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VERTICAL AXIS WIND TURBINE DEVELOPMENT

Final Report, Executive Summary for March 1, 1976—June 30, 1977

By
R. E. Walters
J. B. Fanucci
P. W. Hill
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July 1979
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West Virginia University
Morgantown, West Virginia

U.S. Department of Energy

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PROJECT SUMMARY

This project has been funded by the U.S. Energy Research and Development Administration (ERDA) to study innovative concepts for wind energy conversion turbines. Original work started at West Virginia University (WVU) in 1975. This report contains the results of research conducted from March, 1976, through June, 1977.

The purpose of the work at WVU, which is reported here, is to evaluate the potential of a circulation controlled vertical axis wind turbine (cc VAWT). This concept is that of a vertical axis wind turbine which uses straight blades composed of airfoil shapes having high efficiency, i.e., high lift to drag ratios. This would be attained by using circulation controlled airfoils for the blades; these airfoils contain slots near rounded trailing edges through which a small amount of compressed air is blown to obtain high lift forces. The straight blades allow cyclic pitch control, which could be used to further increase machine efficiency.

Early in the project it was recognized that both extensive theoretical and experimental research efforts would be required. Initial theoretical work, using an aerodynamic "strip theory", showed that circulation control increased the turbine operating efficiency while lowering the rotational speed at which peak efficiency occurred. Various necessary assumptions of the theory resulted in some uncertainty regarding the accuracy of the results. Therefore, the research effort has been continued with two basic purposes first, a more exact aerodynamic solution was to be developed, and second, a test model VAWT was to be constructed to obtain aerodynamic measurements required to verify the accuracy of the theory. Preliminary cost estimates of the cc VAWT design were also to be made.

The aerodynamic solution developed utilizes a non-steady lifting surface theory, which allows calculation of the real effects of finite blade size, blade number, blade shed-vortex/blade interactions, and blade pitch change. This theory development has been approached in steps starting with (a) one blade analysis (blade with symmetrical airfoil section) having no pitch change, and subsequently adding (b) multi-blades, (c) variable pitch, and (d) cc blade calculations. Results of steps (a) and (b) are reported here. In general, the calculation results agreed with the previous analytical results. However, the effects of solidity, which could now be analyzed, showed that there must be careful tradeoffs of blade size and number in order to realize the maximum turbine efficiency. Parametric studies are continuing in order to better define the effects of the various design parameters on turbine performance.

Initial consideration has been given to the boundary layer flow on the turbine blades. The qualitative results from inspection of the formulated flow equations suggest that the high centrifugal forces present at the blades during their circular motion may cause important flow changes, perhaps including premature separation, of the blade boundary layer flow.

In order to complement the theory, and provide input data of blade and rotor drag data necessary to allow the performance calculations, a test model VAWT was designed and constructed at WVU. The model, which has a two-bladed rotor 3.05 m (10 ft) in diameter and blades 3.25 m (10 ft 8 in) long, has also allowed better cost estimates and operating experience to be obtained. Nothing has been found to date which would indicate that the vertical axis straight bladed wind turbine cannot be cost competitive with the more conventional horizontal axis wind turbines. Initial testing has been performed with blades having symmetrical airfoil sections (NACA 0015) and giving a turbine

solidity of 0.114. Future tests are described which will include higher solidity blades (0.26) made of the same airfoil shape, and which will be followed by tests of the cc blades.

A structural parametric analysis of VAWT blades for larger machines was also performed. Personnel of the Allegany Ballistics Laboratory of Hercules, Inc., performed this study under subcontract to WVU. This study is of considerable interest since, on large VAWTs, the blades may contribute a large percentage to the total turbine cost. Blades of various construction methods and materials were analyzed, including those of metal and composite materials. Results of the analysis indicate that the cheapest material may not provide the lowest cost blade or the lowest cost turbine energy output. For certain design points the most feasible blade construction may be of composite materials. This analysis is continuing in order to provide more insight into the optimum structural blade designs.

Other cost studies were performed for various wind energy conversion systems (WECS). The results indicate the expected decreased cost of electricity generated with large turbines. However, the many assumptions and estimates necessary at this time result in a large uncertainty in the final cost of WECS-provided power. Also, the wide range of prices observed for commercially available WECS are indicative of the infant state of the industry.

1. INTRODUCTION

The work reported herein was supported by the U.S. Energy Research and Development Administration. Work started in 1975, and has been concerned with the evaluation of an innovative concept in wind turbines, the circulation controlled vertical axis wind turbine (cc VAWT). Both theoretical and

experimental investigations are continuing in order to evaluate the potential of the cc VAWT. This report presents the results of the research conducted from March, 1976, through June, 1977.

The cc VAWT concept under investigation utilizes straight blades; the blades are composed of special circulation controlled airfoil sections (Fig. 1)

Fig. 1. Circulation controlled airfoil cross section.

which contain slots near the rounded trailing edges through which a small amount of compressed air is blown to obtain high lift forces. Straight blades allow blade cyclic pitch control, which can further increase turbine efficiency. The major effects of utilizing circulation control are to increase the turbine power coefficient (efficiency) and to reduce the tip speed ratio (rotational speed) where the peak efficiency occurs (Fig. 2).

Fig. 2. Calculated effect of circulation controlled blades on vertical axis wind turbine performance.

The degree of this improvement and the cost effectiveness of such a turbine are under study.

2. PROGRAM STUDIES AND RESULTS

2.1. NUMERICAL SOLUTION OF THE AERODYNAMICS OF CROSS-FLOW WIND TURBINES

A numerical procedure has been developed for determining the unsteady lift and moment characteristics of multiple-blade cross-flow wind turbines. The method employs a force-free wake model, accounts for wake/blade interaction, and reflects transient aerodynamics. This theory extends the single-blade analysis previously developed. Blade cyclic pitch changes and winds containing gusts can also be allowed for with this theory.

The problem is approached in the spirit of classical potential flow aerodynamic theory, i.e., fluid viscosity is neglected and the flow is assumed to be irrotational. The blades are assumed to be of infinite span, and their speeds are considered small enough to treat the flow as incompressible. Under these circumstances, the lifting characteristics are well predicted theoretically by replacing the airfoil with its mean camber line. The problem is then resolved into that of finding a flow pattern having the instantaneous streamline coincident with the mean camber line and insuring that the flow leaves the trailing edge smoothly. The calculations, carried out with a digital computer, determine the load distribution on the lifting surface, i.e., the blade. This distribution can then be used to calculate the turbine power coefficient, C_p , at various turbine rotational speeds and wind speeds.

The described theoretical analysis is very complex, and requires a considerable amount of computer time. In order to allow faster development

of the theory, and to allow the results to be more quickly compared with experimental results, initial calculations have been made with "conventional" turbine blades. These blades are of NACA 0015 airfoil construction. Consideration of the more involved theory with circulation controlled blades will be accomplished after verification of the initial theoretical results has been accomplished by comparison with test results.

As with all potential flow aerodynamic theory, the drag coefficient of the blade cannot be determined by calculation. However, as found previously, the drag is an important contribution to turbine performance (power coefficient, C_p). This finding has been confirmed using the present numerical solution with various selected values of blade drag coefficient. Fig. 3

shows the results of such a calculation, which indicates that increasing values of blade profile coefficient, C_{D_o} , decrease the C_p values considerably, and also decrease the tip speed ratio (blade speed/wind speed) at which maximum C_p occurs. An interesting calculation result shown (Fig. 3) is that

where the total blade drag coefficient, C_{D_T} ,

Fig. 3. Calculated vertical axis wind turbine performance for a straight-bladed turbine with constant blade attitude.

(which includes three-dimensional aspect ratio effects) is set equal to zero. This produces a result which is somewhat analogous to the Betz limit on C_p which applies to horizontal axis (propeller-type) rotors. It can be seen that the potential for vertical axis (cross-flow) wind turbines appears to be as good or better than for the horizontal axis turbines. These results are with fixed blade pitch for the VAWT; cyclic blade pitch and improved blade lift (circulation control blade) will increase the performance considerably.

Results of a parametric study of some VAWT turbine parameters are shown in Fig. 4. Here, C_p vs. tip speed ratio (TSR) is shown for calculations where the blade number (N_b), blade chord-to-radius ratio (C/R), rotor solidity (σ), and blade aspect ratio (AR) are varied.

The blade profile drag coefficient (C_{D_o}) is held constant at 0.015.

Perhaps the most interesting result of this analysis is that the two calculations for the same rotor solidity, but with two and three blades (Curves 2 and 3), show considerably different peak

curve number	1	2	3	4
N_b , blade number	2	3	2	2
C/R , chord/radius	0.08	0.08	0.12	0.12
σ , solidity	0.08	0.12	0.12	0.12
AR, aspect ratio	18.7	18.7	18.7	12.5

Fig. 4. Calculated vertical axis wind turbine blade performance for various design parameters, straight blade, constant blade attitude.

values of C_p . The turbine with two blades is almost 50% more efficient than the one with three blades.

Further analysis of various rotor configurations utilizing this theory will provide valuable insight into the optimum design features of vertical axis wind turbines. Accurate experimental data is needed to select proper values of blade drag coefficients for use with the theory.

2.2. BOUNDARY LAYER CONSIDERATIONS FOR A VERTICAL AXIS WIND TURBINE

As discussed in the previous section, the efficiency of a vertical axis wind turbine is highly dependent on the aerodynamic drag associated with the blades. The boundary layer flow on the turbine blades has considerable influence on the drag of the blades, since boundary layer effects may either cause premature or delayed flow separation. Since the blades move in circular paths and in addition may undergo cyclic pitch changes, a brief study was made of possible effects of this motion on the boundary layer flow. Utilizing the appropriate conservation equations and the proper coordinate systems, the boundary layer equations for the incompressible flow on the blades have been derived. These equations are typically involved viscous flow equations, which have not been solved. However, the form of the equations may be compared to those of boundary layer flows over curved or rotating surfaces. Such comparison shows that the usual classical assumption that the pressure gradient normal to the blade surface is small may be in serious error, and, in fact, the gradient is proportional to the square of the tip speed ratio.

This result implies that the usual procedures in boundary layer theory, that the pressure may be calculated from potential theory and assumed constant through the boundary layer, may not be sufficiently accurate. Furthermore, this strong radial pressure gradient may lead to premature laminar boundary layer separation with its attendant increase in drag.

2.3. WVU VAWT OUTDOOR TEST MODEL

In order to provide verification of the theoretical calculations of VAWT performance, and to provide VAWT blade and support structure drag data for input to the theory, an outdoor test model VAWT was constructed at WVU. The turbine is a two bladed model with a rotor diameter of 3.05 m (10 ft) and blades 3.25 m (10 ft 8 in) in length (Fig. 5).

The rotor was constructed with provisions to allow easy future changes of blades and other parameters, such as blade length and machine radius. The total height of the machine, measured from the top of the shaft to the bottom of the base pads, is 7.62 m (25 ft). Three equally spaced cables connected to a bearing support the top of the shaft; the base of the shaft is supported by two self-aligning radial/thrust bearings which are contained in a cylindrical housing.

Fig. 5. WVU VAWT test model with low solidity (0.114) blades.

The turbine is located on the roof of a small building at WVU; the turbine shaft extends through the roof to the instrumentation/control test stand. The stand contains a generator, a motor used to drive the VAWT for starting and testing purposes, a pulley drive system, and instrumentation. The instrumentation consists of a torque cell for power measurements, a tachometer generator for speed measurements, and low-noise slip rings which allow the various strain gages on the rotor to be monitored while it is turning. Rotor gages are located on the shaft, on load cells integral with the rotor support wires, and at several places on the blades themselves.

The rotor was tested indoors by static loading to verify its structural integrity. After outdoor installation, the material strains were measured with the rotor turning to establish the margin of safety for the design. The experimental results agreed well with the theory. An anemometer system was also established at the test site, consisting of two cup anemometers and a hot-wire sensor. All three are periodically calibrated in the WVU subsonic wind tunnel. Data is recorded with an analog strip-chart recorder. Initial operation of the VAWT test model and site instrumentation indicated that a reliable and useful test facility has been established.

2.4. LOW SOLIDITY BLADE TESTS

Results of the theoretical aerodynamic analysis had indicated that the VAWT power coefficient was a strong function of blade profile drag coefficient (Fig. 3). Unfortunately, this drag coefficient is difficult to predict for the blade flow where Reynolds number and centrifugal effects

exist in a curved flow field. The WVU VAWT test model was designed to provide blade drag data which could be used for theoretical analysis and design purposes. Initial test emphasis has been concerned with aerodynamic study of the blades. Thus far, blades of NACA 0015 airfoil sections and a chord-to-radius ratio of 0.114 have been tested; the two bladed configuration also gives a turbine solidity of 0.114.

Tests were conducted at various tip speed ratios, using an electric motor to rotate the turbine rotor. By testing with and without blades, and measuring the torque required, the blade support structure tare torque was determined. Then torque test data with blades installed was reduced to yield the net blade torque. Blade torque then was presented in the form of power coefficient vs. tip speed ratio, or as blade drag coefficient.

Power coefficient data for the low solidity blades is shown in Fig. 6. The blade chords were tangent to the circular blade paths, which was not necessarily the optimum blade setting angle. These test results are in general agreement with the theory developed for this case (Fig. 3), but the curves are more peaked. The variation of C_p with ωR suggest that perhaps both blade Reynolds number and centrifugal force effects are present. It should be noted that the "correct" value of blade profile drag coefficient is difficult to deduce by comparison of theoretical and test results (Figs. 3 and 6). The blade C_p values (Fig. 6) are not optimum for several reasons, and could be improved by optimizing blade angle and turbine solidity, as well as incorporating cyclic blade pitch and improving blade design (airfoil cross section). Thus, the relatively high values of C_p obtained are encouraging.

Analysis of the turbine torque equation allows calculation of the blade drag coefficient, for the special case of testing at zero wind velocity. This is true if the blade moment coefficient is known, or can be assumed to be zero for the blades constructed with symmetrical airfoils. Such data is shown in Fig. 7, where blade drag coefficient is plotted vs. the blade setting (0° is for the blade chord tangent to the blade path). The data show that as blade speed (and Reynolds number) increases, the drag coefficient increases, which is a surprising result. Also, the curve shapes are similar to those for a slightly cambered airfoil. Reconsideration of the assumption of zero airfoil moment coefficient should be made. The curved-path trajectory of the blade causes a "virtual" camber effect, even though the blade is physically symmetrical.

Fig. 6. Experimental blade power coefficient (C_p) vs tip speed ratio (TSR) for various blade velocities (ωR).

Fig. 7. VAWT test model blade drag coefficient (C_D) as a function of blade pitch angle (α') and blade velocity (ωR).

The effect is increased for increasing sizes of blade chord-to-radius ratios, and at low tip speed ratios. The effect of the non-zero moment coefficient is to reduce the torque output, and to cause the effective value of C_D , as presented in Fig. 7, to be increased. This virtual camber effect appears to be of considerable importance in determining the VAWT blade aerodynamic characteristics, and turbine performance.

Values of NACA 0015 airfoil minimum drag coefficients from several test sources as a function of Reynolds number are shown in Fig. 8. The WVU two dimensional wind tunnel test data show the expected decrease in blade drag coefficient with increasing Reynolds number. However, the data reduced from the WVU outdoor tests with the VAWT test model show an increasing blade drag coefficient with Reynolds number. This difference, along with the relatively low values obtained with the VAWT, is yet to be explained, but it is hypothesized that the blade boundary layer flow is a contributing factor.

It is clear that a complex flow situation exists around the blades of a VAWT, where a combination of Reynolds number, centrifugal force, and virtual

Fig. 8. Blade minimum drag coefficient ($C_{D_{min}}$) as a function of Reynolds number.

camber effects determine the aerodynamic characteristics of the blades and their "effective" drag. Although test results of VAWT performance are encouraging, the optimum performance design has not been determined. More theoretical and experimental study of this subject is needed.

2.5. HIGH SOLIDITY BLADE DESIGN

To more fully evaluate the VAWT aerodynamic performance and the accuracy of the theoretical calculations, two blades of high solidity were built. These blades were composed of NACA 0015 airfoil sections, and had a chord-to-radius ratio of 0.26; with a two bladed turbine that also gives a solidity of 0.26. The blades were 3.25 m (10 ft 8 in) long and had chords of 0.395 m (15-9/16 in). They are of conventional "aircraft type" construction, with a main spar at quarter chord utilizing aluminum ribs and skin. The blades are shown installed on the WVU VAWT in Fig. 9.

Some design consideration was given to blade cyclic articulation using an aerodynamic control surface, i.e., a tail. This method appears attractive, since it might allow the blade angle of attack, with respect to the local resultant velocity vector, to be kept constant throughout the cycle. Control forces needed to change the tail attitude would be much less than those required to change the blade pitch directly. Initial calculations show that reasonable forces are required, and that operation

Fig. 9. WVU VAWT test model with high solidity (0.26) blades.

at the higher TSR values (e.g., the range of 3 to 8) seems feasible with tail surface pitch control.

Testing of the aerodynamic properties of the higher solidity blades and tail surface blade pitch control is being initiated, and results will be available in the next project report.

2.6. COST ANALYSIS OF THE WVU VAWT TEST MODEL

It is not yet possible to establish definite costs for various sized VAWTs. Optimum turbine configurations are not known, and the exact power output is uncertain. Cost-effectiveness will depend on machine size, structural materials, etc. Although many uncertainties remain, it was useful to determine the cost of the WVU VAWT test model as a starting point for cost analysis of VAWTs. Specialized research equipment costs are not included, but the generator and blade pitch control system was accounted for.

The cost analysis was complicated since the test model is a singular unit, and no economy resulted from mass-production techniques. Also, the research machine status of the WVU VAWT resulted in an overdesign in the sense that parts were fabricated to provide versatility and large safety factors. Some items were also purchased to minimize time loss, and not necessarily at lowest cost.

Results of the analysis include the breakdown shown in Table I. The cost of a circulation control air supply system has not been evaluated completely, but at this time it is not estimated to significantly increase the cost.

TABLE I
WVU VAWT TEST MODEL COST SUMMARY

<u>ITEM</u>	<u>MATERIAL</u>	<u>LABOR</u>	<u>TOTAL</u>	<u>% OF TOTAL</u>
Support Stand	\$ 486	\$ 638	\$1124	23%
Rotor	744	712	1456	28
Blades*	164	60	224	4
Guy Wire System	492	181	673	13
Power Generating System and Control System	1073	450	1523	29
Assembly and Painting	33	160	193	4
Totals	\$2992	\$2161	\$5153	100%
% of Totals	58	42	100%	

---

*Two conventional symmetrical airfoil blades, 0.174 m (6.85 in) chord.

The use of aluminum, wood, and composite material blade construction has also been studied. This analysis used blade sizes of 22.86 m (75 ft) length and 2.44 m (8 ft) chord, which would be representative of perhaps a 100 KW turbine. Initial results show promise that the use of composite materials will be cost effective, and will allow machine operation at higher rotational speeds.

Exact turbine performance data must be obtained to allow determination of the initial turbine cost per unit of power output. This will allow a meaningful cost comparison with other types of wind turbines.

2.7. STRUCTURAL PARAMETRIC ANALYSIS OF VAWT BLADES

For both functional and economic reasons, blades are the most critical components of wind energy conversion system. A principal reason for the

study of VAWTs of the straight blade type is the conceptual simplicity of the blade, expected to provide both lower cost and higher efficiency. The objective of this task was to find the influence of operating conditions, material properties, and design features on blade mass/unit length and cost/unit length. This is believed to be the first work on the subject which includes advanced materials processes.

A structural model was formed for the blades which allowed calculations of blade mass and cost (per unit length) as a function of blade length for various design features and materials. The WVU-developed VAWT aerodynamic theory was used to determine aerodynamic blade loadings. Analysis was made for the design controlling loads, i.e., those associated with either rated or gust wind conditions. NACA 0015 airfoil sections were assumed, and fundamental beam theory used for the structural analysis. The cost model was developed by including costs of materials, prefabrications, and assembly; each varied with the material used. Materials selected were 2024-T6 aluminum and S2-Glass, E-Glass, Kevlar-49, and Graphite composites.

A typical result of the analysis is shown in Fig. 10 for S2-Glass composite, where blade cost and mass (per unit length) are given as functions of blade length and TSR ($\omega R/V_\infty$). The dashed line indicates the minimum blade mass which is practical to fabricate. The calculation was also performed for gust condition, as well as for the normal operating conditions shown in Fig. 10.

The general results indicate that different materials may provide the lowest cost/unit length and the lowest mass/unit length. Therefore, for the VAWT system, the effect of the blade mass on the entire VAWT cost must

be considered. In other words, a more expensive (but lighter) blade may minimize the cost of the entire system. The design points of most of the blades analyzed were determined by the normal operating conditions. However, the Kevlar blade design was determined by gust conditions.

Fig. 10. Calculated VAWT blade mass and cost for S-2 glass composite material construction.

The VAWT structural and cost analysis is being continued to include the entire machine. At present, the notion that the cheapest blade material provides the lowest system cost remains open to question.

2.8. COST STUDY OF CURRENT WECS

Although many available cost estimates of WECS must be considered preliminary at present, it is important to determine that innovative systems are not going to be prohibitively costly. Thus, the costs of VAWTs should be compared with the costs of the more developed horizontal axis wind turbines (HAWTs). Fig. 11 presents the results of a survey of costs to install various WECS having electrical power generating capabilities, but no energy storage systems. These include historical WECS and those commercially available. Costs are adjusted to 1977 prices.

Fig. 11. Initial costs of various wind turbines as a function of output capacity. See Table II, p. 20, for turbine characteristic list.

TABLE II
CHARACTERISTICS OF SOME WIND TURBINES

ID#	MANUFACTURER/MODEL	DIAMETER (FT)	RATED ¹ SPEED (MPH)	POWER IN (KW)	POWER ¹ OUT (KW)	EFFICIENCY	CAPITAL COST (\$/KW)	NOTES	ESTIMATED 1977 CAPITAL COST (\$/KW)		
1	Amerenalt	1500	8	12	27	5.02	1.5	.299	1766	2	1996
2		2500	8	16	36	11.93	2.5	.210	1140	2	1243
3	Windworks		12	11.2	25	8.99	1.87	.207	900	3	900
4	Kedco	1200	12	9.8	22	6.11	1.2	.195	1913	4	1913
5		1600	16	7	16	4.19	1.2	.286	2413	4	2413
6		1210	12	11.2	25	8.99	2.0	.222	1298	4	1298
7		1610	16	9.8	22	10.88	2.0	.184	1598	4	1598
8	D.A.F.	15	15	10.3	23	12.43	3.2	.257	607	5	656
9		20	20	10.3	23	19.43	6.0	.308	572	5	618
10	Aeromotor	6	6	8.9	20	1.12	.08	.071	5812	5,6	6277*
11		8	8	8.9	20	2.05	.167	.084	4131	5,6	4461
12		16	16	8.9	20	8.18	.895	.109	4731	5,6	5109
13	Baker	6	6	6.7	15	.485	.075	.154	6946	5,6	7502*
14		8	8	6.7	15	.863	.157	.182	4299	5,6	4643
15		12	12	6.7	15	1.942	.408	.210	3512	5,6	3793
16	Dempster	6	6	6.7	15	.485	.078	.161	5256	5,6	5676*
17		8	8	6.7	15	.863	.165	.191	3696	5,6	3992
18		12	12	8.9	20	4.6	.394	.086	4505	5,6	4865
19	Dunlite		13	11.2	25	10.55	2.0	.190	2000	2,3	2260
20	Grumman Windstream		25	11.6	26	43.89	15	.342	1100	4,3	1100
21	Wincharger		6	10.3	23	1.75	.2	.114	2625	4,3	2625
22	Electro GMB WVS50G		16.5	13.4	30	29.372	6	.204	1333	2,3	1506
23	NASA MOD 0		125	8	18	1860	100	.275	1600	4,3	1600
24	Putnam		175	13.4	30	4600	1250	.272	650	4,3	650
25	Gedser		78.2	13.4	30	659	200	.303	400	4,3	900

NOTES: Costs are for turbine and generator only.

1. Manufacture's specification, except for #s 10-18, where power out was calculated.
2. 1975 price
3. Estimated
4. 1977 price
5. 1975 price
6. Generator not included
7. Based on 8% increase from 1976-77 and 13% increase from 1975-77.

* Not on KW-\$/KW curve, Fig. 11

Two trends are noted. First, costs/KW decrease with increased rated outputs. Second, the graph contains separate clusters of points for "farm" type machines (no generator cost included) in the upper left, smaller commercially available horizontal and vertical axis turbines in the center, and the larger horizontal axis turbines and historical projects on the right. Considerable price scatter exists, which is typical of infant industries.

The cost of the WVU VAWT is estimated at about \$2000/KW for about a 2 KW (6 m/s wind) turbine. Thus, the WVU VAWT appears competitive to those shown in Fig. 11, and expected cost reductions of a production model, plus possible output gains with circulation control blades, would further decrease the cost. Continuing cost analysis is necessary to give an accurate indication of both initial and operating costs.

3. CONCLUSIONS

A comprehensive analysis of straight-bladed VAWTs is underway. Advanced theoretical results show turbine performance dependent on blade drag, rotor solidity, and blade number. Blade boundary layer flow may have an adverse effect on blade aerodynamics. The WVU VAWT test model has provided low solidity blade aerodynamic data for comparison with theoretical results. Large differences have been noted in blade drag of the test model and that expected using two dimensional airfoil test data. This "virtual camber" effect requires further study, and larger blades are scheduled for testing to more fully evaluate this important effect. An initial structural and cost analysis of a VAWT blade design using composite materials has been accomplished. Results indicate that composites may offer lower cost than conventional (aluminum) blade construction, and may be required for high

rotational speed turbine operation. Estimates of costs of the WVU VAWT test model are comparable with other WECS designs of similar output, and future improvements seem likely.

4. RECOMMENDATIONS

Although significant progress has been made on the theoretical and experimental evaluation of straight bladed VAWTs, additional evaluation is required to provide blade aerodynamic data to be used in theoretical calculations, and to verify the predicted turbine performance. Flow effects, including the blade boundary layer flow and those relating to the blade motion along a curved path, must be studied further. The cost and structural analysis should continue to better determine the competitiveness of the straight-bladed vertical axis turbine.