SERI/TP-217-2785
UC Category: 60
DE85012159

System Engineering and Energy Costs of Small and Medium Wind Turbines

P.K.C. Tu

July 1985

Prepared for the International Conference on
Solar and Wind Applications
Beijing, China
3-8 August 1985

Prepared under Task No. 4817.40
FTP No. 562

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A02

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications, which are generally available in most libraries: *Energy Research Abstracts, (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication, NTIS-PR-360 available from NTIS at the above address.

SYSTEM ENGINEERING AND ENERGY COST ANALYSIS OF SMALL AND MEDIUM WIND TURBINES

Peter K. C. Tu
Wind Energy Research Center
Solar Energy Research Institute
Golden, Colorado, U.S.A.

ABSTRACT

A preliminary system-level, computational model was developed to allow broad assessment and optimization of wind turbine design and costs analysis at The Wind Energy Research Center, Solar Energy Research Institute under contract to the U. S. Department of Energy (DOE). This paper briefly describes the basic principles used in the model for energy capture and cost-of-energy (COE), and demonstrates the model's usefulness in determining the effects of rotor and system design modifications. The model's utilization for conducting parametric studies and defining the energy cost of small and medium-sized wind turbines is also shown. Topics of interest to wind turbine engineers and designers include the effects on rotor performance of airfoil geometry, blade pitch angle setting, and the system RPM schedule, etc.

INTRODUCTION

To assist private industry in the production of cost-effective wind turbines has been, for many years, the ultimate goal of the U.S. Federal Wind Energy Program. The Solar Energy Research Institute Wind Energy Research Center (WERC), located at Golden, Colorado, U.S.A., is under contract with the U.S. Department of Energy (DOE) to promote the R&D of economical, reliable, and safe wind energy conversion systems (WECS). The main thrust of the R&D program in recent years is to improve WECS technology by research in the basic science of wind turbines and by advanced components and system research. The technology data base, as a result of such R&D research at WERC, will then be transferred to wind turbine developers for the reduction of machine installed cost, the increase of energy production, and the improvement of lifetime of machine operation.

A system-level analytical model is required to verify the usefulness of the technology data base, to determine the important interrelationships among various sub-systems and to ensure that designs are optimized from a system point of view. A preliminary version of such analytical model was developed to take into account the rotor configuration design, system operation options, and economic conditions under which the WECS cost-of-energy (COE) is calculated.

This paper provides a brief description of the basic principles used in the model and examples of the parametric/tradeoff study and COE calculations.

BASIC PRINCIPLES USED

1. Rotor Performance

The method used for analyzing rotor performance, i.e., the efficiency of extracting available wind energy, is the Glauert Strip Theory[1,2]. The theory determines the rotor performance by utilizing both a two-dimensional airfoil blade element and axial momentum theories on an annular area, which is created by dissecting the rotor swept area into concentric annular strips. An iterative process is required to determine the axial and angular induction factors after equating the blade forces (axial and circumferential forces) based on the blade element theory with that of the axial momentum theory. Once the induction factors are solved, the flow field and the angle of attack on the blade element can be computed. Thus, the rotor power and thrust calculations are achieved through the integration over the entire rotor swept area.

The blade element theory determines the coefficients of axial (C_N) and circumferential (C_T) forces on the blade based on local velocity (W) and ϕ as indicated in Figure 1.

$$C_N = C_L \cos\phi + C_D \sin\phi \tag{1}$$

$$C_T = C_L \sin\phi - C_D \cos\phi , \tag{2}$$

where C_L and C_D are lift and drag coefficient of the airfoil.

When a coning angle ψ is introduced, Equation 1 becomes

$$(C_N)_c = (C_L \cos\phi + C_D \sin\phi) \cos\psi . \tag{3}$$

The local velocities are defined as

$$r\Omega_L = r\Omega(1 + a') \cos\psi \tag{4}$$

$$u = V(1 - a) \cos\psi , \tag{5}$$

where a is defined as axial induction factor

a' is defined as the angular induction factor

Ω is rotor RPM

V is wind velocity component normal to the rotor swept area.

When the pitch angle of blade is set at θ, the angle of attack for the resultant velocity, W, is determined as

$$\alpha = \phi - \theta \ . \tag{6}$$

Using a two-dimensional airfoil table, C_L and C_D are determined as a function of α.

Thrust acting on the blade element can be expressed as

$$dT = (\frac{1}{2}\rho W^2)\ (C_N)_c\ (B \cdot C_c)\ (\frac{dr_c}{\cos\phi})\ , \tag{7}$$

where δ is air density

B is number of blades

C_c is chord length of the blade (airfoil)

$dr_c = dr \cdot \cos\phi$, r is the average radius of annular strip.

The torque acting on the blade element is given by

$$dQ = [(\frac{1}{2}\rho W^2)\ (C_T)\ (B \cdot C_c)\ (\frac{dr_c}{\cos\phi})] \cdot r_c \ . \tag{8}$$

Based on an axial momentum theory, the thrust and the moment of momentum (torque) of the annular strip are determined as

$$dT = (2\pi r_c dr_c) \cdot \rho\ V(1 - a) \cdot 2aV \tag{9}$$

$$dQ = [\rho V(1 - a) \cdot 2\pi r_c dr_c \cdot (r_c 2a'\Omega)] \cdot r_c \ . \tag{10}$$

Combining the blade element and axial momentum theories, i.e., equating Equations 7 to 9 and Equations 8 to 10, we have the following relationships:

$$\frac{a}{1-a} = K_r \cdot \cos^2 \phi \cdot f(C_N,\phi) \qquad (11)$$

$$\frac{a'}{1+a'} = K_r \cdot f(C_T, \phi) \ , \qquad (12)$$

where

$$K_r = \frac{1}{8} \frac{B\ C_c}{\pi\ r_c} \qquad (13)$$

$$f(C_N,\phi) = \frac{(C_N)_c}{\sin^2\phi} \qquad (14)$$

$$f(C_T,\phi) = \frac{C_T}{\sin\phi\ \cos\phi} \ . \qquad (15)$$

a and a' can be determined from an iteration process from Equations 11 and 12. Rotor torque and thrust are calculated from the integration of Equations 9 and 10 over the entire rotor swept area. Thus, the rotor power coefficient is given as

$$C_p = \frac{(\text{Torque}) \cdot (\text{rotor RPM})}{(\frac{1}{2}\rho V^3) \cdot (\text{rotor swept area})} \qquad (16)$$

The above procedure is used in the computer program with the following modifications and additional information:

a. Glauert's empirical formula describing the windmill brake and vortex ring state performance; i.e., the flow field at high tip-speed ratios.

b. Tip loss correction to account for the interaction of the trailing vorticity with the blade flow near the blade tip. A tip loss factor formulated by Prandtl Model[1,2] is used with good success.

c. Subroutine of post-stall synthesization of airfoil data based on newest wind tunnel results.[3]

d. Subroutines taking into account the hub loss, wind shear effect, and off-axis flow effect.

The major outputs of the computational model are the rotor power coefficient (C_p) as a function of tip-speed ratio (λ) and the static loads on the blade root.

2. Annual Energy Production

The rotor power output as a function of wind speeds between the limits of cut-in (V_i) and cut-out (V_o) wind speed can be determined from the C_p curve:

$$P(V) = \frac{1}{2} \rho V^3 A \cdot C_p \ , \qquad (17)$$

where A is the rotor swept area.

To predict the rotor annual energy production, the wind speed characteristics of the site should be specified. The computer model uses a Weibull wind speed frequency distribution as a wind speed model for the site. The frequency function is expressed as

$$f(V) = \frac{K}{C} \left(\frac{V}{C}\right)^{k-1} \cdot \exp\left[-\left(\frac{V}{C}\right)^{k}\right] \ , \qquad (18)$$

where K is distribution dispersion parameter

C is scale parameter of the annual average wind speed $(\overline{V})$.

$\overline{V}$ and C are related by the following equation:

$$\overline{V} = C\Gamma(1 + 1/K) \ , \qquad (19)$$

where $\Gamma(1 + 1/K)$ is a gamma function and can be expressed as

$$\Gamma(1 + 1/K) = (1/K)\Gamma(1/K) \ . \qquad (20)$$

The computer model uses an asymptotic series to express $\Gamma(1/K)$:

$$\Gamma(1/K) = X^x e^{-x} \cdot \frac{2\pi}{x} \left(1 + \frac{1}{12x} + \frac{1}{288x^2} - \frac{138}{51840X^3} \cdots\cdot\right), \qquad (21)$$

where $x = 1/K$.

When K and $\overline{V}$ are given, the annual energy production of the rotor at a wind site is predicted by the following:

$$E(\overline{V}) = 8766 \int_{V_i}^{V_o} P(V) \cdot f(V) \cdot dV \ . \qquad (22)$$

When the efficiency ($\eta(v)$) of the power train (gear box, generator, etc.) is given, then the system energy output is determined as

$$E_s(\overline{V}) = 8766 \int_{V_i}^{V_o} \eta(v) \cdot \rho(V) \cdot f(v) \cdot dV \; . \tag{23}$$

A fluid flow boundary layer formula is used to express the wind speed as a function of rotor hub height:

$$V = V_m \left(\frac{H}{H_m}\right)^n \; , \tag{24}$$

where V_m is the wind speed measured at H_m

H is the rotor hub height

n is wind speed profile exponent.

The energy mismatch between the power supply of wind turbine and the local load demand is estimated by the computer model. Assuming that the wind turbine system responds to the wind speed changes instantaneously and when the local diurnal wind speed and load distributions as cat [illegible] by the seasons are given, the code will then calculate turbine power output as a function of the diurnal wind speed and compare the results with the load distribution to obtain the mismatch picture for that hour. The computer also summarizes the net/total energy mismatch for the entire year.

3. Cost-of-Energy of Wind Turbines

The cost-of-energy (COE) calculation is based on the life cycle cost technique[4], which is a method of determining total cost of a wind turbine system over its life span. This includes the costs of the wind machine, installation, balance of station, and financial cost, as well as all anticipated major costs such as the cost of operation and maintenance (O&M), cost of replacement and disposal value, etc. Other economic factors such as inflation rate, and financial benefits from government tax credits are also included in the calculation.

The approach of the life cycle cost technique is twofold:

a. Bring all costs of owning a wind turbine and system over the life span to a total present value (worth) using standard interest formulas, single or compound amount.

b. Convert the total present value (worth) to a uniform annual cost (also called annualized/levelized cost) over the life span years.

The COE may then be obtained by the following equation:

$$\mathrm{COE} = \frac{\text{Uniform Annual Cost (\$)}}{\text{Annual Energy Production (kWh)}} \,. \qquad (25)$$

Annual cash flow and payback year are also calculated.

INPUT/OUTPUT DATA

1. Input Parameters

The input files include four major groups of parameters:

a. Rotor data: rotor diameter, number of blades, blade chord taper and twist rates, airfoil data (C_L and C_D), coning angle, pitch angle, rotor RPM, and rotor height, etc.

b. System data: System operation (RPM) scheme such as a constant RPM system, a variable RPM system (or constant λ system) or a specified RPM schedule system. Cut-in and Cut-out wind speeds, system/subsystem power efficiency, maximum allowable power output, etc.

c. Wind site data: wind site annual average wind speed, diurnal wind speed, and load distribution as categorized by each season.

d. Financial data: machine cost, O&M cost, replacement cost, discount rate, and other applicable costs and benefits.

2. Output Data

Results of the computation are as follows:

a. Rotor static load distribution such as thrust, torque, and bending moment, etc.

b. Rotor or system power efficiency as a function of blade tip-speed ratio.

c. Rotor or system power output as a function of wind speed.

d. Annual energy production of a rotor or system as a function of annual average wind speed.

e. Diurnal power mismatch between the turbine power supply and demand of local application.

f. Cost-of-energy, cash flow, and payback period.

EXAMPLES OF PARAMETRIC STUDIES

A preliminary tradeoff study of design optimization of a wind turbine and systems can be achieved using the model. The following presents a few examples showing the results of these studies using a 10-ft-diameter, two-bladed, fixed pitch, and downwind horizontal-axis rotor wind turbine.

1. The Effect of Airfoil Geometry

Three airfoil shapes of series FX63-137, G0769, and FXLV-152 are chosen (Figure 2). Airfoil data (C_L and C_L/C_D ratio as a function of α) of these airfoils and others can be found in Ref. 5. The outputs of the computational system model are shown in Figures 3 and 4. It is clear that the FX63-137 airfoil, a highly cambered airfoil, generates the highest performance coefficient (C_p) and annual energy output among the airfoils analyzed.

High performance airfoil research is one of the major aerodynamic research activities at the WERC[6]. Recently, an airfoil being characterized with a laminar boundary layer flow and a high maximum ratio of C_L/C_D (=110) at a Reynolds number of 1×10^6 has been developed. The airfoil is under test at a laminar flow wind tunnel. Other considerations of airfoil research are restraint of C_L maximum (≤ 1.2) while keeping the C_L/C_D ratio high and design of the laminar boundary layer flow according to rotor solidity and annual average wind speed.

2. The Effect of Blade Pitch Settings

Using an airfoil series NACA 0012 at a Reynolds number of 330,000 and the model wind turbine aforementioned, the system model computes Cp curves for various pitch angles ranging from 3° to 15° (Figure 5). The rotor power output as a function of wind speed and annual enrgy production as a function of average wind speed are shown in Figures 6 and 7, respectively. The pitch angle yields significantly different results in terms of rotor power and energy output. Two major design practices can be exercised through the pitch angle variaton:

a. The optimization of pitch angle for a fixed pitch rotor.

b. The determination of pitch schedule as a function of windspeed for a variable pitch rotor when pitch control is used as a means of controlling maximum power output and machine shut-down at cut-out wind speed.

3. The Effect of the System Operation (RPM) Scheme

The difference in rotor performance of a constant RPM rotor from that of a variable RPM rotor can be determined by the system model. The variable RPM rotor is a case for which the rotor RPM is governed to achieve an optimum tip speed ratio (λ), for maximum Cp.

Figure 8 shows the rotor power as a function of wind speed for the two systems. A constant λ rotor produces more power below and above the optimum wind speed (V_t) where Vt is defined as

$$V_t = \frac{R \cdot RPM}{(\lambda)_{optimum}} . \tag{26}$$

The net increase in energy production of a constant λ rotor over the constant RPM rotor under identical maximum power levels is shown in Figure 9. An average 25% energy increase is realized by the constant λ rotor. The final benefit to the system as a whole should be determined with proper subsystem efficiency data. However, this requires bench testing of each drive train component and is considered beyond the scope of the present analysis.

CONCLUSIONS

The present system engineering and cost analysis model has proven to be an effective and user-friendly tool for wind turbine and systems design and analysis. The computational model is very useful for trade-off studies and optimization of major design/operational parameters. Selecting proper rotor configuration and system operational schemes, and determining wind turbine performance and cost-of-energy can be achieved with minimal cost of computer time. The model is also useful for wind turbine component research. Any advancement or cost savings as a result of the component research can be quantified by the model in terms of performance and COE.

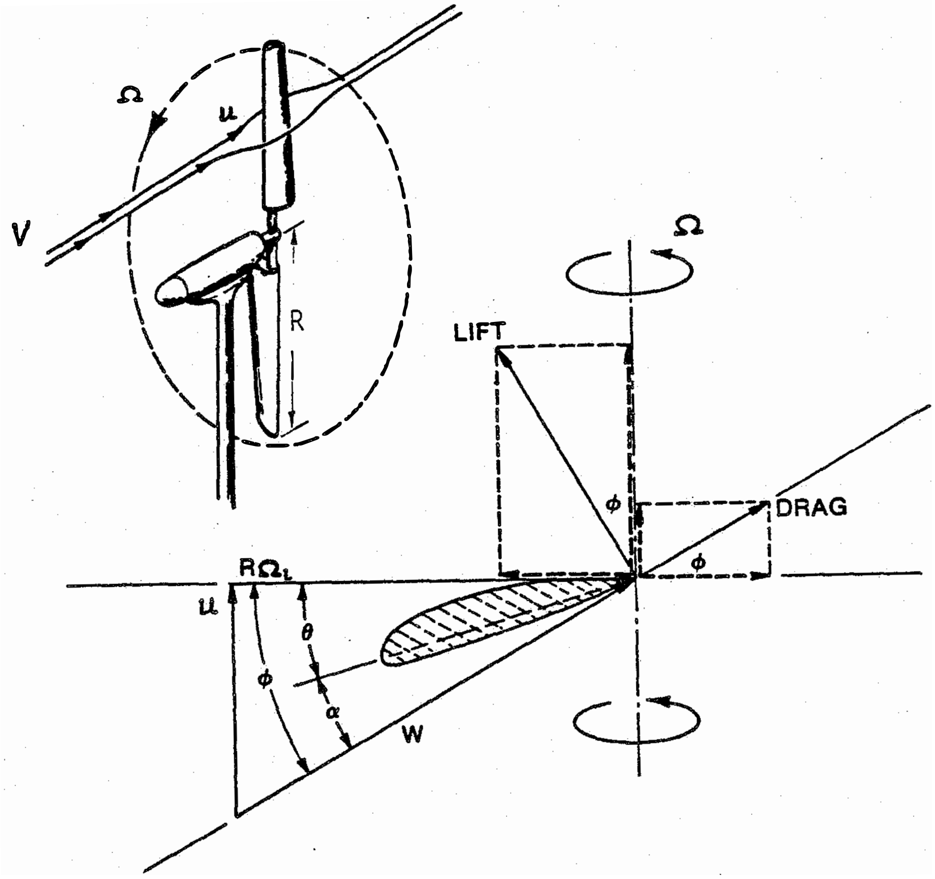
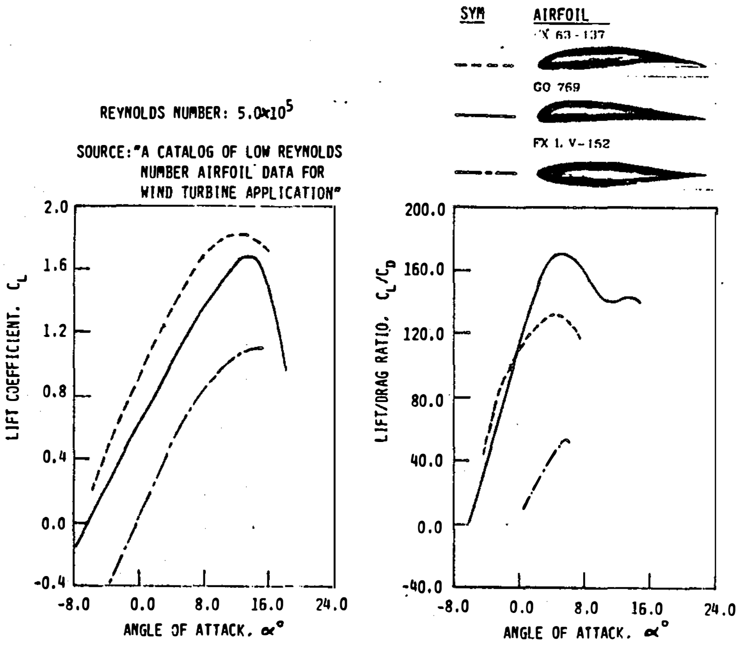


Figure 1. Rotor Force and Velocity Diagram



SOURCE: "A CATALOG OF LOW REYNOLDS NUMBER AIRFOIL DATA FOR WIND TURBINE APPLICATION"

Figure 2. Airfoil Data Used in the Study of Airfoil Geometry Effects on Rotor Performance

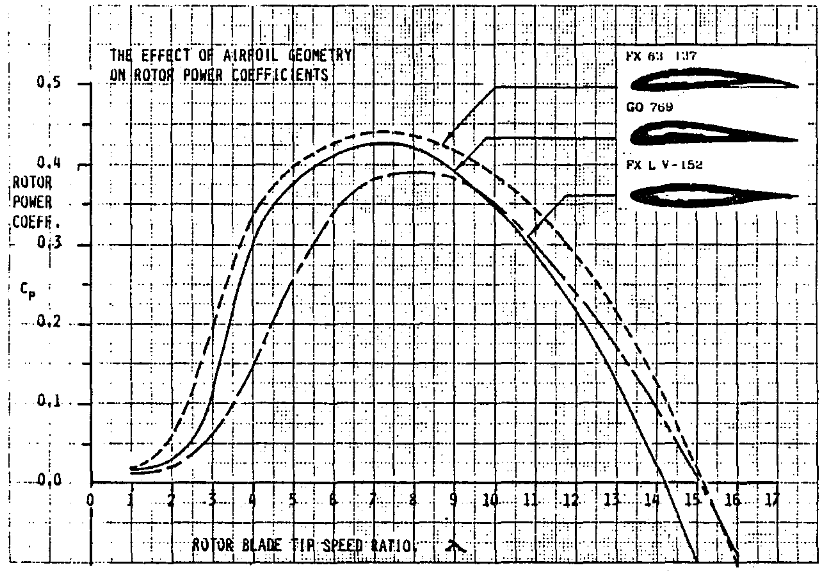


Figure 3. The Effect of Airfoil Geometry on Rotor Power Coefficients

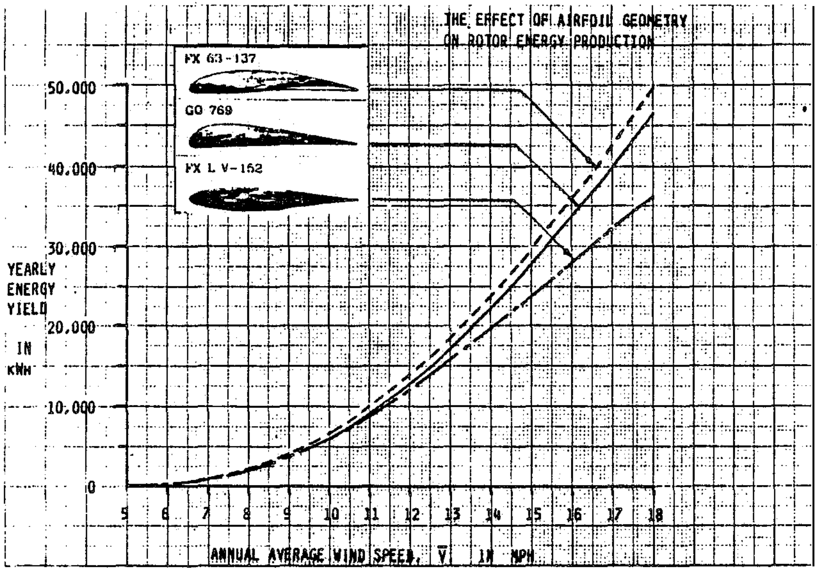


Figure 4. The Effect of Airfoil Geometry on Rotor Energy Production

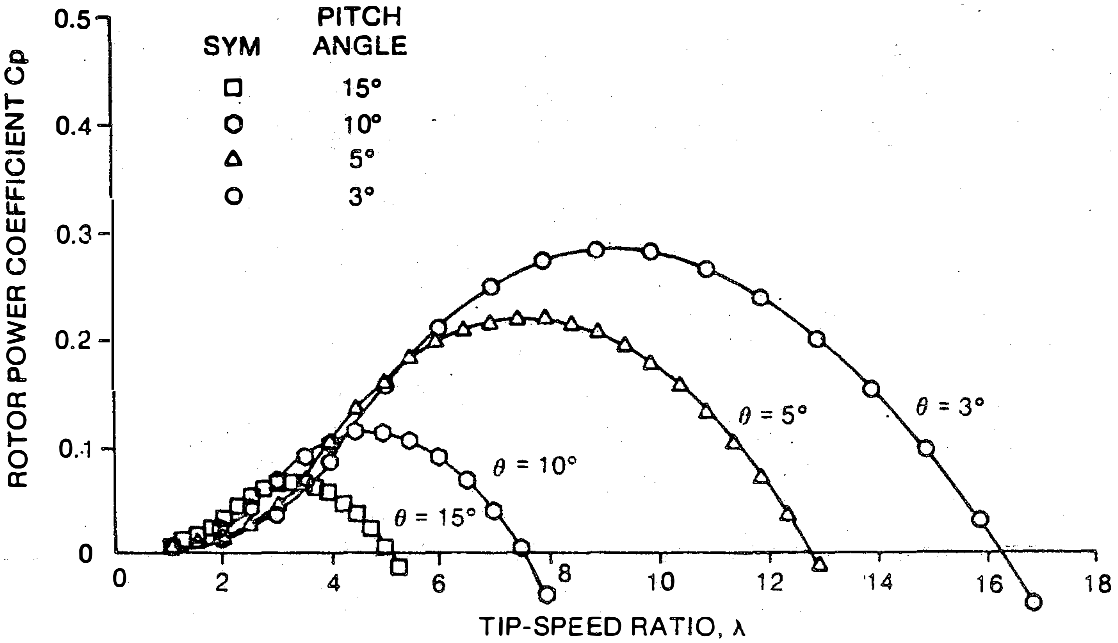


Figure 5. Rotor Power Coefficient Characteristics as Affected by Variation of Pitch Angle Ranging from 15° to 3°

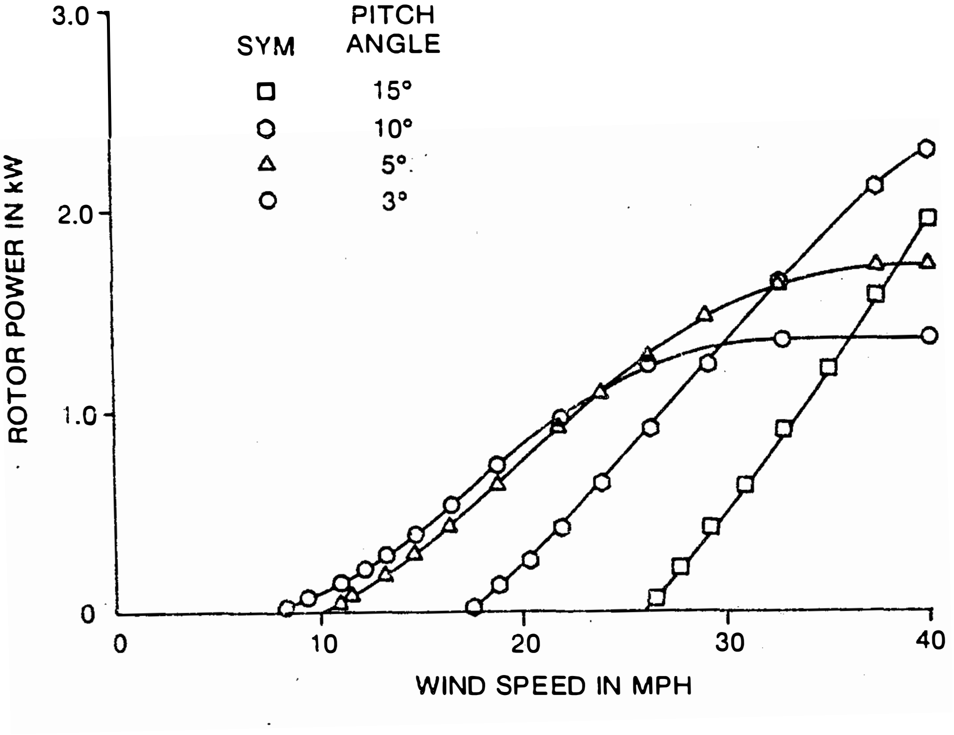


Figure 6. Pitch Angle Effect on Rotor Power for $\theta = 15^o$ to 3^o

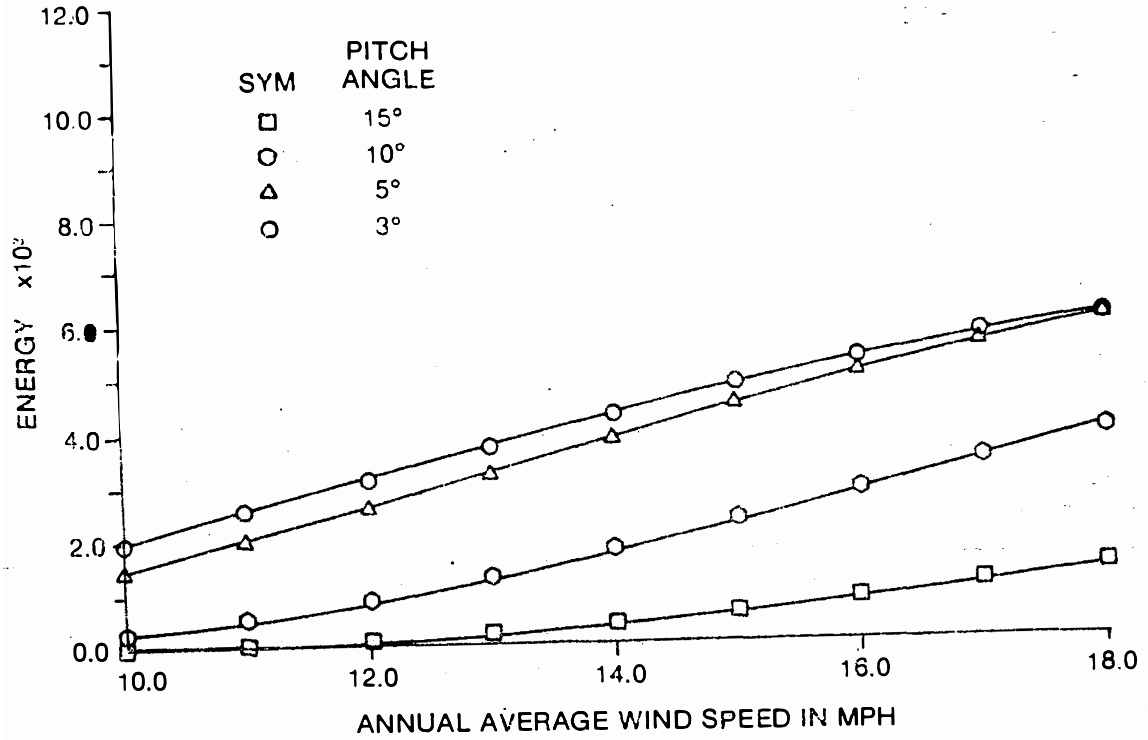


Figure 7. Pitch Angle Effect on Rotor Energy Production for $\theta = 15^o$ to 3^o

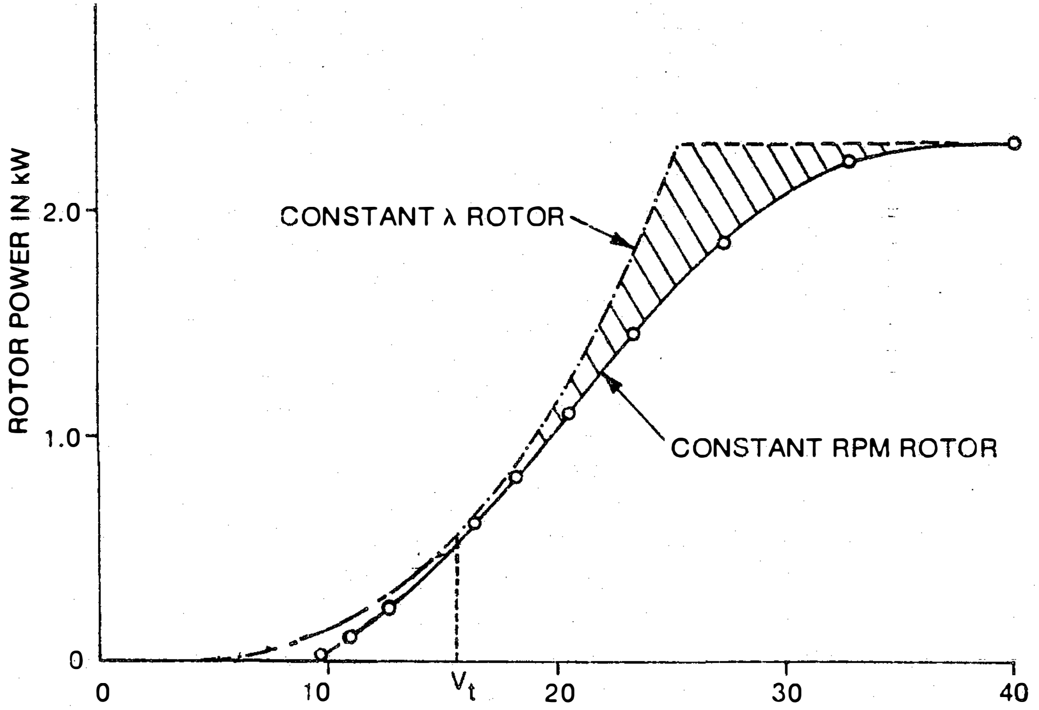


Figure 8. Power Curves of a Constant RPM Rotor and a Constant λ Rotor under Identical Maximum Power Levels

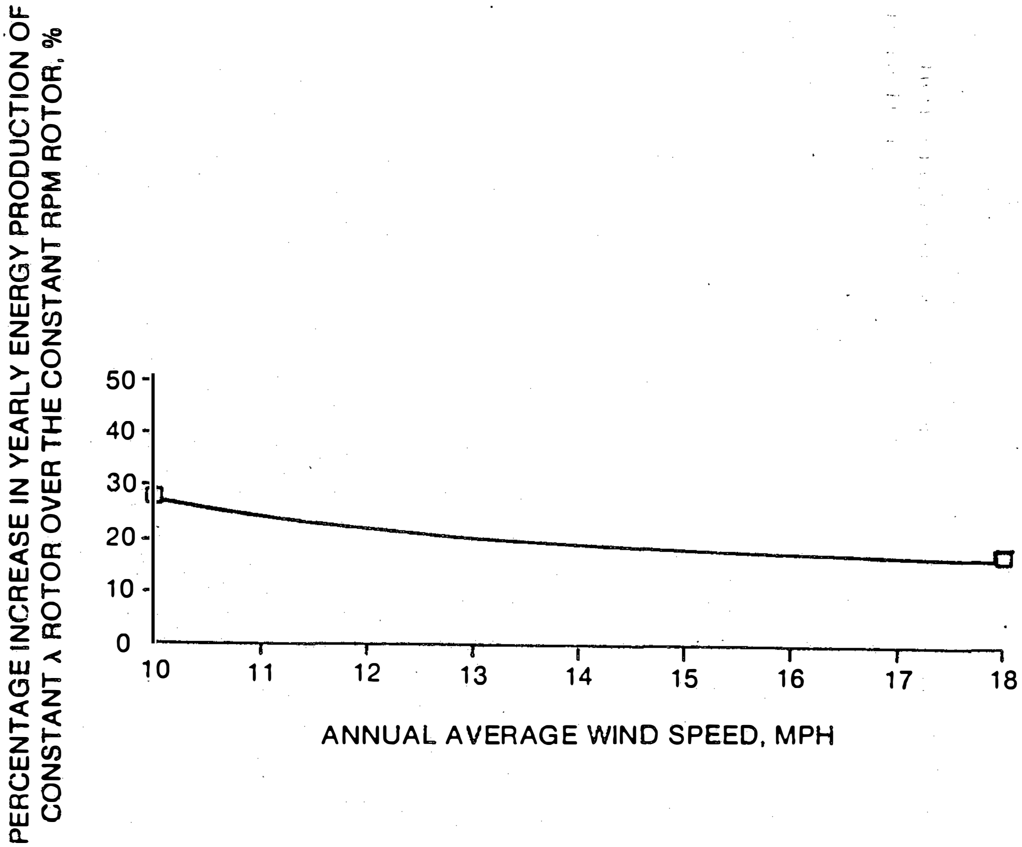


Figure 9. Rotor Energy Production Comparison Between a Constant RPM Rotor and a Constant λ Rotor SWECS

REFERENCES

1. Wilson, R. E., Lissaman, P.B.S., and Walker, S. N., Aerodynamic Performance of Wind Turbines, Oregon State University, June 1976

2. Hibbs, B. and Radkey, R. L., Small Wind Energy Conversion Systems (SWECS) Rotor Performance Model Comparison Study, AeroVironment, Inc. report for DOE/Rocky Flats Wind Energy Research Center, November 1981.

3. Tangler, J. L. and Ostowari, C., "Horizontal Axis Wind Turbine Post Stall Airfoil Characteristics Synthesization," DOE/NASA Wind Turbine Technology Workshop, May 1984, Cleveland, Ohio.

4. Sherman, J. M., Gresham, M. S., and Fergason, D. L. Wind Systems Life Cycle Cost Analysis, DOE/Rocky Flats Wind Energy Research Center Report RFP-3448, July 1982.

5. Miley, S. J. A Catalog of Low Reynolds Number Airfoil Data for Wind Turbine Applications, Texas A&M University reports for DOE/Rocky Flats Wind Energy Research Center, February 1982.

6. Tangler, J. L., "Aerodynamic Research Efforts at SERI Wind Energy Research Center at Rocky Flats", Proceedings of the European Wind Energy Conference at Hamburg, F.R. Germany, October 1984.