PERFORMANCE EVALUATION OF WIND ENERGY CONVERSION SYSTEMS USING THE METHOD OF BINS - CURRENT STATUS

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ABSTRACT

A detailed description of the method of bins, a technique of data collection and reduction for field performance evaluation of Wind Energy Conversion Systems (WECS) is provided. The method of bins is a straightforward yet useful approach to the complex problem of relating the response of a WECS to a variable wind field. Examples of typical results obtained using the method of bins are presented. Methods of determining that the measure of performance of a WECS obtained is correct are outlined. Areas in which further modifications to the technique may be appropriate are also discussed.

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I. Introduction

The need to evaluate performance of Wind Energy Conversion Systems (WECS) in a field environment is an important aspect of the overall development of WECS. Analytical performance prediction techniques in most instances are based upon a steady wind and the application of these predictions requires field verification where possible. No standardized techniques exist for field testing of WECS. However, this report discusses one method in use at Sandia Laboratories as a part of the Vertical Axis Wind Turbine (VAWT) program, sponsored by the Wind Systems Branch of the Department of Energy. This technique termed the "method of bins" is described, experience with its use and verification to date are presented, and areas of continued development are discussed.

The method of bins provides mean performance data. These data, in terms of shaft torque or some form of nondimensional performance coefficient, can be used to predict the output of WECS over a period for which a wind speed probability density function is available. This period could be one hour, one day, or one or more years. An appropriate measure of output is the number of kilowatt-hours produced in the period of interest. This measure of performance is of more use in projections of annual output of a particular WECS than a rated power for the WECS.

II. The Method of Bins

Development

The method of bins was developed at Sandia in conjunction with field testing of a 5 m Vertical Axis Wind Turbine (VAWT).[1] The recent installation of an automated data system at the VAWT test facility has allowed a more detailed consideration of the formulation and application of the method of bins. To date, the method has been applied exclusively to field testing efforts at Sandia to study constant RPM operation. In addition, it has also been used in preliminary measurements at the Rocky Flats Wind Systems Test Center,[2] and with the DOE/NASA MOD-0 wind turbine.[3]

Description

General Approach -- A schematic representation of the method of bins is shown in Figure 1.
Two input parameters are sampled; a measure of turbine output and a reference anemometer.
The measure of turbine output could be shaft torque at the base or hub of the turbine or some
measure of generator output. For the remainder of this discussion the measure of turbine output
will be taken as torque measured before any speed increasers or generators. Such a measure-
ment provides only a measure of the aerodynamic performance of the turbine or WECS. The
location of the reference anemometer is important in the interpretation of the performance data
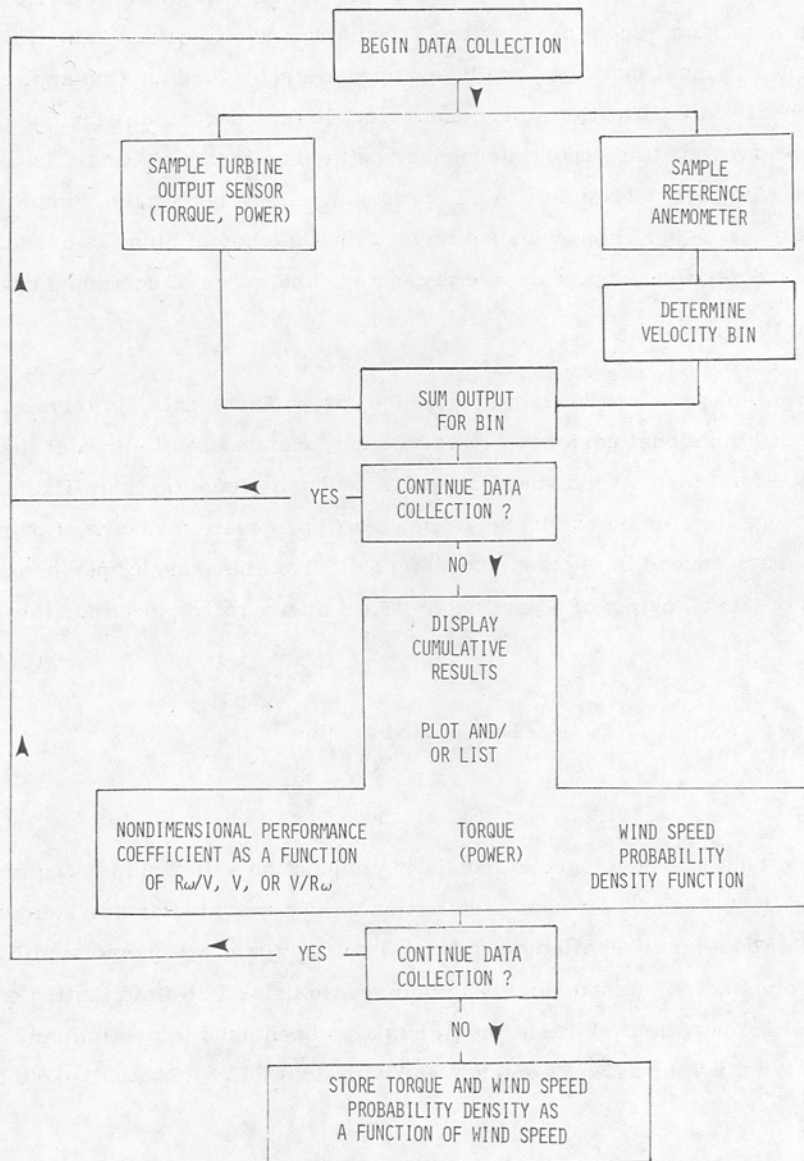and will be discussed in a later section.

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                        ┌─────────────────────────┐
                        │  BEGIN DATA COLLECTION   │
                        └─────────────────────────┘
                                    ▼
     ┌──────────────────────┐            ┌──────────────────┐
     │  SAMPLE TURBINE      │            │     SAMPLE       │
     │  OUTPUT SENSOR       │            │   REFERENCE      │
     │  (TORQUE, POWER)     │            │   ANEMOMETER     │
     └──────────────────────┘            └──────────────────┘
                                                 │
                                         ┌──────────────────┐
                                         │    DETERMINE     │
                                         │   VELOCITY BIN   │
                                         └──────────────────┘
                        ┌─────────────────────────┐
                        │     SUM OUTPUT          │
                        │      FOR BIN            │
                        └─────────────────────────┘
                        ┌─────────────────────────┐
         ◄── YES ───────│  CONTINUE DATA          │
                        │  COLLECTION ?           │
                        └─────────────────────────┘
                               NO  ▼
                        ┌─────────────────────────┐
                        │      DISPLAY            │
                        │     CUMULATIVE          │
                        │      RESULTS            │
                        │                         │
                        │     PLOT AND/           │
                        │      OR LIST            │
                        └─────────────────────────┘
 ┌───────────────────────────────────────────────────────────────┐
 │ NONDIMENSIONAL PERFORMANCE      TORQUE      WIND SPEED          │
 │ COEFFICIENT AS A FUNCTION       (POWER)     PROBABILITY         │
 │ OF Rω/V, V, OR V/Rω                         DENSITY FUNCTION    │
 └───────────────────────────────────────────────────────────────┘
                        ┌─────────────────────────┐
         ◄── YES ───────│  CONTINUE DATA          │
                        │  COLLECTION ?           │
                        └─────────────────────────┘
                               NO  ▼
                 ┌────────────────────────────────────┐
                 │  STORE TORQUE AND WIND SPEED        │
                 │  PROBABILITY DENSITY AS             │
                 │  A FUNCTION OF WIND SPEED           │
                 └────────────────────────────────────┘
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Figure 1. Schematic Representation of The Method
of Bins

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The range of anticipated wind speed readings is partitioned into equal intervals; for instance 100 intervals to span the range 0 to 25 ms^{-1} in 0.25 ms^{-1} increments. As simultaneous readings are taken of both velocity and torque (at 0.1 s intervals), the appropriate velocity bin is identified and a counter associated with that bin is incremented. A running total of torque associated with that particular bin is increased by the torque reading. This operation continues at the specified sampling interval until a decision is provided to stop the operation. At the VAWT test facility data are taken with an on-line minicomputer system and a command to terminate the data collection can be entered in real time. If a time history of torque and wind speed were being analyzed at a later time using a computer facility, a decision to terminate data reduction could be caused by the end of the record or by some internal decision-making process based on the data.

Upon completion of the data recording or of the analysis of an existing data record, the stored wind speed probability density function and the corresponding torque summations may be combined in a number of ways to provide quantitative measures of WECS performance. The average torque produced as a function of wind speed is the primary measure of turbine performance available from this technique. The torque versus wind speed relationship may be examined directly or the information may be put into a nondimensional format. Two nondimensional quantities are computed, a power coefficient, C_p, and alternatively a performance coefficient, K. These quantities are defined:

$$C_p = \frac{T(V_R)\omega}{\frac{1}{2}\rho A V_R^3} \quad \text{power coefficent} \tag{1}$$

$$K = \frac{T(V_R)\omega}{\frac{1}{2}\rho A(R\omega)^3} \quad \text{performance coefficient} \tag{2}$$

where

$T(V_R)$ is the average torque for a particular bin

ρ is the density of ambient air during the test

A is the swept area of the WECS

V_R is the reference velocity for the bin corresponding to the torque (see Vertical Wind Shear Correction)

R is the radius of the WECS

ω is the angular velocity of the WECS

The power coefficient is a measure of the fraction of power extracted from a stream-tube of air passing through the cross section of the WECS. The peak power coefficient does not correspond to the peak power produced by a WECS. The performance coefficient is also used as a measure of WECS output. The performance coefficient is proportional to WECS output in the constant RPM mode of operation. Thus, in the constant RPM application, it provides a more readily understood indication of WECS performance.

These parameters are both listed on an output device and plotted using a standard software package. If more than one anemometer was sampled during a particular test, results for each anemometer are displayed. After the data have been examined quickly, the raw records of torque and wind speed probability density may be stored for future use or data collection may be continued by providing an appropriate command.

Vertical Wind Shear Correction -- The reference velocity in the power coefficient is defined as the centerline velocity of the wind turbine. This velocity would be measured at a height corresponding to the center of a vertical-axis WECS or at the hub height of a horizontal-axis WECS. In general, it is not possible to locate a reference anemometer at this exact height and a correction for vertical wind shear must be made. If measurements of wind speed as a function of height are available at the site in question, the correction may be based on these measurements. If no field measurements of the velocity profile are available, an estimate of the appropriate correction may be made based on existing literature.[4,5] In the present formulation of the method of bins this correction is applied to each instantaneous velocity reading before selecting a bin. No correction is applied to account for horizontal convection or decay of discrete eddies.

The vertical wind shear correction is of particular importance in the calculation of the power coefficient. The reference velocity is cubed in the denominator of this expression and small errors in the reference velocity will lead to errors approximately three times as large in the power coefficient.

Density Correction -- Both the power coefficient, C_p, and the performance coefficient, K, involve the density of the air during the test. The density of air is a function of both temperature and barometric pressure and can vary at a given location by as much as 15%. These variations are generally not sudden and occur over at least a number of hours. Since both C_p and K are nondimensional measures of turbine output, the torque and hence, power produced is a function of density. Therefore it is not consistant to compare actual torque or power for different days without correcting for density variations. To correct for such variations, the measured torque can be normalized to a standard density using the expression,

$$T_{COR} = \frac{T_{ACT} \cdot \rho_{STD}}{\rho_{ACT}}. \tag{3}$$

In this expression ρ_{STD} is a standard density chosen for a particular location. For the VAWT Test Facility in Albuquerque, New Mexico, at an elevation of 1646 m, the density corresponding to a barometric pressure of 830 mb and a temperature of $16^{\circ}C$ was selected as the standard.

A similar correction may be applied to obtain a torque or power reading at sea level. In such a correction, there is a 20% increase in torque between Albuquerque and sea level.

Combining Records. -- In order to obtain an accurate measure of performance of a WECS at a particular location for a specified operating condition, data should be taken for a range of wind regimes which are representative of the site. Such a range of conditions will not be obtained in a short period of testing, and therefore data from a number of different test conditions must be combined. The method of bins allows such records to be combined in a straightforward manner. After each data collection with the WECS, both the torque and wind speed probability density as a function of wind speed are stored in the equivalent of a permanent file in the minicomputer system. These records could also be stored on an external storage medium such as punched cards or punched paper tape. After a number of these data records are accumulated they may be recalled and combined. An averaged torque is computed for each bin weighted by the number of readings in that bin for each record. The probability densities are combined to obtain an overall probability density for the combined record.

When combining torques or any other measure of power, it is important to correct all values to a common density as discussed in the preceding section. Such a combined record of torque provides a useful measure of the average performance of a WECS over a wide range of operating conditions. This description of performance combined with an annual wind speed distribution for a given location provides an estimate of the output which a particular WECS would provide.

Typical Results -- In order to provide a qualitative feeling for typical results obtained with the method of bins, two sets of preliminary performance data for the 17 m VAWT in its two-bladed configuration are presented. The first set of data shown in Figures 2 to 5 are for 11 separate test runs combined using the technique described in the previous section. The combined record consists of 144.236 data points taken at 0.25 s intervals or 10 hours of WECS operation on 9 different days. Figure 2 is the wind speed probability density function of the combined record. Figure 3 is the measured torque at the base of the turbine as a function of wind speed corrected to the centerline of the turbine. Figure 4 is the power coefficient, C_p, as a function of tip-speed ratio, $R\omega/V_R$. Figure 5 is the performance coefficient K, as a function of advance ratio, the inverse of the tip-speed ratio. Figures 6 to 9 are the same plots for one particular test run of about one hour duration. The data from Figures 6 to 9 are used in the following section to provide verification for the method of bins.
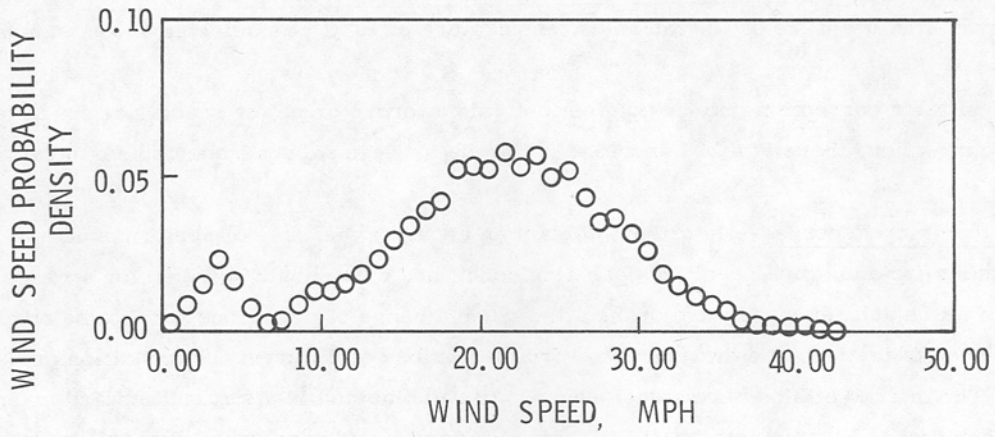
Figure 2.   Wind Speed Probability Desnity (F) - Combined Records
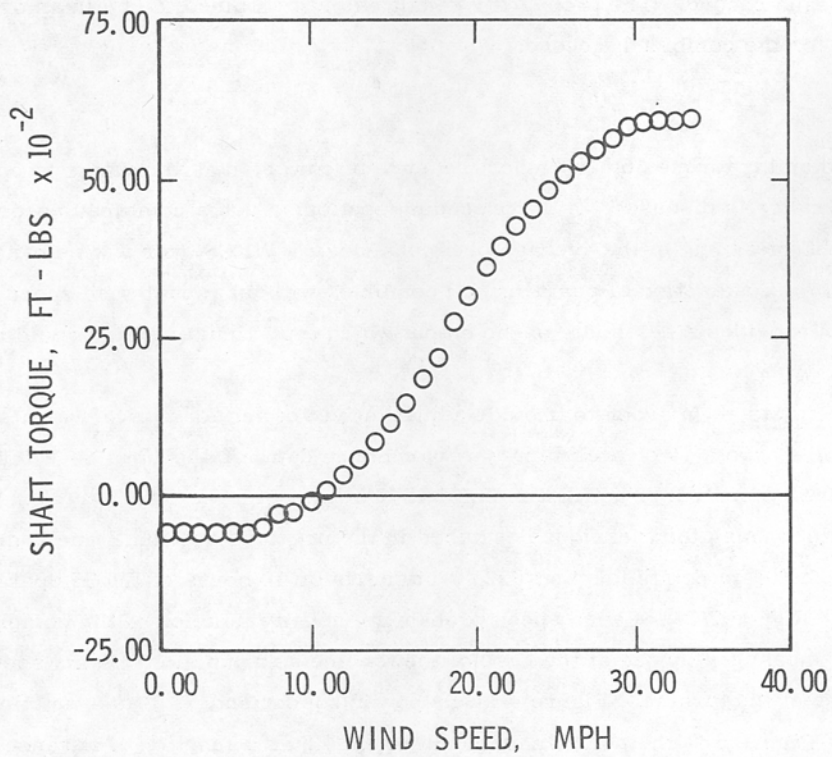

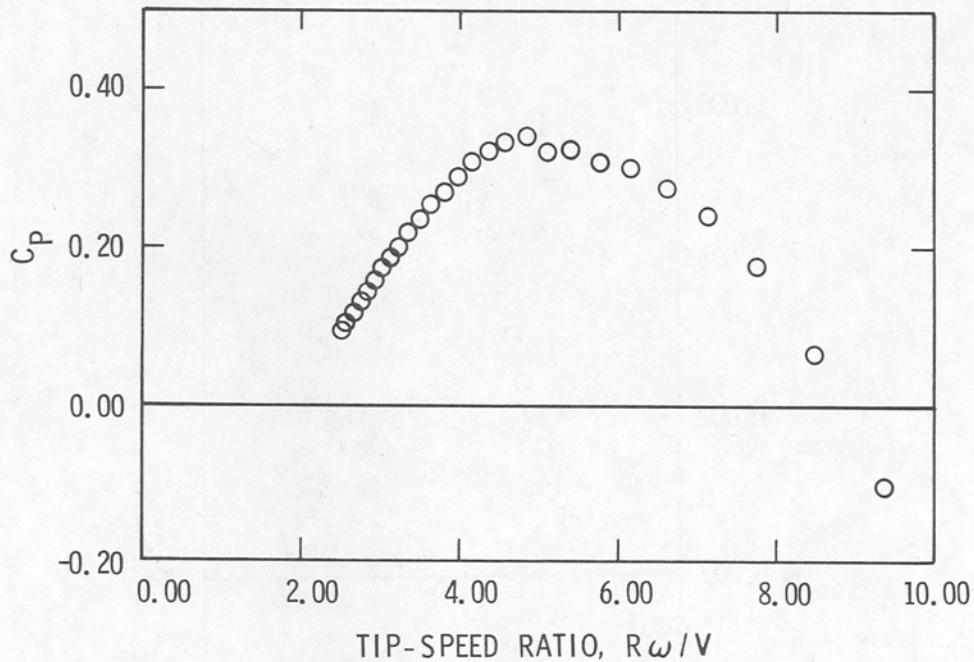Figure 3.   Shaft Torque as a Function of Wind Speed - Combined Records

Figure 4. Power Coefficient as a Function of Tip-Speed
Ratio - Combined Records

The Data from the combined records cover a much wider range of velocities and provide a better definition of the C_p and K curves than do the data from the single run.

III. Verification

In order to develope confidence in the method of bins, a number of approaches to verify the technique have been pursued.

In the initial presentation of the method of bins[1] the repeatability of the performance data was discussed. The fact that the torque or performance coefficient as a function of wind speed was repeatable is not conclusive evidence that the method provides valid results. Consequently additional methods of verification have been investigated as a part of the field testing of the 17 m VAWT.
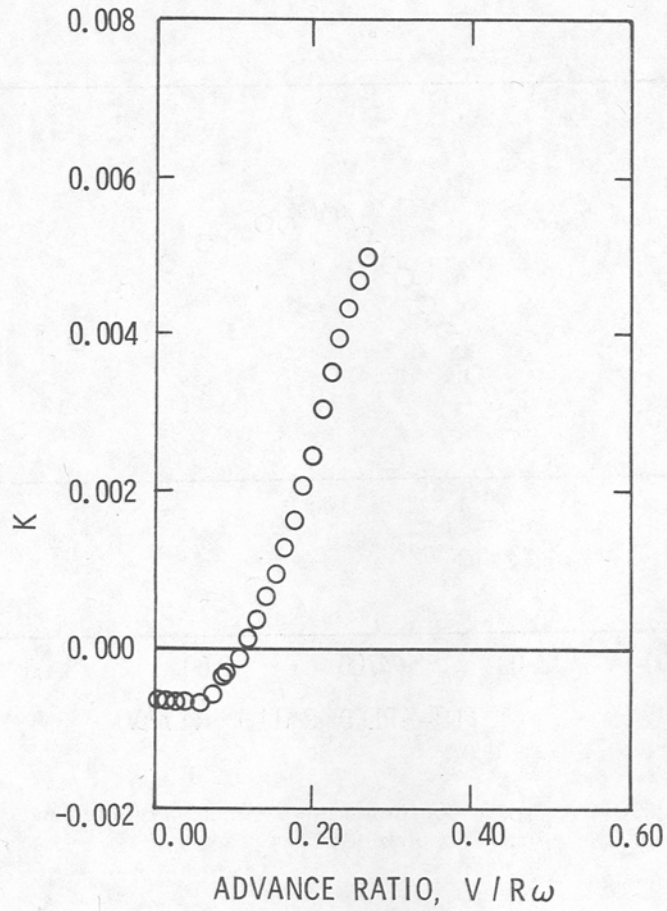
Figure 5.   Performance Coefficient as a Function of Advance
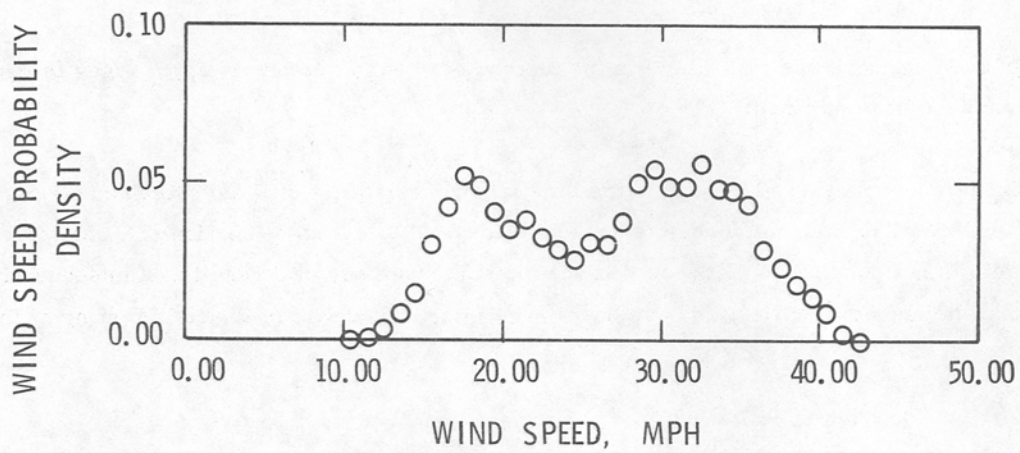Ratio - Combined Records

Figure 6.   Wind Speed Probability Density (F) - Individual Record
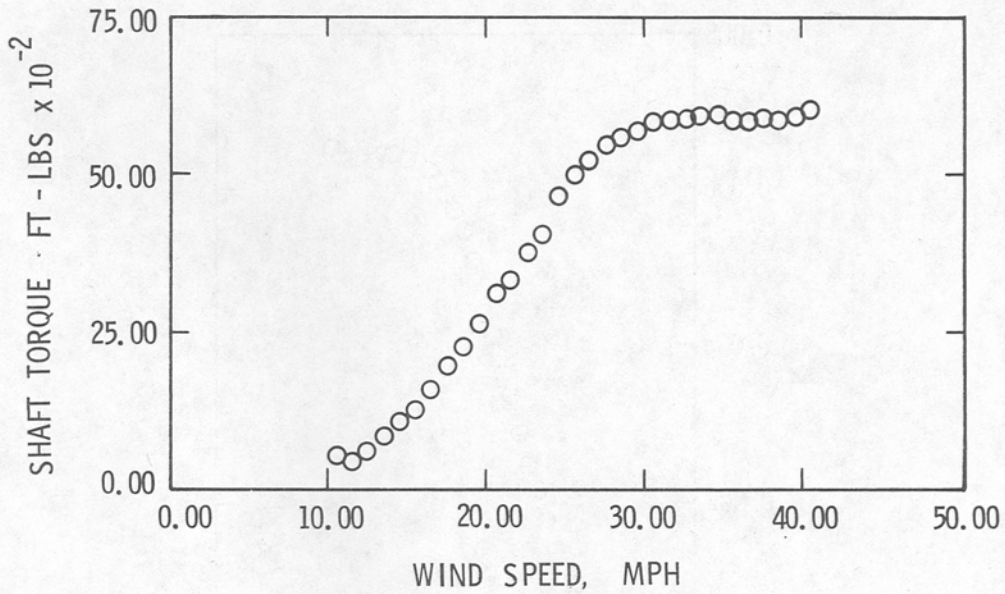
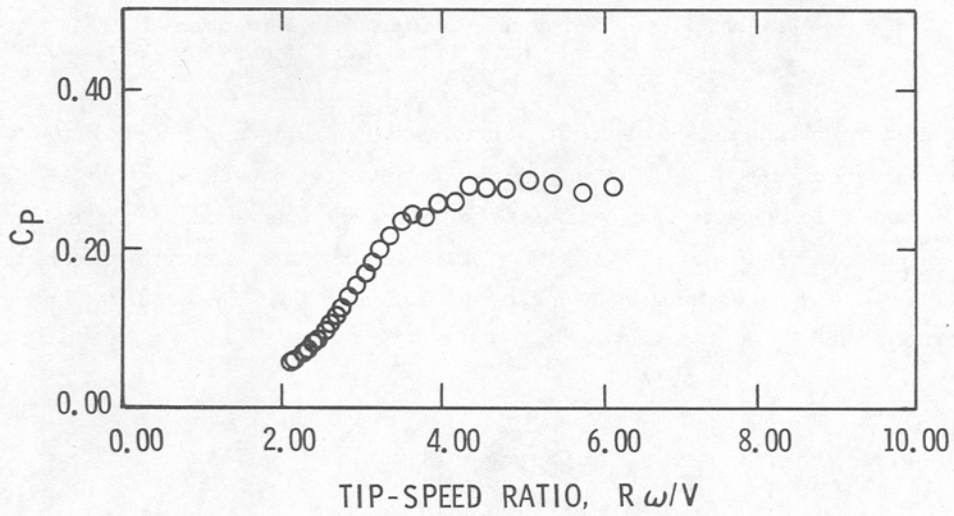Figure 7. Shaft Torque as a Function of Wind Speed - Individual
Record

Figure 8. Power Coefficient as a Function of Tip-Speed
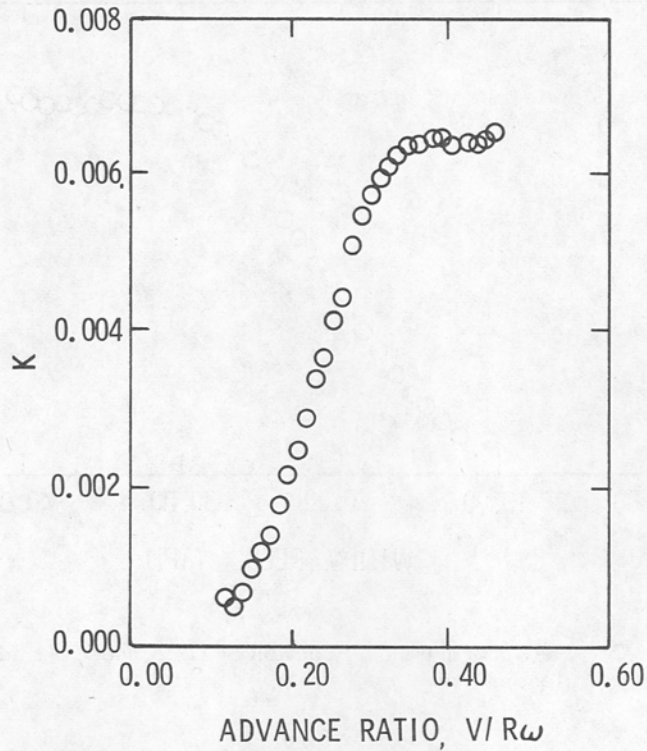Ratio - Individual Record

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Figure 9. Performance Coefficient as a Function of
Advance Ratio - Individual Record

The most promising method verification involves a comparison of the predicted WECS output using a measured wind speed distribution with the actual energy produced by the WECS during the same period. The predicted output is obtained using techniques discussed in Reference 6. This calculation requires a known power or performance coefficient determined from prior testing and the wind speed distribution at hub or centerline height. The predicted energy, E_p, producted in a period T_o is given by

$$E_p \quad \int_o^{T_o} \left[\int_{V_{CI}}^{V_{CO}} F(V) \, C_p(V) \frac{1}{2} \rho V^3 \, dV \right] dt \; . \tag{4}$$

The integral in brackets for a fixed T_o is not a function of time and the expression may be re-written

$$E_p = T_o \int_{V_{CI}}^{V_{CO}} F(V) \, C_p(V) \frac{1}{2} \rho V^3 \, dV \; , \tag{5}$$

where F(V) is the probability density of the wind speed, V_{CI} is the cut-in speed of the WECS, and V_{CO} is the cut-out speed of the WECS.

This value of E_p was compared with the actual energy produced in the same period, E_A. The value of E_A was obtained from a direct integration of shaft torque as a function of time. The C_p used in equation (5) had been obtained from earlier tests. In some cases a reference anemometer located 83 m away from the WECS was used to determine F(V). A summary of verification runs is shown in Table I. The close agreement between the measured and predicted energy production is evidence that the experimentally determined C_p curve is correct. The fact that a C_p curve determined using readings taken at 0.25 s intervals can be used with a wind speed probability density based on 1 minuted averaged speeds is a further indication of the reliability of the performance data obtained using the method of bins. This fact demonstrates that this C_p curve obtained is independent of sampling interval.

<center>IV.   Areas for Continued Development</center>

Even though the present version of the method of bins provides useful performance data, areas remain in which useful development of the technique may be pursued. The technique is presently applied using instantenous values of reference velocity and WECS output. The output of many WECS is periodic and related to the operating rpm. It is possible that the WECS output and the reference wind speed should be averaged over one or two periods of rotation of the WECS. Such an averaging may provide reliable C_p and K curves with less total data collection time than the present technique.

A second area for further study involves the correction of the reference wind speed to provide an accurate measure of the wind speed at the centerline of the WECS. In the current version the instantaneous wind speed 0.6 diameter above the WECS is corrected using the mean vertical wind shear measured at the VAWT test facility. For a 1 to 10 minute average such a correction is valid, but the use of such a correction for instantaneous velocity assumes a perfect correlation between velocity fluctuations at the two locations. For the distances involved there will be a positive correlation between such locations, but the correlation coefficient will be less than 1.0. The averaging which takes place in the process of combining readings into bins accounts for some of this difference, and averaging both torque and wind speed may result in a more accurate vertical shear correction. A similar problem exists if there is a horizontal separation between the reference anemometer and the WECS. Fluctuations in wind speed are not only convected horizontally but are also constantly changing as the dynamics of turbulent flow affect them.

TABLE I

Comparison of Predicted and Measured Energy Production

Run	Anemometer Location	Wind Speed Observation Method	Energy (kwh)		Diff (%)
			E_p	E_A	
1	b	1	51.1	54.3	5.9
2	a	1	28.8	28.8	0.0
2	b	1	28.8	28.9	0.3
2	b	2	28.9	29.8	3.3

Anemometer Location   a - Directly above WECS

b - WECS centerline on tower 83 m away

Wind Speed Observation Method   1 - Instantaneous readings every 0.25 s

2 - 1 minute averages based on 0.25 s readings

Consequently, an instantaneous correction for horizontal wind speed differences contains some error also. Possibly the large number of readings associated with the present form of the method of bins involve sufficient averaging to deal with these inaccuracies. Further studies should address this question.

The maximum horizontal separation between a WECS and a reference anemometer used for performance evaluation should be defined. The need for this information is related to all methods of field performance evaluation, but is also related to applications of the method of bins.

Some measures of the minimum number of points associated with a particular test condition which are required in order to obtain reliable performance estimates must be determined. Such criteria could be applied to determine minimum test durations.

V. Summary

The present form of the method of bins provides a simple yet viable method of performance evaluation of WECS. It is effective for determination of average performance characteristics such as power or performance coefficients. It allows performance data taken at different times to be combined to provide WECS performance characteristics to include a wide range of wind regimes.

Comparisons of predicted WECS output using performance characteristics obtained with the method of bins agree well with actual measured performance. This comparison in addition to prior studies concerning the repeatability of results is evidence that the method of bins is a valid method of evaluating WECS performance.

References

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