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CUSTOMIZED AIRFOILS AND THEIR IMPACT ON VAWT COST OF ENERGY*

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ABSTRACT

Sandia National Laboratories has developed a family of airfoils specifically designed for use in the equatorial portion of a Vertical-Axis Wind Turbine (VAWT) blade. An airfoil of that family has been incorporated into the rotor blades of the DOE/Sandia 34-m diameter VAWT Test Bed. The airfoil and rotor design process is reviewed. Comparisons with data recently acquired from flow visualization tests and from the DOE/Sandia 34-m diameter VAWT Test Bed illustrate the success that was achieved in the design. The economic optimization model used in the design is described and used to evaluate the effect of modifications to the current Test Bed blade.

INTRODUCTION

All commercial Vertical Axis Wind Turbines (VAWTs) utilize aviation-type airfoils for their blades, usually the NACA 0015 or NACA 0018 profiles. However, the operating regime of VAWT blade elements is very different from that experienced by airfoils used in aviation applications:

VAWT blade elements function under inherently unsteady conditions, passing through zero angle-of-attack twice per revolution as they oscillate between relative maxima and minima often exceeding ± 90°, respectively, while aviation airfoils usually function under nearly steady conditions at near-zero angles-of-attack.

VAWT blade elements routinely encounter stall during operation in high winds, while aviation airfoils encounter stall only in unusual operating conditions.

VAWT blades operate at Reynolds numbers (Re) between a few hundred thousand and a few million, while most aviation airfoils operate at Reynolds numbers between three and thirty million.

Systems studies by Kadlec[1] in 1978 revealed a significant potential for decreasing the VAWT-generated cost of energy (COE) by using VAWT-specific blade element designs in place of those borrowed from aviation circles. In particular, Kadlec determined that the VAWT COE could be decreased by tailoring the blade airfoils to:

increase the maximum power coefficient

force blade stall at a windspeed closer to that at which the maximum power coefficient occurs

allow the turbine to operate at a higher rotational speed.

In 1980 Sandia National Laboratories (Sandia) began a program to develop a family of airfoil sections specifically tailored for use in the VAWT environment.

AIRFOIL SECTION DESIGN

Our initial step in the development of the VAWT-specific airfoil profiles was to identify specific blade element aerodynamic characteristics which would achieve the performance changes that Kadlec[1] found to be desirable. This was accomplished through a parametric study, in which we first postulated sets of lift and drag characteristics for airfoils and then used CARDAA[2], a conservation-of-momentum based, double-multiple streamtube (DMST) aerodynamic performance code, to predict the performance of turbine rotors incorporating various combinations (chords and spans) of these airfoils. The version of CARDAA we used incorporated the Gormont dynamic stall model[3], as modified by Masse[4], and accounted for local Reynolds number effects. These performance predictions were then used as input for an economic analysis code known as ECON16[5] which estimated the COE for turbines with the various rotor configurations (ECON16 is described in some detail later in this paper). This study revealed that the COE is reduced when the blade profile in the equatorial region exhibits the following features:

modest values of maximum lift coefficient

low drag at low angles-of-attack (α) and high drag at high α

sharp stall

low thickness/chord ratio.

The low drag at low angle of attack yields somewhat improved performance at low wind speeds, while the modest values of maximum lift coefficient, sharp stall, and high drag at high angle of attack yield a flat power curve at high wind speeds (power regulation). The net effect of these features is illustrated schematically in Figure 1 where the performance of a VAWT with NACA 0015 blades is compared to the 'preferred' performance that we were striving for with the tailored blades.

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A turbine with the 'preferred' performance curve operates near the drivetrain design condition throughout the power regulation region. At this condition, the transmission and generator efficiencies are near maximum, so the relative drivetrain losses are low. The maximum power produced is far less, so the rotor and drivetrain loads are much reduced and they can be built lighter and cheaper. Although substantially less power is produced in high winds, these high winds occur quite infrequently (as seen in Figure 2) so the energy lost is rather small and is outweighed by the cost savings in the drivetrain and rotor and the decreased losses of the drivetrain.

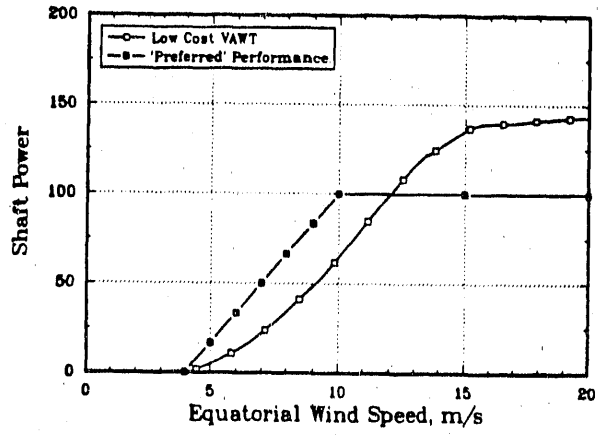

Figure 1. Wind Turbine Performance

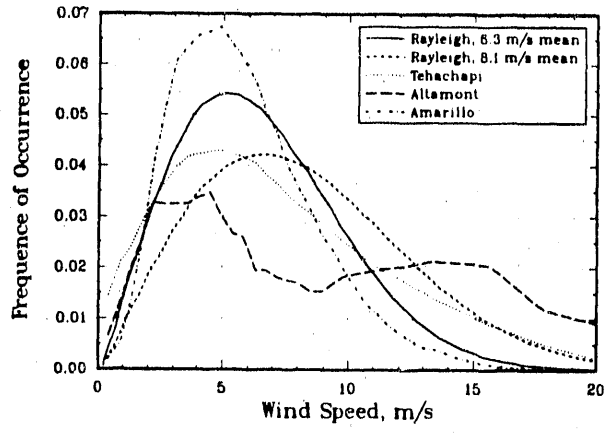

Figure 2. Wind Speed Distributions

From another perspective, optimal power regulation as illustrated in Figure 1 makes possible the installation of a much larger rotor on a drivetrain of a given size. Since the drivetrain costs are the same as for a smaller, unregulated rotor, the only additional costs associated with the increased energy capture are those due to the larger size of the regulated rotor. Again, the net result is a lower COE.

Once we had determined the airfoil characteristics that optimized the COE, we worked with Dr. Gerald Gregorek of The Ohio State University to achieve the actual airfoil profile. Gregorek used the NASA-supported airfoil design code PROFILE[6], written by Richard Eppler, to design airfoils with characteristics that approached those we considered to be optimum.

The resultant symmetric airfoils, featuring large extents (approximately 50% of chord) of natural laminar flow (NLF) with thickness-to-chord ratios of 15, 18, and 21%, are referred to as the SAND family of airfoils (the SAND 0015/47, SAND 0018/50, and SAND 0021/50, respectively). They are compared with the NACA 00XX profiles in Figure 3. The SAND airfoils have a much sharper leading edge, a maximum thickness further aft, and a slight reflex near the trailing edge. As illustrated in Figure 4, these airfoils exhibit low drag at low angles of attack and experience sharp stall (flow separation with its attendant increase in drag and loss of lift) at 10^0 to 12^0 angle of attack.

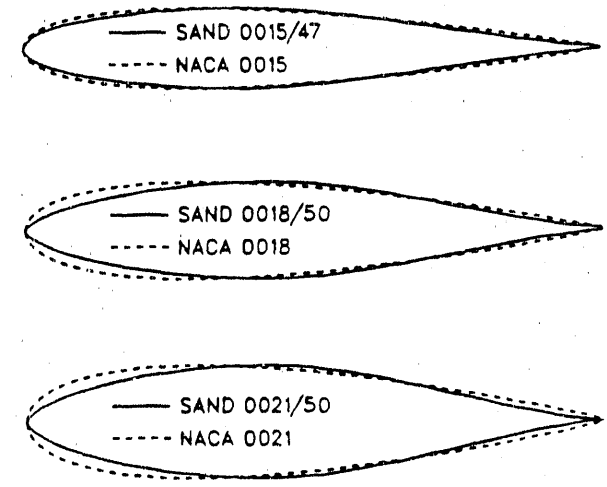

Figure 3. SAND and NACA Airfoil Sections

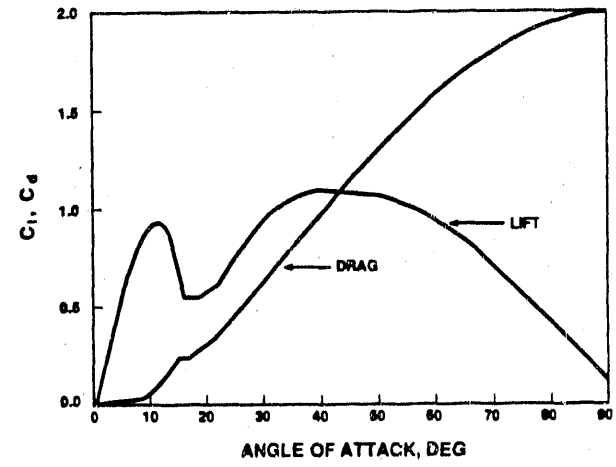

Figure 4. Lift and Drag Characteristics for the SAND 0018/50 Airfoil

Reda[7] used new flow visualization techniques to investigate the details of boundary layer flow around the SAND 0018/50 under dynamic conditions. His results are summarized in Figure 5 (from

Reference 7). The locations of boundary layer transition (from laminar to turbulent) and turbulent boundary separation exhibited the general trends predicted by the PROFILE code, but occurred at somewhat higher angles of attack.

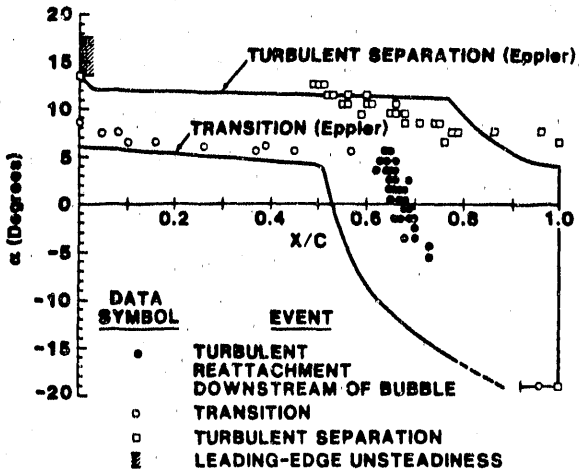

Figure 5. SAND 0018/50 Boundary Layer Transition and Separation Locations

The SAND airfoils resemble uncambered members of the NACA 6-series family which were developed by NACA forty or more years ago. Early attempts to utilize the NACA 6-series airfoils on airplanes were unsuccessful because airframe fabrication techniques of that era were incapable of producing airfoil surfaces that could maintain significant extents of laminar flow; surface waviness and rivet heads quickly caused transition to turbulent flow. Since then, however, advances in manufacturing techniques have made possible the production of airfoils with surfaces smooth enough to support laminar flow. In addition, our experiences with extruding aluminum blades for other VAWTs had shown that very good surface finishes could be attained, so we felt confident of our ability to fabricate airfoils that could support laminar flow.

Another concern regarding the use of laminar flow airfoils on wind turbines is the degradation of performance that will occur due to roughening of the blade surfaces by dust, rain or the residue from insect impacts. The performance of turbulent flow airfoils such as the NACA 00XX series now commonly used on VAWTS will also be degraded by this type of roughness, however, and the real question becomes: "Does the laminar flow airfoil outperform the turbulent one under these conditions?". This situation was examined analytically by using PROFILE[6] to predict the performance of two airfoil profiles-the NACA 0018 profile and the SAND 0018/50 profile. The boundary layer on each profile was artificially tripped near the leading edge by introducing an analytical surface roughness. The results are illustrated in Figure 6. While the performance of the laminar flow section was degraded by the surface roughness, it was still superior to the performance of the roughened NACA 00XX section; the drag of the SAND airfoil remained less than that of the NACA 0018 airfoil, and the stall characteristics (rapid increase in drag accompanied by a small increase in lift) of the SAND airfoil remained more abrupt. Additional information on design of these airfoils and roughness effects may be found in references 8 and 9.

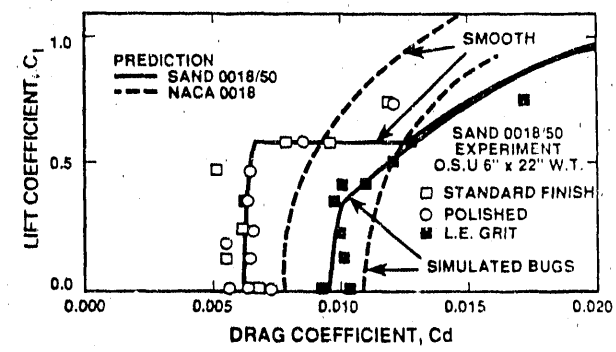

Figure 6. Effect of Roughness on Airfoil Characteristics

The complete design of the SAND blade sections required several iterations on the airfoil profiles incorporating results from static and dynamic wind tunnel tests and field tests on two research VAWTs[10,11]. These tests substantiated our predictions that extruded aluminum airfoils could generate and sustain significant chordwise extents of natural laminar flow. They also confirmed the predicted relative performance differences between the roughened SAND and NACA 00XX geometries.

As mentioned above, the SAND family of airfoils was developed for use near the equator of a VAWT. The airfoils near the tower operate in a much different environment, and our attempts to design airfoils that outperform the NACA 00XX airfoils in that environment have not been successful. The NACA 00XX airfoils are far better suited for that environment than are the SAND airfoils.

TURBINE BLADE DESIGN AND PERFORMANCE

Although the SAND 0015/47 and 0018/50 airfoils were tested on the Sandia 5-m and 17-m research VAWTs [10,11], their full potential can be realized and evaluated only on a turbine specifically designed to utilize those blades. The 34-m diameter VAWT Test Bed at Bushland, TX, shown in Figure 7, is the first wind turbine designed to, among other things, utilize and evaluate the SAND airfoil sections. Additional information on this machine may be found in References 12 and 13.

Both SAND and NACA 00XX airfoil sections were incorporated into the blade-the SAND 0018/50 airfoil near the equator and the NACA 0021 airfoil near the tower. Use of the step-tapered blade configuration illustrated in Figure 8 keeps blade material stresses low while maintaining high rotor energy capture. The increasing chord values from the blade equator to the blade root also kept a relatively constant Reynolds number over all the SAND airfoil sections, allowing them to operate quite efficiently.

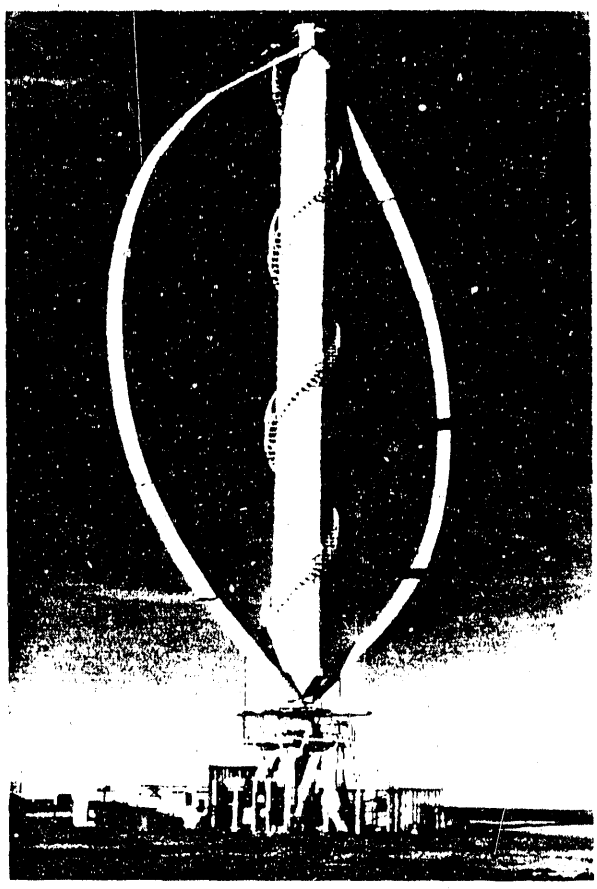

Figure 7. 34-m VAWT Test Bed

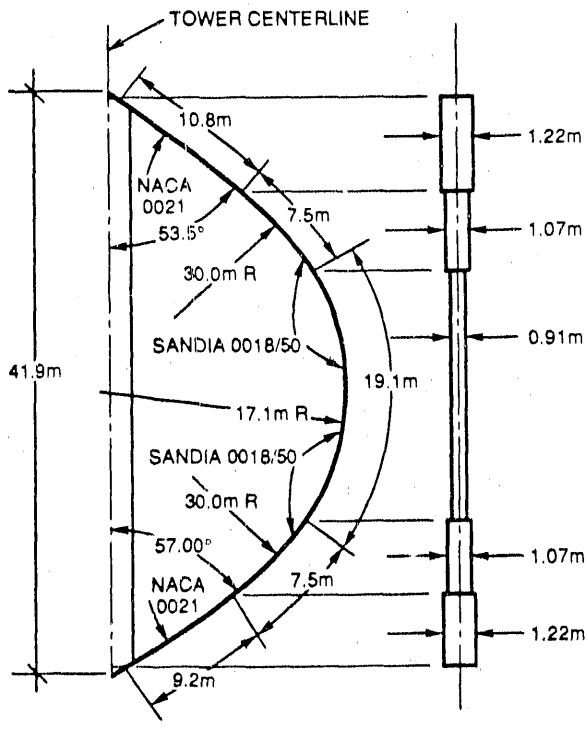

Figure 8. Test Bed Blade Configuration

Turbine Performance

Modelling results mean little if we cannot predict the performance of a turbine fairly accurately. Figures 9 and 10 compare the predicted performance of the Test Bed with data measured in January, 1990. The agreement between measurement and prediction at moderate to high wind speeds is very good. The power regulation in the high-wind area of Figures 9 and 10 is particularly worthy of notice-it is due to the stall characteristics of the SAND airfoil sections, and this regulation was one of the key objectives of the Test Bed blade design effort.

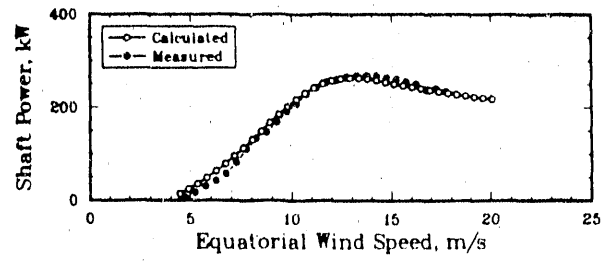

Figure 9. Test Bed Performance at 28 rpm

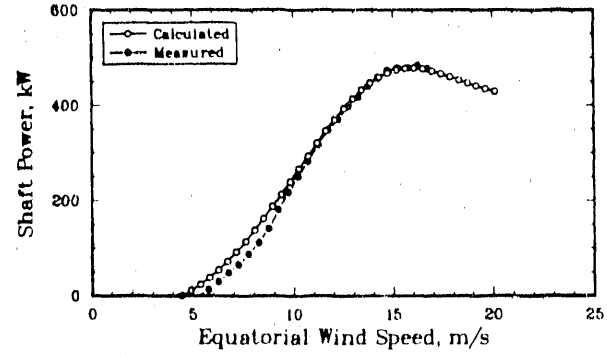

Figure 10. Test Bed Performance at 34 rpm

The agreement at low wind speeds is not as good. As indicated in Reference 13, we feel that the high drag associated with the blade-to-blade joints is contributing to this disagreement, and we are taking steps to minimize that drag.

SYSTEMS ECONOMIC STUDIES

ECON16 (now ECON90) allowed us to evaluate the effect of the various blade design parameters on the Test Bed COE, and this, in turn, drove the final design of the blades. This type of analysis would have been very difficult without a fairly detailed systems economic model. The next section describes that model in more detail, and the following section illustrates the power of that model by investigating the effect of the SAND 0018/50 airfoil on the Test Bed COE.

Economic Optimization Model

The COE results presented in this paper were obtained with ECON90, a modification of the ECON16[5] code. ECON16 is a VAWT economic optimization model which was developed in 1978 to estimate the costs of the various system components (blades, tower, tiedowns, transmission, generator, foundation, and assembly), subject to structural constraints on the blades, tower, and tiedowns. ECON16 does not include any learning curves or other quantity discounts in the model cost formulas. The following assumptions/restrictions are inherent in the code:

The rotor operates at constant rpm, controlled by the utility grid through a synchronous or induction generator.

Blade construction is of thin-walled, hollow aluminum extrusions, using manufacturing techniques existing in the United States. Multiple extrusions may be used for each blade section, and multiple sections may be joined to create the rotor blade.

The tower is steel, of tubular cross section, supported at the top by a three-cable tiedown system.

Vibratory stresses for all structural components are kept below 42 MPa (6000 psi) in 27 mps (60 mph) windspeeds at normal operating rotor rpm.

Rotor components are sized to survive 67 mps (150 mph) windspeeds at the rotor centerline.

The cost estimates are based on recurring component costs for an established production industry. The non-recurring die and setup costs are amortized over a production run of 100 turbines.

Losses due to the transmission and generator are included in energy capture calculations.

The total annual system cost, including operation, maintenance, and financing, is assumed to be 15% of the total capital cost.

Optimization is based on minimizing the annual system cost per unit of energy supplied.

ECON90 incorporates CARDAA performance predictions for greater accuracy and permits the use of multiple-chord blades. The 1978 cost models in ECON16 were not updated for ECON90. Although the actual costs estimated by the model are badly outdated, the cost distribution between major elements and relative costs of those major elements should still be valid (subject to the above assumptions/restrictions), so all COE results will be presented in relative terms.

Blade Configuration Impact on Turbine COE

ECON90 can now be used to investigate the impact of various changes in the blade configuration on the Test Bed COE. The accuracy with which these impacts may be assessed is obviously dependent on the accuracy with which ECON90 models the efficiencies and costs of all of the Test Bed components. Although ECON90 is a relatively primitive model, it does determine the optimum turbine rpm and includes variable transmission and generator loss models.

In the following examples, the rotor diameter and height-to-diameter ratio (H/D) are fixed at the Test Bed values of 34 m (110 ft.) and 1.25, respectively. The COE is relatively insensitive to small changes in these parameters, and H/D is driven mainly by structural considerations. All optimizations were performed for a 6.3 mps (14 mph) mean wind speed (Rayleigh distribution) at 10 meters above the ground, a 20 m/s cut-out wind speed, and a 1/7 shear exponent. All COEs are relative to that of the Test Bed rotor operating at its optimum speed of 35.4 rpm, which has been assigned a COE of 1.0.

The effects of various blade configuration changes are summarized in Table I.

Figure 11 compares the predicted power curve for the Test Bed at 35.4 rpm (line 1 in Table I) with that for a turbine with the same blade chord distribution (Test Bed taper), but utilizing all NACA 0018 airfoil sections (lines 2 and 3 in Table I). This later configuration will be referred to as the MOD1 turbine. At 35.4 rpm, the maximum power produced by the MOD1 turbine is more than double that produced by the Test Bed, and the MOD1 turbine COE is 1.29. ECON90 predicts a minimum COE of 1.16 for this turbine at 25.4 rpm, with an associated peak power below that of the Test Bed. As seen in Figure 11, the MOD1 turbine power curve falls well below that of the Test Bed for wind speeds above 9 mps. This certainly contributes to the increased COE. There is, however, another major contributor to the increased COE-the lower rotational speed of the MOD1 turbine. Since the power produced by the turbine is the product of the shaft torque and the shaft rpm, this lower rotational speed translates directly into higher torque requirements on the drivetrain (the transmission) and thus higher drivetrain costs. ECON90 also indicates a slight decrease in the cost of the generator for the MOD1 turbine, due to the decrease in peak power, but that is far smaller than the increase in transmission cost.

Lines 3 and 4 of Table I show that the use of a tapered blade actually increases the COE for a turbine with all NACA 0018 blades. A blade with a constant 1.08-m (42.5-in.) chord would have the same projected area (and the same solidity or ratio of blade projected area to turbine swept area) as the tapered blade. A turbine using all NACA 0018 blades with this chord (line 4 of Table I) has a minimum relative COE (at 24.3 rpm) of 1.10, about 6% below that for the tapered blade. Examination of the ECON90 output shows that the small increase in peak power for the constant chord blade increases the cost of the transmission and generator slightly, but more energy is captured due to the larger chord at the equator. In addition, the blade cost drops significantly for the configuration of line 4,

since only two extrusions are needed for the 1.08-m chord and three are needed for the 1.22-m chord blade section of the tapered blade.

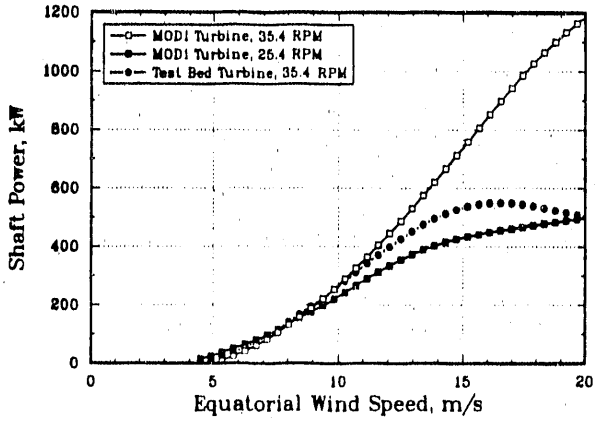

Figure 11. Effect of SAND Airfoil Section on Turbine Performance

Considering lines 5 and 6 of Table I, we see that increasing the chord on a constant-chord NACA 0018 blade from 1.08 to 1.22 m drives the COE up by about 15%. More energy is captured by the larger blade; in fact, the energy captured per unit swept area of the rotor is 5% higher for the larger chord turbine. The increased cost of the three extrusions and the thicker blade walls required for the larger blade offsets this effect, however.

Finally, if we compare a turbine with tapered NACA 0018 blades with a turbine with tapered NACA 0021 and NACA 0018 blades (entries 3 and 6 of Table I), we see that the difference in performance is insignificant, at least from a COE point of view.

These studies indicate that the use of the SAND 0018/50 in the Test Bed blade reduces the Test Bed COE by about 17% compared to the COE for a similarly sized turbine with tapered rotor blades utilizing only aviation-type NACA 0018 and NACA 0021 airfoils.

From the Table I entries for Specific Energy and COE, it is obvious that Specific Energy is not always an accurate reflection of the COE, even if the rpm is optimized. For example, the Specific Energy for a constant-chord 1.22-m chord blade turbine (line 5) is high, but so is the COE. In this case, it's mainly because the 1.22-m chord blade requires three rather thick-walled extrusions, rather than the two thin-walled extrusions that are required for the 1.08-m chord blade. Most systems will contain some non-linear parameters such as this-a small change in the parameter will cause a large change in COE.

Again, ECON90 is a fairly simplistic economic model of a VAWT turbine. It does not incorporate into the COE calculations the economic costs of the higher stresses associated with the configurations summarized as lines 4, 5, and 6 in Table I. As illustrated by these examples, however, it is still a very powerful tool for investigating the impact of blade changes on system COE.

Table I. ECON90 Results for Blade Configurations Studied

Line	Configuration	rpm	Annual Energy Produced MW-Hr	Specific Energy kW-Hr / m^2	Peak Power kW	COE
1	Test Bed (reference)	35.4 (optimized*)	1019	1067	551	1.00
2	Test Bed taper**, all NACA 0018 airfoil	35.4	1000	1051	1192	1.29
3	Test Bed taper, all NACA 0018 airfoil	25.4 (optimized)	900	942	495	1.16
4	Constant chord 1.08 m NACA 0018 airfoil	24.3 (optimized)	923	966	506	1.10
5	Constant chord 1.22 m NACA 0018 airfoil	23.3 (optimized)	965	1010	531	1.25
6	Test Bed taper, 1.22 m NACA 0021, 1.07 & 0.91 m NACA 0018	25.4 (optimized)	869	909	494	1.18

Notes: *rpm at which COE is minimized (as calculated by ECON90)

**blade chord distribution for the Test Bed as illustrated in Figure 8

SUMMARY

Using the ECON16 systems economics model, the CARDAA double-multiple steamtube performance prediction code, and the PROFILE airfoil design code, Sandia National Laboratories designed the SAND family of airfoils (the SAND 0015/47, SAND 0018/50, and SAND 0021/50 airfoils) with characteristics which are specifically tailored for the flow environment encountered by a VAWT blade near the turbine equator.

The ECON16 and CARDAA codes were then used to design the blade for the first VAWT to incorporate a SAND airfoil-the 34-m VAWT Test Bed. The Test Bed blade incorporates the SAND 0018/50 and NACA 0021 airfoil sections in a step-tapered blade that has a 1.08-m chord at the equator and a 1.22-m chord at the turbine tower. Predicted turbine performance agrees very well with measured performance at moderate to high wind speeds, but the agreement is not as good at lower wind speeds.

An updated version of ECON16 was used to calculate the relative COE for several variations to the Test Bed blade design, illustrating the power of even a relatively simplistic systems economics model in performing system tradeoff studies. These studies indicate that the use of the SAND 0018/50 in the Test Bed blade reduces the Test Bed COE by about 18% compared to the COE for a similarly sized turbine with tapered rotor blades utilizing only aviation-type NACA 0018 and NACA 0021 airfoils.

ACKNOWLEDGMENTS

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