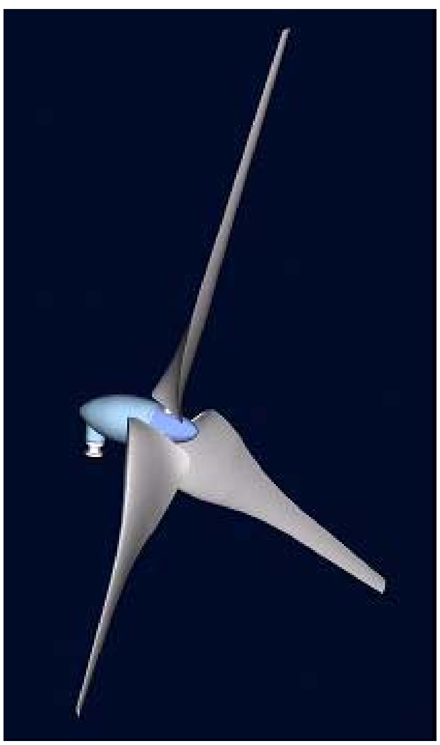

Figure 1. Early depiction of the ***Storm*** turbine illustrating visual simplicity and appealing shapes. The baseline blade was optimized for aerodynamic performance. Large chord and twist near the blade root yield good low wind performance.

COST

The measures of merit for the turbine are COE, with a goal of 10 ¢/kWh or less, and payback period, with a goal of 5-years or less. .

To reduce the cost of energy, Southwest chose a tailless downwind design without a furling mechanism or mechanical brake. Instead, the turbine uses an integrated power-electronics suite for RPM control (patented technology), peak-power regulation, electrical braking, power conditioning, and communications. The inverter and controls are located near the top of the tower. These choices, in turn, enabled Southwest to use a simple integrated nacelle, yaw system, alternator stator and heat sink. Southwest also hoped to reduce costs by using injection molded blades.

Although these features provided a framework for low cost, part of the cost reduction was offset by the cost of the free-standing tubular tower.

NOISE

In addition to reducing cost, Southwest wanted to reduce noise with its new design. To produce a quieter machine, engineers from Southwest and NREL used results from wind tunnel tests, field tests, and analysis codes to guide their design decisions. Their low-noise design strategy included:

- Restrain tip speed using electronic controls – both for performance optimization and noise reduction. This is probably the most powerful tool, because sound intensity is related to tip speed to the 5th power.
- Avoid noise from furling or flutter by using electronic stall control to regulate power.
- Use a quiet alternator with a slotless design that promotes low-wind cut-in.
- Use NREL wind tunnel aerodynamic and aeroacoustic test data to select a "quiet" airfoil that also provides high performance.
- Investigate potential low noise tip shapes.

Figure 2 shows data obtained in NREL field tests[3] of a Bergey XL.1 turbine, one of the quietest turbines tested. For this particular test, the mean value of background noise at a wind speed of 8 m/s (a common reference point) is about 44 dBA.

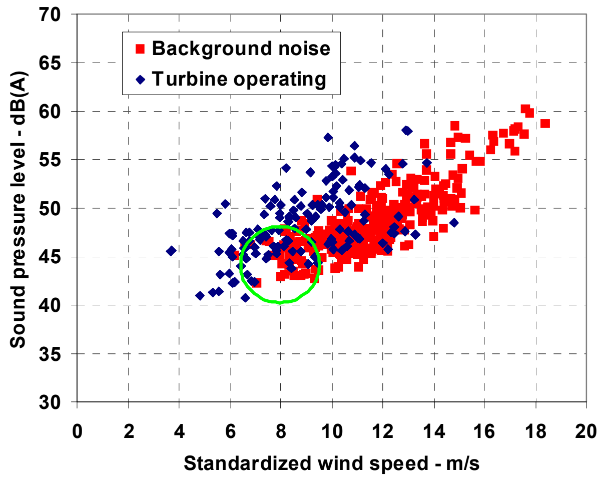

Figure 2. The chart compares the noise signature (sound pressure level) of an operating Bergey XL.1 turbine to background noise. Measurements were taken a distance of approximately 10.25 m downwind of the rotor.

(In some situations, particularly in rural areas at night, background noise can be much lower.) The sound level increases to approximately 49 dBA with the turbine operating. Researchers at Southwest and NREL believe this level should be reduced at least 3 dBA to promote the acceptance of small wind turbines in residential settings. Current research suggests that such a reduction is achievable by a combination of means.

Figure 3. Design choices relied heavily on wind tunnel aerodynamic and aeroacoustic data obtained from NREL-contracted tests. References 4-6 provide detailed information on the S822, S834, SG 6043, SH 3055, FX63-137, SD2030, and benchmark NACA 0012 airfoils that were tested.

Rotor design efforts have been significantly aided by the publication of NREL's wind tunnel aerodynamic[4] and aeroacoustic[5,6] test data for six airfoils (Figure 3) currently used or planned for use on small wind turbines. The tests provided several important insights regarding noise.

All of the airfoils tested in an unsoiled condition exhibited pure tones at the low Reynolds numbers that are typical of small wind turbines. Southwest wanted to choose an airfoil that would eliminate the pure tones, which resemble a monotonous whistle or buzzing, depending on frequency. According to the test results shown in Figure 4, tripping the boundary layer eliminated the pure tones *and* decreased broadband noise. Comparing the airfoils by various means, such as the noise spectra in Figure 5, showed that some airfoils are quieter than others. The important implication is that if designers do not have access to aeroacoustic test data, they might choose an airfoil for performance or other reasons and inadvertently make a bad aeroacoustic choice.

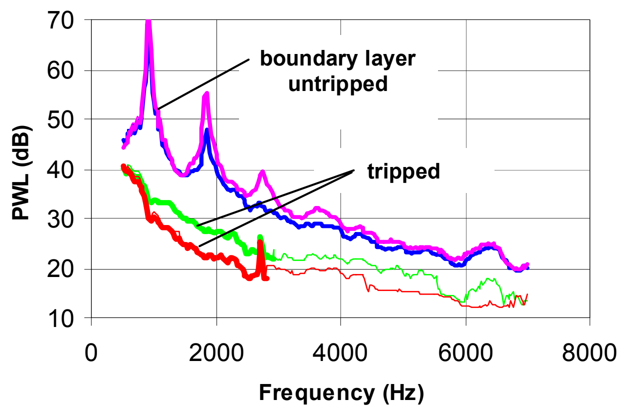

Figure 4. Airfoil noise spectra from wind tunnel tests exhibit pure tones (seen as spikes in the upper two curves) resulting from laminar boundary layer vortex shedding. Tripping the boundary layer eliminates pure tones (spikes disappear) and reduces sound levels across the frequency range (broadband noise).

In addition to airfoil, planform shape, and tip speed (assuming that mechanical and alternator noise are quieted), the NREL/Southwest team will address other important aeroacoustic considerations such as trailing edge thickness and blade tip shape. Figure 6 shows several potential low-noise blade tip shapes to be tested on the ***Storm*** prototype at the NWTC.

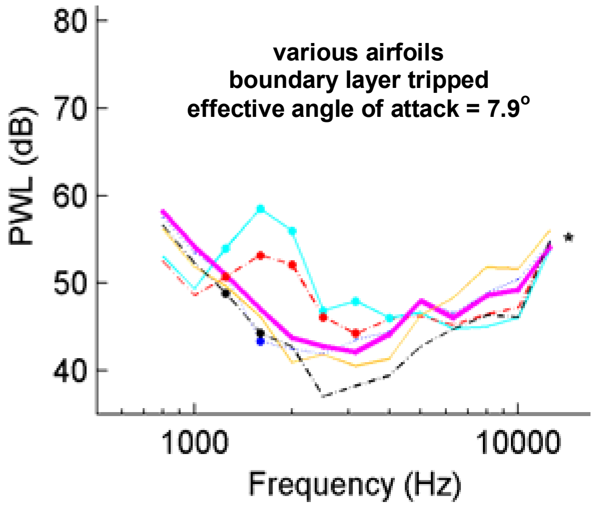

Figure 5. Wind tunnel test data were consulted during the design phase. Some airfoils are definitely quieter than others.

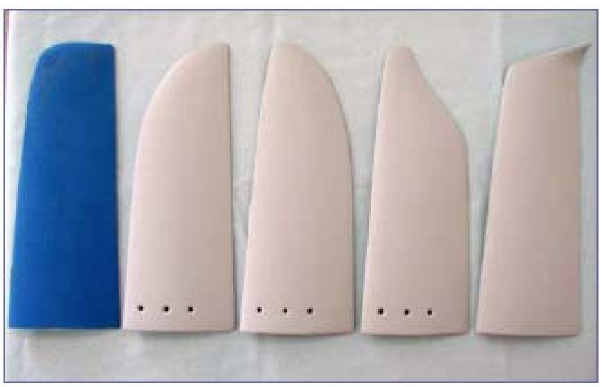

Figure 6. Southwest is working with NREL to evaluate prospective low-noise blade tip shapes.

PERFORMANCE

Aerodynamic performance, including optimal control, manifested in annual energy capture, is the most important measure of merit for all wind turbines. Consequently, high performance is the primary objective of a new turbine design. Power coefficient (Cp), defined as the ratio of power converted by the turbine to that available in the wind, is the measure of aerodynamic efficiency for wind turbine rotors. The best large wind turbines, operating at very high Re, achieve a Cp of about 0.5 measured at the rotor. Small wind turbines rarely approach this efficiency because they operate at low Re where airfoil aerodynamic performance is poorer. With this awareness, and the NREL wind tunnel data, project engineers developed the following design strategy for high performance.

- Use the wind tunnel aerodynamic data, from NREL-sponsored University of Illinois tests, and the wind tunnel aeroacoustic data, from the NREL-sponsored Netherlands National Aerospace Laboratory tests, to select an airfoil with good aerodynamic and aeroacoustic performance.
- Favor low maximum lift coefficient with gradual fall-off for better stall regulation.
- Favor thicker sections for structural and noise considerations.
- Consider both clean and soiled conditions to maximize energy capture.
- Optimize the rotor for low tip speeds to emphasize low noise.
- Evaluate the impact of the optimized rotor on COE. For example, chord and twist effects on thrust and torque will impact tower, alternator, and other component costs.

The subtle and extremely important impact of low Re aerodynamics is illustrated in Figure 7. Much can be learned by analyzing these drag polars, which are plots of airfoil lift coefficient (c_l) versus drag coefficient (c_d) from the wind tunnel tests. Notice the aerodynamic behavior in the plot on the left. C_d increases dramatically with decreasing Re at a constant c_l. At very low Re, even small changes in c_l result in large increases in c_d. For an operating wind turbine, such changes in c_l and/or Re are the result of wind velocity changes (gusts), because Re is directly proportional to wind speed, and gusts change the angle of attack.

Blade aerodynamic efficiency is largely determined by lift/drag ratio, so it is desirable to operate near the optimum c_l/c_d, a task made difficult by sensitive, low-Re aerodynamics. Consider as an example the S822 airfoil shown in Figure 7 operating clean at Re = 200,000 with an optimum l/d of about 73 (green circle, left graph, Fig.7). A hypothetical reduction of 25% in Re and 2 degrees in angle of attack will cause a reduction of l/d to 35 (red circle, left graph, Fig. 7). Interestingly, the airfoil with its boundary layer tripped, representative of a soiled blade, suffers no reduction of its optimum l/d = 40 under similar conditions (right

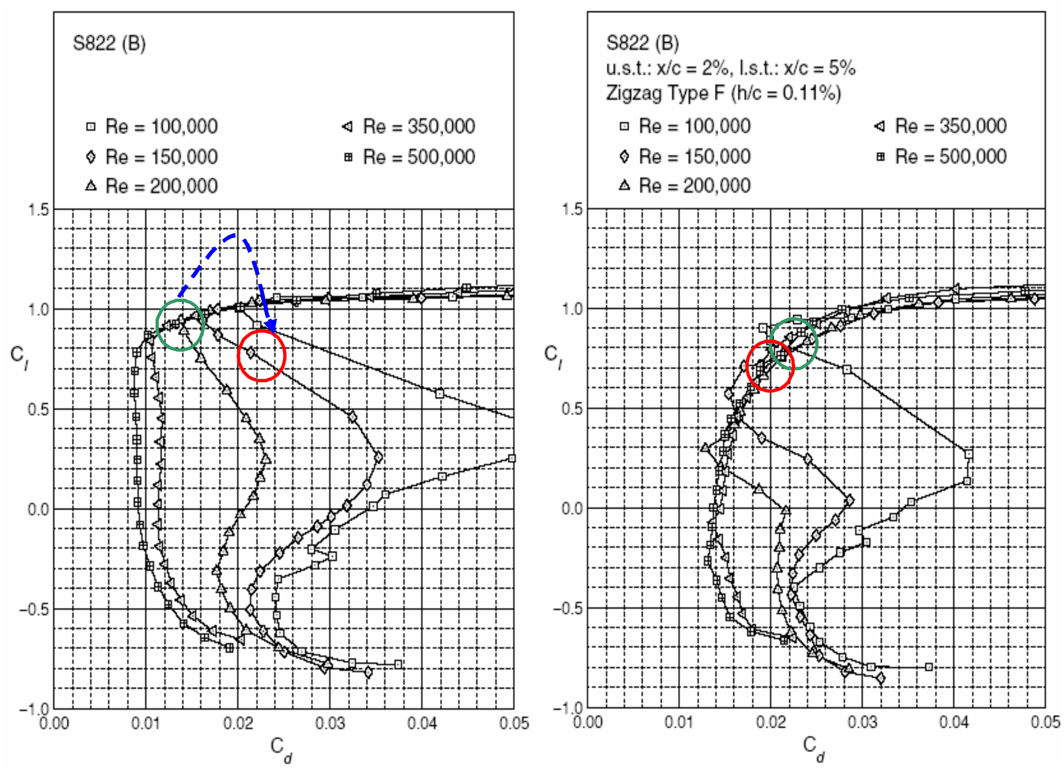

Figure 7. Wind tunnel data indicate that airfoil aerodynamic behavior is very sensitive to Re in the range tested. The data collapse somewhat and are less sensitive to Re when the boundary layer is tripped (right graph) than when the boundary layer is untripped (left graph).

graph, Fig. 7). Dealing with the aerodynamic and aeroacoustic behavior of clean airfoils at low Re was an important objective in the optimization of the ***Storm*** blade. Its evolution was as follows.

Based on wind tunnel data, the design team selected the NREL S822 airfoil as it seemed to be the best choice from both an aerodynamic and aeroacoustic perspective. The team used classical blade-element momentum-theory codes to obtain an optimum twist and chord distribution for an assumed tip speed ratio (TSR) of 7.0 and blade span of 3.35 m. Evaluation of off-design performance showed improved energy capture at even lower TSRs. Coupled with the desire for lower tip speeds for aeroacoustic reasons, this led to a redesign of the planform at a lower TSR.

The energy capture objective of 400 kWh per month was not achieved by the baseline design, so the diameter was increased to 3.7 m. Although the redesigned blade had excellent aerodynamic performance, the root chord and twist were reduced to mitigate the impact on design thrust (thus, tower cost) and torque (thus, alternator cost). A parabolic equation was used to precisely define the leading edge shape (plan view) that was integral to the baseline tip shape. This blade (Figure 8) was tested on Southwest's pre-prototype turbine (Figure 9) in Flagstaff, Arizona.

Figure 8. Pre-prototype blade set for 1.8 kW turbine tested by Southwest in Flagstaff, Arizona.

Figure 9. This pre-prototype test turbine, shown with straight blades, was used to investigate various configurations.

To address downwind tower thump and add visual interest to the ***Storm,*** Southwest also evaluated *swept* blades. After testing a rotor with swept blades (Figure 10), both the straight and the swept blades were modified (Figure 11) to improve structural efficiency and enhance aeroelastic stability (avoid flutter).

Figure 10. Swept blades were tested with a prototype nacelle on a free standing tubular tower.

Most rotor optimization studies attempt to balance noise, cost, and energy capture. Successful designs depend on appropriately defining the project objectives, having an accurate cost model, and paying attention to analysis results. Unfortunately, these simple but critical elements of the design process are sometimes overlooked. The Southwest/NREL team attempted to avoid this error in the evolution of the ***Storm*** turbine.

Figure 11. Southwest believes swept blades have promise for reducing aeroacoustic noise. These prototype blades will be tested at the NWTC.

FIELD TESTS

Southwest conducted its pre-prototype tests in Flagstaff, Arizona. NREL staff members assisted with test planning and instrumentation and conducted a test readiness review to verify safety procedures and the efficacy of the data acquisition system. Figures 12 and 13 show the most important results.

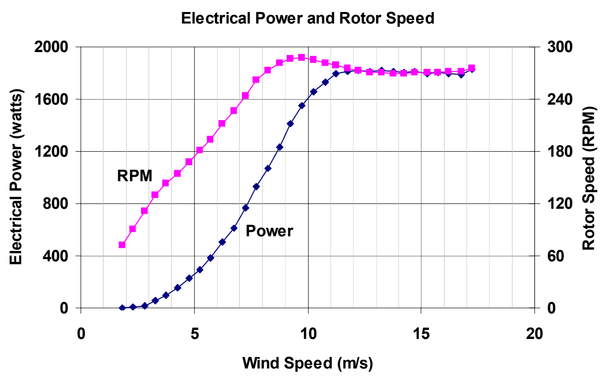

Figure 12. Pre-prototype tests demonstrated successful regulation of power and RPM. Data are one-half m/s binned values of 20-second averages.

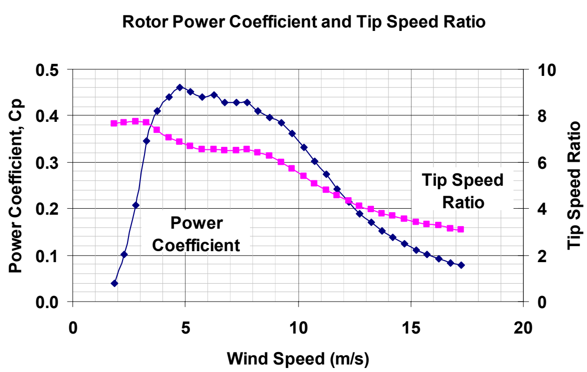

Figure 13. The pre-prototype rotor achieved a rotor power coefficient of approximately 0.45.

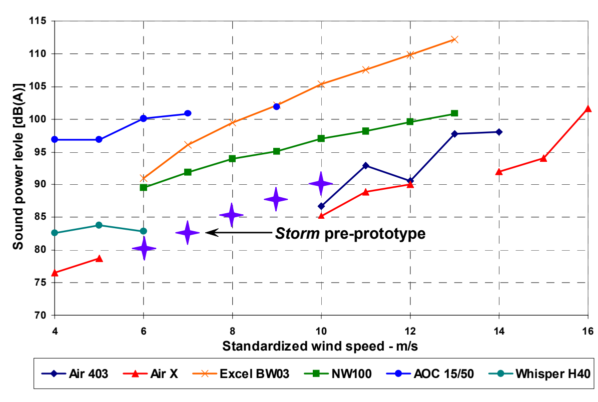

Figure 14. The pre-prototype ***Storm*** turbine exhibited an acoustic signature similar to Southwest *AIR-X* and *Whisper H40* turbines.

Although fine tuning the control system was challenging, the team managed to conclusively demonstrate the successful regulation of power at 1.8 kW and maximum RPM at 300. This result was the paramount objective of the tests. Most variable-speed turbines employ pitch control for peak power regulation. Although fixed-pitch variable-speed stall-regulated operation has been demonstrated at the NWTC on a large turbine[7] (AWT-26), the tight control demonstrated by the ***Storm*** may be a milestone for small wind turbines. Furthermore, the peak power coefficient is exceptionally high for a turbine operating at low Re. Using field-test data of measured electrical power and dynamometer tests of alternator efficiency, the team deduced a peak rotor Cp ≅ 0.45. A combination of good blade aerodynamics and rotor speed control produced a broad, flat Cp curve with Cp ≅ 0.43 over a 4 m/s wind speed range. Team members found these preliminary test results very encouraging.

The pre-prototype tests also produced some aeroacoustic data. These results, shown in Figure 14, were also encouraging because they indicated the ***Storm*** noise signature is similar to that of much smaller turbines, such as Southwest's *Air-X* and *Whisper H-40*. Southwest anticipates further improvement in the noise level, because the pre-prototype used a conventional alternator that was quite noisy, whereas the prototype uses a quieter slotless alternator.

Tests of the prototype turbine (Figure 15), currently underway at the NWTC, will provide high-quality measurements of power, acoustics, and structural loads for both the straight and swept blades. Thus far, the preliminary data (Figure 16) are in reasonable agreement with Southwest's pre-prototype tests. Evolution is expected, however, as a result of fine-tuning the blade geometry, control software, alternator design, and power electronics. The design team expects the NWTC data to point the way to future improvements in all those areas.

SUMMARY

DOE, with NREL and Sandia assistance, supports cost-shared industry partnerships for the development of new small wind turbines. The partnership with Southwest Windpower resulted in the design, fabrication, and testing of the ***Storm*** three-blade, downwind, variable-speed, stall-regulated turbine rated at 1.8 kW. The primary design goals were for the turbine to be quiet, unobtrusive, and have

Figure 15. ***Storm*** prototype turbine is being tested at NREL's National Wind Technology Center.

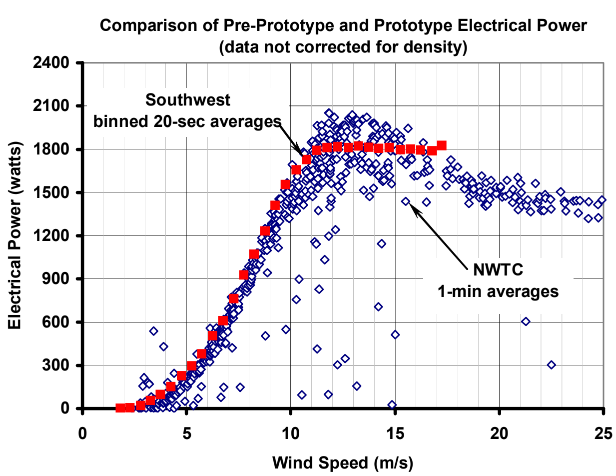

Figure 16. Preliminary results of NWTC tests are similar to Southwest's pre-prototype tests.

good low wind speed performance, a payback period of five years or less, and a COE of 10 ¢/kWh or less. The rotor design was influenced by an appreciation for the idiosyncratic aerodynamic and aeroacoustic behavior of unsoiled airfoils at low Re. Preliminary field-test data verified a primary project objective of achieving power/RPM regulation by a patented "electronic" stall control method. Preliminary tests indicate a favorably broad Cp curve with a peak of approximately 0.45. Noise tests indicate an acoustic signature similar to much smaller turbines and a sound power level (source strength) of approximately 85 dBA at a wind speed of 8 m/s. The NWTC is currently conducting definitive power, noise, and structural loads tests of both straight (un-swept) and swept blades. Tests of potential low noise blade tip shapes are also planned. Although Southwest plans to offer the ***Storm*** turbine for sale in 2006, extensive value engineering is anticipated in the future to improve energy capture, acoustic signature and cost effectiveness.

ACKNOWLEDGEMENTS

We acknowledge and thank the DOE Wind and Hydropower Technologies Program for providing funding for the Storm turbine development project. More than a dozen engineers, technicians, and consultants at NREL, Sandia, and Southwest Windpower made valuable contributions. We sincerely hope that our gratitude and their pride are not diminished by our not naming them individually. Lastly, we appreciate the efforts of NREL's Kathleen O'Dell in editing this document.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
August 2005	Conference Paper	

4. TITLE AND SUBTITLE	
Balancing Performance, Noise, Cost, and Aesthetics in the Southwest Windpower "Storm" Wind Turbine: Preprint	**5a. CONTRACT NUMBER** DE-AC36-99-GO10337
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) P. Migliore, J.Green, D. Calley, and J. Lonjaret	**5d. PROJECT NUMBER** NREL/CP-500-38157
	5e. TASK NUMBER WER5.5101
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	NREL/CP-500-38157
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)** NREL
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

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15. SUBJECT TERMS

small wind turbine; wind turbine aerodynamic design; wind turbine airfoils

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
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