CHARACTERISTICS OF FUTURE VERTICAL AXIS WIND TURBINES (VAWTs)*

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Introduction

As a DOE facility, Sandia Laboratories is developing Darrieus VAWT technology whose ultimate objective is economically feasible, industry-produced, commercially marketed wind energy systems. The first full cycle of development is complete, and resulting current technology designs have been evaluated for cost-effectiveness[1]. First-level aerodynamic, structural, and system analyses capabilities have evolved during this cycle to support and evaluate the system designs. This report presents the characteristics of current technology designs and assesses their cost-effectiveness. Potential improvements identified in this first cycle are also presented along with their cost benefits.

Current Design

Aerodynamics

The aerodynamic designs feature symmetric airfoils, starting with the NACA 0012 and now using the NACA 0015. The NACA 0018 has been used in some of the Canadian machines. Constant planforms are used over the entire length of the blade, and solidities (blade area/turbine swept areas) center in the 10 to 15% range for economic reasons. Recent test results promise 40% or higher maximum power coefficients.

Current designs use the inherent self-limiting feature because of aerodynamic stall (K_{pmax}) at tip speed ratio of 3 or less. The corresponding maximum power coefficient (C_{pmax}) occurs at a tip speed ratio of 5 to 6. Thus, regulation occurs when $\left(\frac{R\omega}{V}\right)_{K_{pmax}} \Big/ \left(\frac{R\omega}{V}\right)_{C_{pmax}}$ or $\frac{K}{m} = .5$ to .6.

These aerodynamic design characteristics yield turbines that are relatively efficient, can be manufactured by low-cost methods, and produce low-cost energy.

Structures

The structural characteristics of these designs are generally conservative. The blades have a uniform cross-section and end-to-end properties (Fig. 1). To account for uncertainties in the design and analyses, a margin of 2 is used between the calculated fatigue stresses and the allowable stress. These fatigue stresses are calculated for operation at 60 mph while the buckling response is calculated at 150 mph.

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Similarly, a factor of safety of 10 is used for tower buckling where conventional practice calls for a safety factor of 5. Current design philosophy is to set cable resonant frequencies above the possible excitation frequencies induced by turbine operation.

Current design towers are large-diameter, thin-wall steel tubes to minimize weight and cost. Fabrication tendencies have been to thicken the wall and reduce the diameter, making the towers more durable from a handling viewpoint. However, substantial weight and cost penalties are paid. The most cost-effective balance of weight, wall thickness, diameter, and ease of handling must be identified.

Blades are being designed using cross sections comprised of multiple extrusions (Fig. 1) except for blade chords of 24" or less, in which case a single extrusion is used. Multiple extrusions are joined by longitudinal welds whose chordwise location is chosen to minimize or prevent weakening of the blade cross section. These designs have used a constant wall thickness both chordwise and lengthwise.

The optimum rating of the current designs tends to be at a windspeed of approximately twice the annual mean, based on minimizing the cost of energy. These designs are two-bladed, have a height-to-diameter (H/D) ratio of 1.5, and a solidity of 12 to 14%. These designs yield about 10 to 12 kWhr/lb at a 15 mph mean windspeed and have a plant factor of approximately .25.

Cost Status

An economic analysis of this current design has recently been completed. The characteristics of the turbine were those previously stated; the turbines were considered to be in a grid application. A general configuration is shown in Fig. 2. Sandia Laboratories conducted this study, with A. T. Kearney, Inc. and Alcoa Laboratories furnishing actual cost estimates of several point designs. Alcoa and Kearney used these cost estimates to compute a profitable selling price for the individual point designs if they were manufactured, delivered, and installed by private industry.

Results are shown in Fig. 3.

These same results are plotted in Fig. 4 showing the effect of annual charge rate and dispatching.*

Following are conclusions from this study:

- In production, the most favorable systems investigated apparently can provide utility electricity with a cost of from 4 to 6¢/kWhr with existing technology. Conditions associated with this estimate are a 100 MW/yr production rate, 15 mph median windspeed,

*Dispatching refers to the standard utility procedure of regular inspection of machine output to record output, redirect output and check for abnormality.

90% machine availability, an 18% annual charge rate, a 0.17 wind shear exponent, and operation and maintenance (O&M) levelized with a factor of 2.

- The cost of energy decreases as VAWT rotor size increases up to the largest system investigated (1600 kW), largely because of the presence of costs that vary slowly or not at all with rotor size. Such costs are associated with O&M, automatic control hardware, and labor charges on all components. These slowly varying costs dominate the smaller systems and tend to limit their cost-effectiveness in this application.

- The cost of energy of all size systems is sensitive to the median annual windspeed and the annual charge rate for financing. Larger systems (above 100 kW) are sensitive to the wind shear exponent.

- The effect of production rate on the estimated selling price compares to a 90% learning curve.

Small systems in this application are less cost-effective. However, they do have certain inherent advantages over large systems. Among these are reduced development costs and technical risks, and lower capital investment requirements per unit. There are also markets that can use only small systems effectively: only because of energy demand limitations. These factors can increase the value-effectiveness of the energy produced by small systems. This potential should be recognized in assessing future significance of small VAWT systems as energy producers.

Future VWAT Design

Aerodynamics

Several aerodynamic changes are desirable to reduce the cost of energy. Several of these are to:

1. Increase maximum power coefficient.

2. Move the tip speed ratio associated with stall regulation (K_{pmax}) closer to the tip speed ratio of the maximum power coefficient.

3. Increase the tip speed ratio of all points on the power coefficient curve.

These characteristics have been identified through the use of CPTAILR, an offshoot of the system optimization code VERS16.[1] CPTAILR can accept a six-parameter characterization[2] of a power coefficient curve for use in the optimization process. The cost of energy (COE) for changed aerodynamic characteristics was compared to that for standard characteristics.

Note that these preliminary investigations are being conducted to identify desirable features, estimate benefits, and establish goals and direction for future aerodynamic efforts. The low-cost 17 meter turbine was used as a test case for this investigation operating at sea level in a 15 mph median windspeed regime.

Changing the power coefficient curve to correspond to a change in C_{pmax} from .39 to .41 reduces the COE by 5%. The rated power is increased and the total energy increased while the operating speed remains unchanged. (Early test results using the extruded NACA 0015 blades on the 17 meter research turbine are showing maximum power coefficients of .41 to .42.)

Moving the stall or regulation tip speed ratio closer to the maximum C_p tip speed ratio increases the operating speed, drops the rated windspeed, and reduces energy costs by 8% for K/M = .7.

Shifting the power coefficient curve uniformly to a 25% higher tip speed ratio increases operating rpm and reduces energy costs by 2.5%.

The combined effect of increasing C_p, changing the regulation point, and shifting the C_p curve increases the rating, the total annual energy, and the operating speed, while reducing the rated windspeed and lowering energy costs by 14%.

These kinds of effects may be made possible by using cambered airfoils or nonuniform planforms on blades with little or no cost increases. Continued investigation of these potential changes will determine if inclusion in advanced VAWTs is feasible.

Structures

Advanced structural requirements will be substantially reduced through the use of design requirements consistent with large horizontal machines, a more refined structural analysis capability, and the experience gained through a matured structural test program.

Probable changes in structural requirements will reduce:

- Parked buckling criterion for blades from 150 to 120 mph.
- Machine design/operational windspeed from 60 to 40 mph.
- Cable support system tiedown tension.
- Tower buckling safety factor, from 10 to 5.
- Blade weight, by tailoring blade wall thickness based on predicted operating stresses as a function of blade position.

These new criteria result in the following benefits:

Table I

Item	Weight Reduction (%)	Cost Reduction (%)
Blade Weight	50	~ 35
Spirally Welded Tubular Tower Weight	55	55
Generator/Electrical System		8
Transmission		10
Foundation and Tiedown		45
Shipping and Assembly		30
Total Net Reduction in Cost of Energy		25

Blade weight is reduced by approximately 50% and blade cost by 35% based on the use of several aluminum extrusions welded longitudinally. These extrusions would have wall thickness tailored for chordwise location. See Fig. 5. The weight reduction should also apply blades fabricated using steel or composites.

The weight and corresponding cost of the spirally welded tubular tower are reduced by 55%.

Because of the change in the relative costs of components, the light systems optimize at lower rated power and windspeed. This results in reduced generator/electrical and transmission costs. The generator/electrical costs are reduced by 8% and the transmission cost by 10%.

Since the total system weight and cable tension are reduced, the foundation and tiedown costs are reduced. This cost reduction is estimated to be 45%. Accordingly, the shipping and assembly costs reduction is estimated to be 30%.

The net effect of the new structural requirements is to reduce energy costs by 25%.

Transmission Investigations

In the existing technology designs, the transmission or speed increaser represents 15 to 20% of the total installed system costs. Reduction of the structural requirements for the future VAWTs changes the balance of costs so that the transmission's share of the total cost is 25%. Since the transmission costs are for standard hardware applied in a conventional manner to wind turbines, a new look at the speed increaser design and the application rationale is warranted. Topics such as design requirements, service factors, torque ripple, and cumulative damage will be examined in an attempt to better match speed increaser capability with wind turbine system requirements.

Improbed Blade Fabrication

While the cost of blades fabricated from aluminum extrusions is expected to be $3 to 4/lb, improvement in these costs would enhance the like-

lihood of success of wind energy conversion systems. Candidates include improvements in the joining/extrusion methods and the use of other materials such as composites or steel.

Since the VAWT is amenable to the use of a constant planform, the pultrusion process for a glass/resin composite may be suitable for fabrication of VAWT blades. This process has been suggested in the past and may be a candidate for low-cost investigation.

Roll/stretch formed steel has also been suggested as a low-cost blade fabrication method. See Fig. 6. This process is also suitable for fabricating constant planform blades and uses a cheap, abundant raw material.

Summary of Cost Status

Better aerodynamics (.41 maximum power coefficient and moving the stall tip speed ratio to .7 of the tip speed ratio at C_{pmax}) and future structural requirements combine to produce the following economies:

Solidity	12-14% No Change
Operating Speed	Increased by 30%
Rated Power	Reduced by 20%
Annual Energy	No Change
kWhr/lb System Wt.	20
Plant Factor	.30
Cost of Energy	Reduced by 35-40%, 2.5 - 4.0 Cents/kWhr for 15 mph, 18% ACR, O&M Factor 2.0

Conclusion

The existing technology for VAWT yields energy costs which are of interest. Improved technology (second generation) VAWTs show promise to achieve competitive energy costs through the use of improved aerodynamic and structural techniques.

References

1. SAND78-0962, Economic Analysis of Darrieus Vertical Axis Wind Turbine Systems for the Generation of Utility Grid Electrical Power, Volume I, Executive Summary; Volume II, Economic Optimization Model; Volume III, Point Designs; and Volume IV, Summary and Analysis of the A. T. Kearney and Alcoa Laboratories Point Design Economic Studies, to be published.

2. P. C. Klimas and R. E. Sheldahl, Four Aerodynamic Prediction Schemes for Vertical Axis Wind Turbines: A Compendium, Sandia Laboratories Report, SAND78-0014, June 1978.

Discussion

Q. I would like to know what is the investment cost at present and after production. Also, what is the installation cost of that machine, and how long would it take to install it?

A. I am not prepared to answer all of those questions. The answers exist. As far as cost is concerned, roughly the installed cost is between 500 and 1000 dollars per rated kilowatt. For example, if I recall, the 1600-kilowatt machine cost is about $700,000, while the 500-kilowatt design was around $400,000. This is at the hundred megawatt per year production rate. The pre-production prototype cost is estimated to be about twice the continuous production cost. Mr. Ai will go over some of these numbers in his presentation.

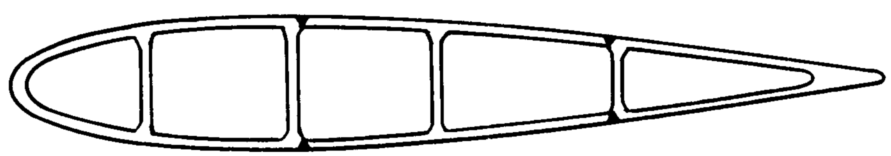


Figure 1. Existing technology blade.

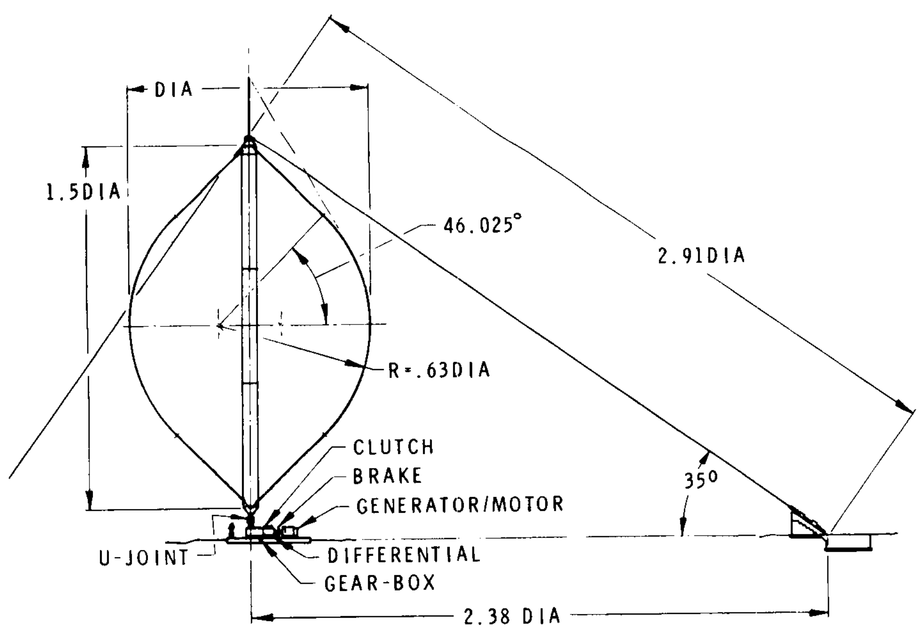


Figure 2. General configuration of turbine used in economic study.

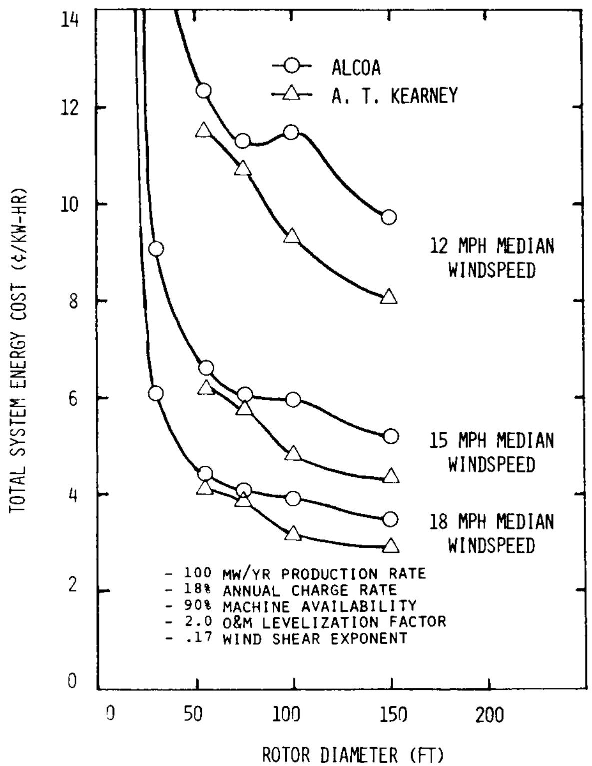


Figure 3. Total system energy cost for all point designs in three median windspeed.

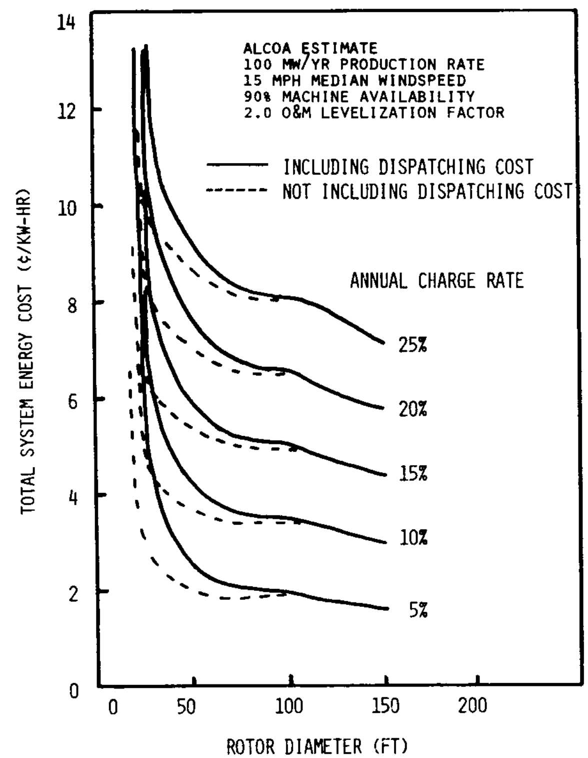


Figure 4. The effect of annual charge rate and dispatching costs on the cost of energy.

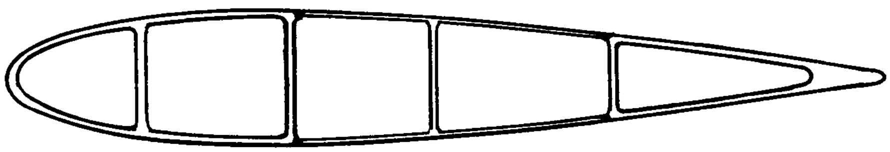
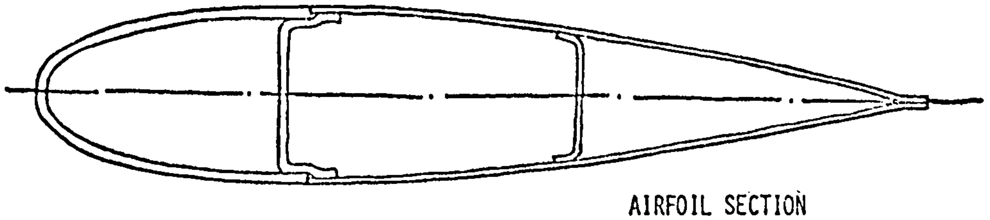


Figure 5. Variable wall blade section.



- ROLL FORMED STRAIGHT STEEL SECTIONS
- STRETCH FORMED INTO CIRCULAR ARC
- SEAM-WELDED STRUCTURE

Figure 6. Possible steel cross-section.