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ECONOMIC ANALYSIS OF DARRIEUS VERTICAL AXIS WIND TURBINE SYSTEMS FOR THE GENERATION OF UTILITY GRID ELECTRICAL POWER

VOLUME I - EXECUTIVE SUMMARY

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VOLUME I - EXECUTIVE SUMMARY

Abstract

The economic analysis of the Darrieus vertical axis wind turbine is contained in four separate volumes. This first volume summarizes the complete study, presenting a description of the technical approach used, key results, and major conclusions.

Acknowledgment

The vertical axis wind turbine economic study was conducted with W. N. Sullivan of Sandia Laboratories as Principal Investigator. Major Sandia contributors to the entire study are R. O. Nellums, E. G. Kadlec, and R. D. Grover. A. T. Kearney, Inc. and Alcoa Laboratories provided the basic cost of energy data.

R. H. Braasch of Sandia and D. D. Teague and G. T. Tennyson of the DOE provided overall project management.

Introduction

The Darrieus vertical axis wind turbine (VAWT) is an aerodynamic device for extracting mechanical energy from the wind. This concept has been investigated recently to establish its potential for producing useful electrical or mechanical energy. Figure 1 shows a typical Darrieus turbine. Dominant features of the design

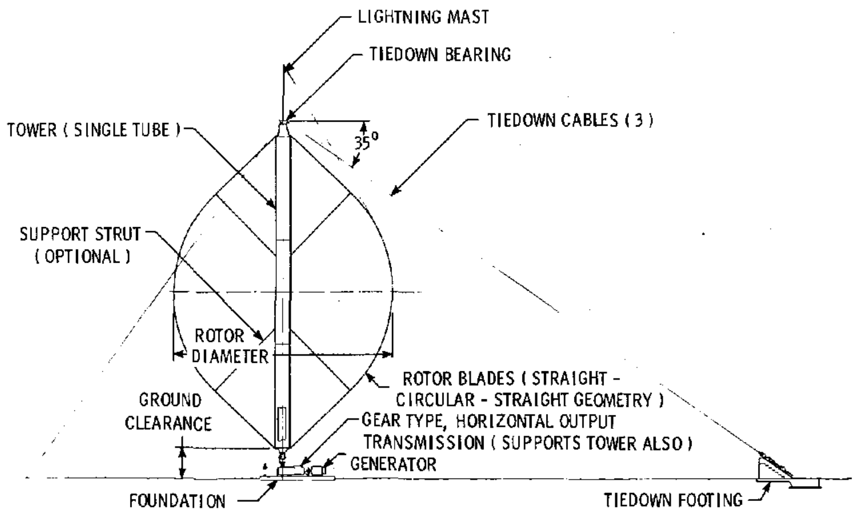

Figure 1 - Typical Darrieus VAWT System and Nomenclature

are its vertical axis and the use of curved, fixed-pitch blades rigidly attached to the central rotating tower.

Several advantages inherent in the VAWT concept have led to its consideration as a possibly superior alternate to conventional propeller-type systems. These advantages include:

- The ability of the VAWT to accept winds from any direction without devices to direct the rotor into the wind.

- The placement of all heavy mechanical equipment at ground level, which eases maintenance and structural problems.

- The amenability of the rotor to simple, low-cost blade fabrication techniques.

- The aerodynamic stall characteristics of the rotor preclude the need for blade pitch-control mechanisms in constant rpm applications.

There are also certain disadvantages of the VAWT, such as somewhat lower theoretical aerodynamic performance (about 10% lower than for a propeller-type machine with the same swept area), and the need for higher peak power ratings in a VAWT drive train due to the nature of its aerodynamic power curve.

The economic utility of the VAWT applied toward production of usable energy has not been thoroughly investigated. Recently, Sandia Laboratories, at the request of the DOE, made a detailed economic analysis of the VAWT. This summary report is the first volume of a four-volume final report on this economic analysis. The other three volumes detail the development and results of the entire study.

The primary objective of this study is simply to estimate the cost of utility grid electrical energy supplied by profitably manufactured, optimized, and structurally acceptable Darrieus VAWT systems. This cost is estimated as a function of rotor size, the scale of the business venture producing the systems, and the wind characteristics of the turbine site. Results indicate that the largest rotors investigated (from 500 to 1600 kW peak electrical output) can provide energy for 4 to 6¢/kWh at wind sites with a 15 mph median annual windspeed if these rotors are mass-produced. The cost of energy, which is roughly halved or doubled, respectively, at 18 or 12 mph median annual windspeed sites, is very sensitive to median annual windspeed.

This study was designed to be accurate based on current knowledge of VAWT technology and available cost data. Nevertheless, certain unavoidable approximations and conservatisms exist in the cost-estimating process. The overall accuracy is intended to be adequate for judging current economic feasibility, identifying cost trends, and determining the future course of the VAWT concept. Continued capability for accurate and up-to-date analyses should be obtained by incorporating new technical developments and economic data into the framework of this study as they become available.

The cost of energy estimates presented in this study can probably be improved upon in actual production systems if an effort is made to reduce design conservatisms, improve aerodynamic performance, and develop more cost-effective mechanical design features. The major conservatism in this study involves the structural requirements imposed on the designs investigated. The ability to reduce these structural conservatisms depends on the development of improved structural dynamic models and field experience with operational systems.

The following two sections summarize the technical approach used to produce the cost estimates and discuss the major results. A final section discusses conclusions, limitations of the study, and recommendations for future work.

Technical Approach

A block diagram (Fig. 2) describes the overall program approach. The first

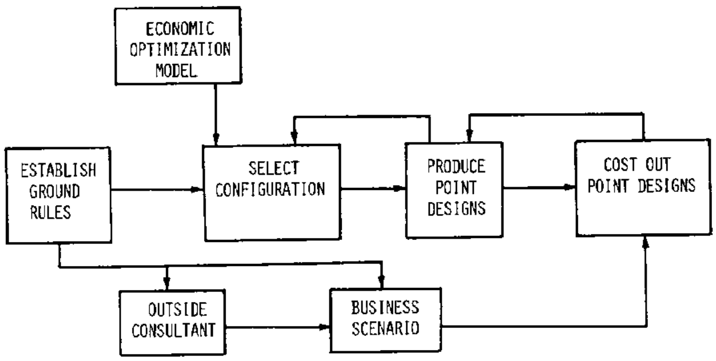

Figure 2 - Overall Organization of the Economic Study

task, to establish ground rules, restricts the scope of the study in order to reduce uncertainties. The most influential ground rules are as follows:

1. Utility Grid Application -- The rotor is assumed to be maintained at constant rpm by an existing utility grid, using a direct-coupled induction or synchronous generator. No storage capacity is provided; the grid is assumed to be capable of absorbing the energy produced at all times.

2. Existing Technology -- All system components are designed using manufacturing technologies (or modest extensions of those technologies) that have been applied successfully on operational research systems. In cases where several demonstrated technologies are available, the lowest-cost technology is used.

3. Structural Requirements -- Structural components are sized to produce fatigue stresses consistent with a 30-year life in a 15 mph median annual windspeed environment. The system design operational windspeed is taken as 60 mph and the parked-rotor survival design windspeed is 150 mph.

4. Cost of Energy Calculation -- The annual cost of owning and operating a VAWT system is calculated by taking a fixed percentage (18%) of the installed system selling price and adding estimated annual operation and maintenance

(O&M) costs that have been levelized* by a factor of 2. This cost, divided by annual energy delivered by the system, yields the cost of energy (¢/kWh). Energy delivery of the system is based upon 90% machine availability.

Capital costs are estimated based on analysis of six hypothetical system designs. These systems, referred to as point designs, were designed primarily by Sandia Laboratories. The point designs, ranging in size from 10 kW to 1600 kW peak electrical output, are technically feasible and use the most economical technologies available at the time they were formulated. Volume III of this report contains detailed design data on the point designs.

Point design specifications (such as number of blades, rotor rpm, annual energy output, etc.) were selected using an economic optimization model. This model, described in Volume II, is a computer-adapted model of system cost and performance factors. It was used to determine combinations of specifications that minimize the cost of energy. In addition to its function in specifying the point designs, the economic optimization model remains a useful tool for rapidly investigating the effects on cost of energy due to changes in the original point design specifications.

Two consultants were contracted to carry out independent cost estimating on the point designs. A. T. Kearney, Inc. (a management consulting firm), and Alcoa Laboratories (a product development laboratory) were to estimate a profitable selling price for the individual point designs if they were manufactured, delivered, and installed by private industry. Toward this objective, the consultants constructed a business scenario in which a hypothetical company with appropriate overhead and profit is included as part of the system selling price. Both consultants used actual component cost quotes from industrial suppliers as their primary source of cost data. The scale of the business producing the systems is governed by the number of units produced annually; both consultants considered a range of production rates varying from 10 to 100 MW of peak capacity installed annually. Prices for preproduction prototype versions of the point designs were also estimated. Volume IV provides complete results from the consultants along with analyses, interpretations, and modifications.

Results

A principal result of this study is the completion and application of a computerized economic optimization model. The model was used to examine the effect

*The levelizing factor is included to account for inflation of operation and maintenance costs during the lifetime of the system.

of varying system specifications on the cost of energy. The specifications varied in this process include the ratio of the rotor height to its diameter (H/D), the number of blades, whether to use blade support struts,* rotor solidity (the ratio of blade area to rotor projected area), the distance from the ground to the lower blade connection (rotor ground clearance), and rotor rpm. Table I summarizes the specifications found most desirable for the VAWT point designs.

Six point designs were considered for economic analysis. These designs have rotors ranging in size from 18 to 150 feet in diameter. Table II lists the dimensions and performance characteristics of the designs. Major elements of the designs are the use of extruded aluminum blades, thin-walled tubular steel central towers, and a three-cable tiedown system for supporting the top of the rotor. Field assembly joints are provided for the blades and central tower on the largest systems to permit shipping of completed subassemblies to the site by conventional trucks. The central tower and blades for all the systems are designed to be assembled at the site horizontally at ground level. The entire rotor is then raised to its ultimate vertical position by crane, hydraulic lift, or winch. This procedure substantially limits expensive aboveground site operations. The point designs also are relatively easy to maintain since critical mechanical components are at ground level.

A. T. Kearney and Alcoa Laboratories estimated the installed per-unit selling prices for the point designs as listed in Table III. As shown in Table III, the consultants estimated selling prices for single prototypes and for continuous production rates varying from 10 to 100 MW of installed peak capacity per year. These production rates correspond to an approximate annual sales volume ranging from $5 to $50 million. Table III gives the number of units produced annually for these production rates. The decrease in unit cost as production increases from 10 to 100 MW/yr is typically 20-35%. The major sources of this decrease are economies of scale in business overhead expenses and discounts for quantity purchases of shelf components.

*Blade support struts connecting the central tower to the curved blade section (see Fig. 1) have been used in some rotor designs. They may be eliminated provided the curved blade section is appropriately strengthened.

Table I

Typical Properties of Optimized Systems
(15 mph Median Windspeed Distribution)

Rotor	H/D = 1.5, two blades, unstrutted (struts may be desirable for diameters above 150 feet).
Solidity	Ranges between .12 and .14 depending on rotor diameter.
Rated Windspeed	Approximately 30 mph @ 30 foot reference height.
Cut-In Windspeed	Approximately 10 to 12 mph @ 30 foot reference height.
Plant Factor	From 20 to 25%, depending on rotor size.
Rotor Ground Clearance	As low as possible, with enough room for drive train placement, except for smaller rotors (< 30 foot diameter) where a 10 to 20 foot clearance is advantageous.

NOTES: (1) Plant factor is the ratio of the average annual power output to the rated output.

(2) Rated windspeed, cut-in windspeed, and plant factor are all governed by the rotor rpm. The rotor rpm is selected to minimize the cost of energy.

Table II

Point Design Specifications

Nominal Rating (kW)	10	30	120	200	500	1600
Rotor Diameter (ft) x Height (ft)	18 x 27	30 x 45	55 x 83	75 x 120	100 x 150	150 x 225
Rotor Area (ft^2)	324	900	3000	5600	10,000	22,500
Number of Blades	2	2	2	2	2	2
Blade Chord (in)	6	11	24	29	43	64
Total System Weight (lbs)	1450	4970	18,100	40,800	95,200	284,000
Actual Rated Output (kW) @ 30' Ref. Height Windspeed (mph)	8 @ 34	26 @ 32	116 @ 31	226 @ 30	531 @ 31	1330 @ 30
Annual Energy Output (MW-hrs), 100% Availability, 15 mph Median Distribution	13.7	51.6	246	490	1070	2950

Table III

Installed Turbine Cost Summary (K$)

Nominal System Size (kW)	Source	Production Rate: 1 Prototype Cost	10 MW/yr Cost	(Units/Year)*	100 MW/yr Cost	(Units/Year)*
10	Alcoa	77.2	11.9	(1130)	9	(7460)
30	Alcoa	97.9	20.3	(310)	14.1	(4831)
120	Kearney	226.2	77.1	(83)	68.8	(830)
	Alcoa	193.5	89.8	(84)	69.4	(1285)
200	Kearney	375.3	150.7	(50)	133.6	(500)
	Alcoa	289.5	154.1	(46)	117.5	(704)
500	Kearney	600.7	291.7	(20)	249.0	(200)
	Alcoa	517.3	367.5	(18)	270.0	(270)
1600	Kearney	1425.8	766.3	(6)	619.1	(62)
	Alcoa	1263.2	1020.0	(6)	714.0	(99)

*Unit production for Alcoa does not precisely correspond to the stated annual megawattage.

Sandia used the prices from Table III to calculate the cost of energy. In making this calculation, Sandia corrected minor omissions made by the consultants, added the capital cost of automatic control hardware,* and included estimated annual operation and maintenance costs. Figure 3 presents the cost of energy so calculated

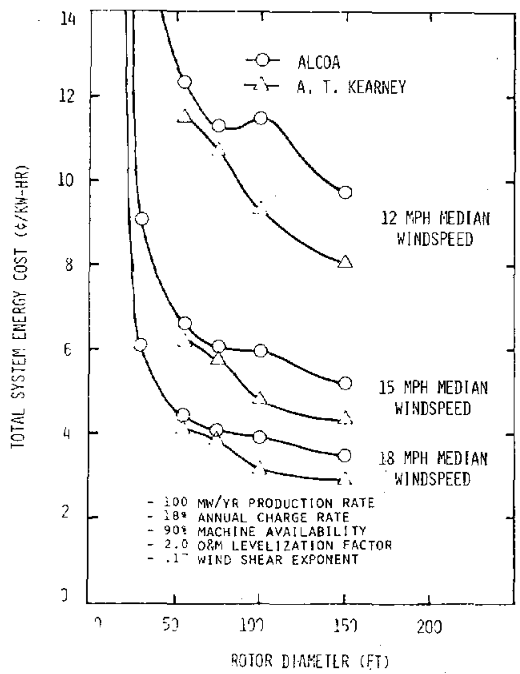

Figure 3 - Total System Energy Cost for All Point Designs in Three Median Annual Windspeeds

for all the point designs at 100 MW/yr production in three median annual windspeed sites (12, 15, and 18 mph).

It is evident from Fig. 3 that the cost of energy is quite sensitive to median annual windspeed. Relative to the 15 mph median annual windspeed distribution, the cost of energy is reduced by 33% and increased by 86% for the 18 and 12 mph sites, respectively.

There is a trend in Fig. 3 toward decreasing energy cost as rotor size increases. This trend is due primarily to the presence of costs that vary slowly or not at all with system size. The slowly varying costs become significant relative to the total

*The point designs are complete systems for manual operations. The automatic control hardware provides the additional capability for unattended operations of the turbine.

system cost as system size decreases, thereby causing large increases in the cost of energy for small systems. Major sources of slowly varying costs are the annual operation and maintenance charges, automatic control hardware, and the labor charges on all components.

Figure 3 indicates that reduced energy costs may be possible by considering rotors larger than 150 feet in diameter. However, experience with the economic optimization model and examination of the results from the consultants suggest that as rotor size increases, the cost of energy decreases at a much slower rate and will probably increase for rotors above 150 to 250 feet in diameter. This is because as rotors increase in size, the rate of growth of raw materials required for a system slightly exceeds the rate of growth of energy production.

The results of Fig. 3 are quite sensitive to certain assumptions made in this study. Figure 4 shows the effect of wind shear (the tendency of the windspeed to

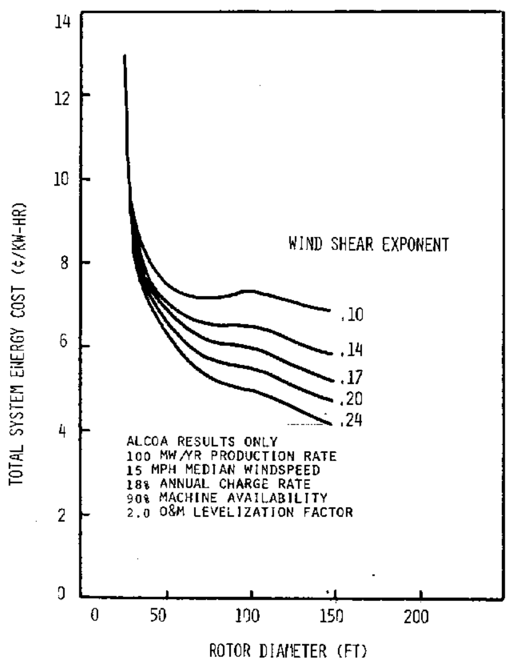

Figure 4 - The Effect of Wind Shear Exponent, A Site-Dependent Quantity, On the Cost of Energy

increase with height above the ground) on the cost of energy. The quantitative measure of wind shear is the wind shear exponent, a site-dependent quantity assumed to be .17 for this study. As shown in Fig. 4, sites with larger wind shear exponents favor larger (and hence taller) rotors, while lower wind shear sites penalize larger rotors.

Figure 5 indicates the importance of structural conservatism on the ultimate

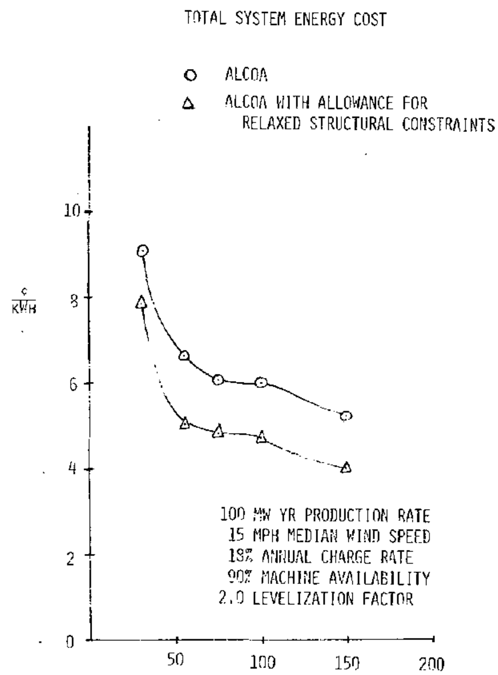

Figure 5 - Possible Cost of Energy Reductions Associated with Relaxed Structural Requirements

cost of energy. In this figure the economic effects are estimated for reducing the design operational windspeed from 60 to 40 mph, the rotor survival design speed from 150 to 120 mph, and relaxing certain stiffness requirements on the cable tiedown system. More experience and technical development are required to establish if such reduced conservatism can be achieved without undue compromise of system life and reliability.

Energy costs are sensitive to the circumstances of the VAWT user. This study assumes that in 1978 utility owns and operates the wind turbine. As a result, the cost of energy includes dispatching* costs and an 18% annual charge on capital investment. Different charges might be appropriate depending upon the existence

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

of tax incentives, special interest rates and financing, or the type of applications. The assessment of professional fees for dispatching may be particularly inappropriate for small machines (< 30 kW) operated by their owners. Figure 6 shows the

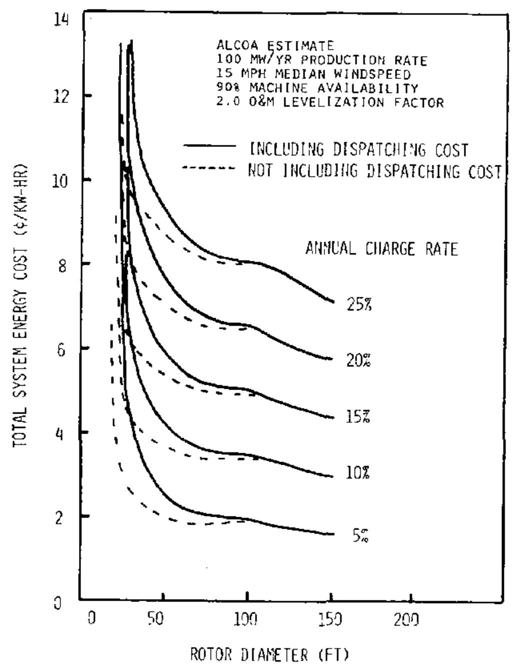

Figure 6 - The Effect of Annual Charge Rate and Dispatching Costs on the Cost of Energy

sensitivity of energy cost to annual charge rate and dispatching cost. The cost of energy curve is nearly flat for rotor sizes 30 feet and larger if dispatching charges are eliminated.

Conclusions and Recommendations

Conclusions from this study are as follows:

- The most favorable systems investigated can, in production, apparently provide utility electricity with a cost in the range of 4 to 6¢/kWh with existing technology. The most promising means for improving this cost appears to be through reducing structural conservatism in the design. Estimates indicate that a 1-2¢/kWh reduction in cost of energy may be possible by eliminating excessive structural conservatisms.

- Energy cost decreases as VAWT rotor size increases up to the largest system investigated (1600 kW), primarily because of the presence of costs that vary slowly or not at all with rotor size. These costs are associated with operation and maintenance, 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 each system 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 economic trend of energy cost-dependence on system size indicates an incentive to develop larger Darrieus rotors. This development should be paralleled by periodic reexamination of these conclusions accounting for new technical and economic data as they are acquired in the R&D program.

In this application, small systems are less cost-effective. However, small systems do have certain inherent advantages over large systems, such as reduced development costs and technical risks and lower capital investment requirements per unit. There are also markets 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 attempting to assess the future significance of small VAWT systems as energy producers.

It is important to associate the conclusions and cost estimates in this summary with the study's principal ground rules (see Technical Approach section). These ground rules are generally conservative; i.e., they are biased toward obtaining reasonable accuracy rather than lower bounds on the possible cost of VAWT-produced energy. Of particular importance is the restriction concerning proven, existing technology. Obviously, there is potential for different technologies to reduce the costs of virtually all components and operation and maintenance, and to increase aerodynamic performance. Another important ground rule concerns structural design requirements. The appropriateness of these requirements needs to be examined with improved structural dynamic models to ensure that excessive structural conservatism is not unduly affecting energy costs. Future research efforts aimed at reducing the cost of energy for next generation VAWT systems should focus on these areas.

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