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Characteristics of Future Vertical Axis Wind Turbines

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CHARACTERISTICS OF FUTURE VERTICAL-AXIS WIND TURBINES

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ABSTRACT

As a DOE facility, Sandia Laboratories is developing Darrieus vertical-axis wind turbine (VAWT) technology. The objective of this technology is to assess the practicality of wind-energy systems for low-cost production and commercial marketing by private industry. This report describes the characteristics of current technology designs and assesses their cost-effectiveness. Better aerodynamics and future structural requirements combine for potential energy cost reductions of 35 to 40%.

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Introduction

Using funding provided by the US Department of Energy (DOE), Sandia Laboratories is developing Darrieus VAWT technology with the ultimate objective of 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 describes 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 $\left(K_{pmax}\right)$ at tipspeed ratio of 3 or less.[2] The corresponding maximum power coefficient $\left(C_{pmax}\right)$ occurs at a tipspeed ratio of between 5 and 6. Thus, regulation occurs when

$$\left(\frac{R\omega}{v}\right)_{K_{pmax}} \Big/ \left(\frac{R\omega}{v}\right)_{C_{pmax}} \quad \text{or } K/m = 0.5 \text{ to } 0.6$$

*National Advisory Committee for Aeronautics, predecessor of NASA, the National Aeronautics and Space Administration.

where

$R\omega \equiv$ turbine tipspeed

$v \equiv$ wind velocity

$K_{pmax} \equiv$ maximum coefficient of performance for constant tipspeed operation

$C_{pmax} \equiv$ maximum power coefficient

$K \equiv$ tipspeed ratio for K_{pmax}

$m \equiv$ tipspeed ratio for C_{pmax}

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 uniform cross sections and end-to-end properties (Figure 1). To account for uncertainties in 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.

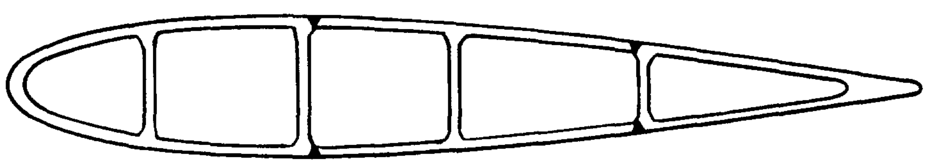


Figure 1. Existing Technology Blade Cross Section

Similarly, a safety factor 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 towers are large-diameter, thin-wall steel tubes designed to minimize weight and cost. Fabrication tendencies have been to thicken the wall and reduce the diameter to make the towers more durable from a handling viewpoint. However, since substantial weight and cost penalties ensue, 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 (Figure 1) except for blade chords of 24 in. 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 two-bladed designs, which have a height-to-diameter (H/D) ratio of 1.5 and a solidity of 12 to 14%, yield about 10 to 12 kWh/lb at a 15-mph mean windspeed and have a plant factor of ~0.25.

Cost Status of Current Design

An economic analysis of this current design has recently been completed. The characteristics of the turbine are those previously described and the turbines are considered to be in a grid application. Figure 2 shows the general configuration of this turbine using ratios. Sandia Laboratories conducted the 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 to be manufactured, delivered, and installed by private industry.

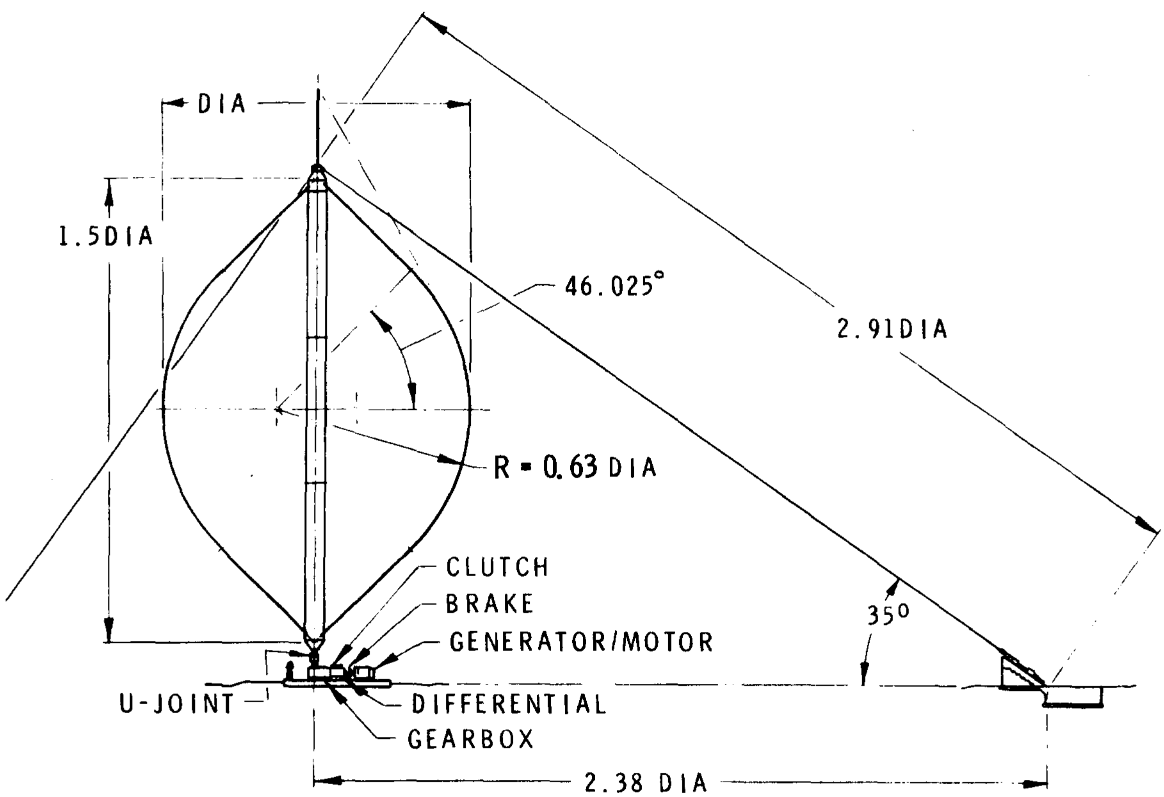


Figure 2. General Configuration of Turbine Used in Economic Study

Figure 3 shows the results of this economic analysis. Figure 4 plots the same results to show the effect of annual charge rate (ACR) and dispatching* costs on the cost of energy.

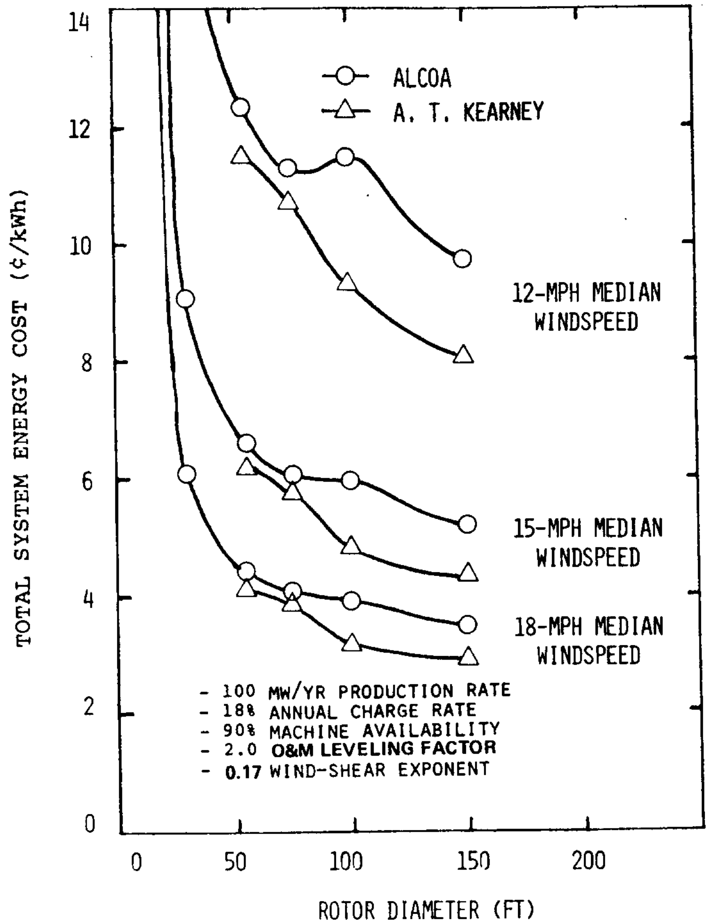


Figure 3. Total System Energy Cost for All Point Designs in Three Median Windspeeds

Following are conclusions from this economic study:

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

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

- Energy costs decrease as VAWT rotor size increases up to the largest system investigated (1600 kW); this is largely because certain costs 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.
- Energy costs for all system sizes are sensitive to the median annual windspeed and the annual charge rate for financing. Larger systems (>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.

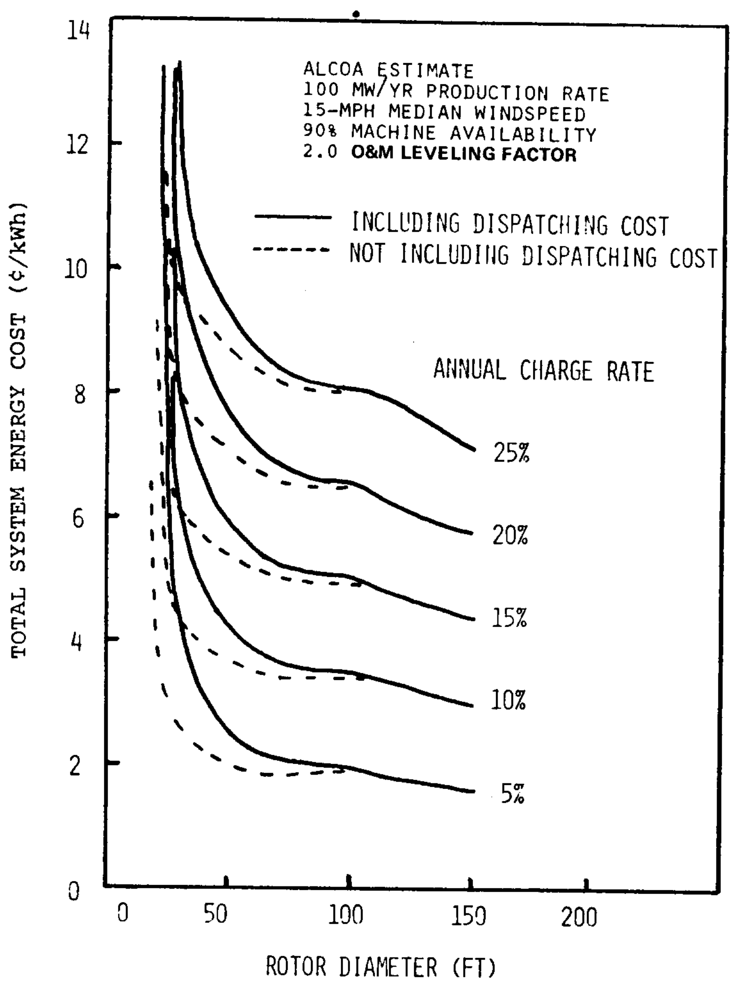


Figure 4. The Effect of Annual Charge Rate and Dispatching Costs on the Cost of Energy

Although small systems in this application are less cost-effective, 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. Certain markets exist that can use only small systems effectively 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 VAWT Design

Aerodynamics

Several aerodynamic changes are desirable to reduce the cost of energy. Among these are changes that will

- Increase the maximum power coefficient
- Move the tipspeed ratio associated with stall regulation $\left(K_{pmax}\right)$ closer to the tipspeed ratio of the maximum power coefficient
- Increase the tipspeed 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[3] 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-m turbine, operating at sea level in a 15-mph median windspeed regime, was a test case for this investigation.

Changing the power coefficient curve to correspond to a change in C_{pmax} from 0.39 to 0.41 reduces the COE by 5%. The rated power and total energy are increased while the operating speed remains unchanged. (Early test results using the extruded NACA 0015 blades on the 17-m research turbine are showing maximum power coefficients of 0.41 to 0.42.)

Moving the stall or regulation tipspeed ratio closer to the maximum C_p tipspeed ratio increases the operating speed, drops the rated windspeed, and reduces energy costs by 8% for $K/m = 0.7$. Shifting the power coefficient curve uniformly to a 25% higher tipspeed 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 their feasibility in advanced VAWTs.

Structures

Advanced structural requirements will be substantially reduced by using design requirements that are 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 the following:

- 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.

Table 1 calls out the benefits resulting from the new criteria.

TABLE 1

Benefits of Probable Changes in Structural Requirements

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

NOTES for TABLE 1:

Blade weight is reduced by ~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 to blades fabricated with steel or composites.

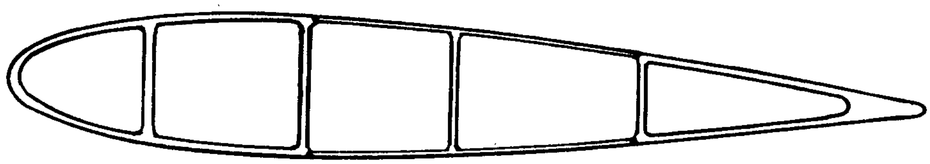


Figure 5. Variable Wall Blade Section

The weight and corresponding costs 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 and electrical and transmission costs. Generator/electrical costs are reduced by 8% and transmission costs by 10%.

Since total system weight and cable tension are reduced, foundation and tiedown costs are reduced by an estimated 45%. Accordingly, shipping and assembly costs are estimated to be reduced by 30%.

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

Transmission Investigations

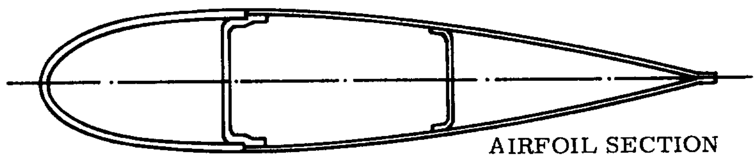
In existing technology designs, the transmission or speed increaser represents 15 to 20% of total installed system costs. Reduction of structural requirements for future VAWTs changes the balance of costs so that the transmission's share of the total cost is 25%. Since transmission costs are for standard 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.

Improved 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 likelihood of success for the wind-energy conversion systems. Candidates include improvements in joining and 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 or stretch-formed steel has also been suggested as a low-cost blade fabrication method (see Fig. 6). This process, which uses a cheap, abundant raw material, is also suitable for fabricating constant planform blades.



Roll-Formed Straight Steel Sections

Stretch-Formed Into Circular Arc

Seam-Welded Structure

Figure 6. Possible Steel Cross Section

Summary of Cost Status

Better aerodynamics (0.41 maximum power coefficient and moving the stall tipspeed ratio to 0.7 to the tipspeed ratio at C_{pmax}) and future structural requirements combine to produce the characteristics shown in Table 2.

TABLE 2

Potential Improvements Identified in First Cycle of VAWT Technology

Item Investigated	Effect
Solidity	No change
Operating speed	Increased by 30%
Rated power	Reduced by 20%
Annual energy	No change
kWh/lb system wt	20
Plant factor	0.30
Cost of energy	Reduced by 35 to 40%
	At 15-mph Mean Windspeed - 2.5 to 4¢/kWh
	Annual Charge Rate - 18%
	O&M Factor - 2

Conclusion

The existing technology for VAWT yields energy costs that are of interest. Improved (second-generation) VAWTs show promise of achieving competitive energy costs by using improved aerodynamic and structural techniques.

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