PERFORMANCE OF AN ENERTECH 44 DURING 11 YEARS OF OPERATION

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ABSTRACT

An Enertech 44 wind turbine with a 13.4-m rotor diameter was installed in the Southern Great Plains at the USDA Conservation and Production Research Laboratory, Bushland, TX in May 1982 and was operated to assist in providing electricity to a 23 kW irrigation pump motor. The original turbine was a 240 V, single-phase generator with a rated capacity of 25 kW. This prototype unit was changed to a three-phase, 40 kW generator production unit in 1984 and later that year, a three-phase, 480 V generator rated at 60 kW was installed. All three units used the same size rotor and design. The wind turbine has generated power for over 55,700 hours during the 11 years and produced almost 840,000 kWh of electricity. The wind turbine operated for 61.6% of the hours since installation and recorded a capacity factor of 23.4%. Although several component failures occurred during the testing period, the wind turbine had an availability of 97%. The 3% down time was estimated as 1% for routine maintenance and service, 1% for repair of component failures and 1% for weather related events, mainly icing.

INTRODUCTION

Wind electric systems were used extensively during the 1930's and 40's to provide small amounts of electric power in rural areas. These units had DC generators that produced enough power to keep several batteries charged; providing electricity for lights and radio. Rotor sizes ranged from 2 to 5 m and consisted of 2 to 4 blades (Park, 1981). Systems based on these old designs are still manufactured and used mainly for battery charging.

The development of the modern wind turbine began in the late 1970's and the transition from prototypes to production units in the 1980's was rapid with over 10,000 units sold by 1985. Most early prototypes utilized either DC generators or an alternator using a synchronous inverter to make the electricity utility compatible. Machines that use either DC generators or alternators require an external mechanism to regulate rotor speed. This regulation is normally provided by a mechanism to vary the pitch of the rotor blades or to turn the rotor out of the wind. With increased machine size, the variable pitch mechanism became more complicated and costly. In 1978, two manufacturers began using induction motors, operated above synchronous speed, as generators in wind turbines. An induction generator operates essentially at a constant speed with a gearbox between the rotor and generator. The induction generator offered several advantages over the other systems; the main ones being that the pitch control system could be eliminated and that interfacing to the electric utility was greatly simplified (Park, 1981). A disadvantage of the induction generator is that it requires excitation from an external source, usually the utility line. Almost all of the wind electric generators sold today use an induction generator.

The USDA-Agricultural Research Service began experimental studies with wind electric generating systems in 1976 and acquired several prototype machines in the 1978 to 1983 time period. In this paper, we report on the tests results of a wind electric generator acquired in 1982 as a prototype and later converted to a production machine. Daily kWh meter records and a data logger have been maintained on this system since it was installed. Dates when the machine was modified or

TABLE 1. SIGNIFICANT EVENTS DURING THE TESTING OF ENERTECH 44, BUSHLAND, TX, 1982 - 1993

DATE	MONTH	ACTIVITY
May 28, 1982	0	Installed 25 kW
July 1, 1982	1	Began performance testing
February 27, 1984	20	Removed 25 kW
March 20, 1984	21	Installed 40 kW
November 5, 1984	29	Removed 40 kW
November 13, 1984	29	Installed 60 kW
October 27, 1986	53	Removed 60 kW (Tower leg cracked)
February 12, 1987	56	Reinstalled 60 kW
May 13, 1988	71	Removed 60 kW Gearbox (Leaking seal)
July 19, 1988	73	Installed 40 kW Gearbox
July 1, 1993	132	Still running

when significant repair was required are reported in Table 1. Continuous operation of the 25 kW prototype was started on July 1, 1982 and continued until February 27, 1984. The 25 kW prototype was changed to a 40 kW production model with the same rotor size. After 8 months of operation, the 40 kW unit was changed to a 60 kW. Even though the 60 kW unit was the first 60 kW built, only the generator and gearbox were different and all parts were interchangeable with the 40 kW unit. During operation since the 60 kW was installed on November 13, 1984, two significant events required the turbine to be removed from the tower for repair. In October 1987, the up-wind tower leg cracked just below the turbine mounting plate. Three months were required to determine the proper corrective action and secure repair parts. Then in 1988, the front gearbox oil seal began leaking excessively and the turbine was again removed from the tower. At this time we chose to replace the 60 kW gearbox with a 40 kW gearbox to reduce the rotor speed. Each of these events are discussed under the reliability section.

WIND TURBINE DESCRIPTION

The horizontal-axis wind turbine had a 13.4-m diameter, three-bladed, fixed pitch rotor mounted on a 24.4-m free-standing tower. The rotor blades were fabricated from laminated epoxy-wood and attached to a steel hub. The specifications of the wind electric generating system are listed in Table 2. The 25 kW prototype had a single-phase generator operating at 240 V, while the 40 and 60 kW units both had three-phase generators operating at 480 V. The unit was manufactured by Enertech Corporation[1] as a Model 44 (Enertech Corporation ceased operation about 1987).

The wind turbine start-up and shut-down was controlled by a signal from an anemometer located on the tower just below the blade tips. The parking brake held the rotor stationary until the control system determined that adequate wind was available to produce power, then the brake was released and the generator was utilized as a motor to accelerate the rotor to its operational speed. Normally this required about 15 seconds to bring the system from a stopped position to full operational speed. The controller was set to have the wind turbine start when the wind speed averaged 5.4 m/s and to stop when the average wind speed dropped to 3.2 m/s. A high wind speed shut-down occurred when the controller sensed an

[1]Mention of a manufacturer or product name does not constitute a recommendation or endorsement for use by the USDA-Agricultural Research Service, but is given for informational purposes only.

TABLE 2. SPECIFICATIONS OF ENERTECH 44 WIND TURBINE INSTALLED AT BUSHLAND, TX, 1982 - 1993

SYSTEM	
Type	Utility interface
Axis of rotor	Horizontal
Location of rotor (with respect to tower)	Downwind
Number of blades	Three
Centerline hub height	25 m
ROTOR	
Rotor diameter	13.4 m
Rotor type	Fixed pitch
Rotor speed at rated power	53 rpm (25 kW), 57 rpm (40 kW) and 67 rpm (60 kW)
Blade material	Wood/epoxy laminate, fiberglass coat
GENERATOR	
Type	Induction, single-phase (25 kW) and three-phase (40 & 60 kW)
Output voltage	240 V (25 kW) and 480 V (40 & 60 kW)
Frequency	60 Hz
TRANSMISSION	
Type	Triple reduction, helical
Ratio	1:34 (25 kW), 1:32 (40 kW) and 1:27 (60 kW)
YAW SYSTEM	
Yaw control	None, rotates freely 360 degrees
BRAKES	
Normal stops	Dynamic brake
Parking brake	Electro-mechanical, fail safe spring
ROTOR SPEED CONTROL	
Rotor overspeed (Normal operation)	Blades stall in high winds
Rotor overspeed (Emergency)	Control system applied braking
Rotor overspeed (Emergency back up)	Blade tip brakes deploy
TOWER	
Type	Galvanized self-supporting
Height	24.4 m
PERFORMANCE	
Rated wind speed	13.4 m/s
Start-up wind speed	5.4 m/s
Shut-down wind speed	3.2 m/s
Cut-out wind speed	22.3 m/s

average wind speed of 22 m/s or higher for 45 seconds. The controller would not restart the unit until the average wind speed dropped to less than 16 m/s.

The data logger monitored the wind speed, wind direction, electrical power, air temperature, and barometric pressure at a rate of one Hertz and averaged the data over five minutes. Also, these data were averaged and recorded on a hourly and daily basis, thus producing three different data tables for each day. In addition to these computerized data, daily recordings were made each morning of the run-time hours, number of starts, electrical energy produced by the wind turbine, and electrical energy purchased from or sold to the utility. At other times during the 10-year period, data were recorded at 15-sec averaging intervals with data being sampled at 5 Hz. Power curves were developed using the high frequency data, while daily data were used to determine annual or monthly performance.

RELIABILITY

The wind turbine did experience several failures and problems during the testing period. Remembering that the 25 and 60 kW units were both prototypes and the 40 kW was an early production unit, these units performed well. The significant down-time events are summarized in Table 3. A significant down-time event was selected as having an off-time in excess of 100 hours. Most repairs and routine maintenance would not be included in this list.

All major down-times connected with the 25 kW generator were concerned with the controller and in particular the rotor rpm sensor that was used to engage the electric generator. Details of the performance and reliability of the 25 kW system were reported by Vosper and Clark (1985a). The rpm sensor was eliminated in the 40 and 60 kW designs. On February 27, 1984, a blizzard roared through Bushland causing numerous electric power outages. The wind turbine stopped and started 11 times during a 3 hour period. During one of those periods, the rotor shaft failed and the entire rotor crashed to the ground. The new 40 kW wind turbine was already at Bushland and a crane had been scheduled for the next day to

TABLE 3. DOWNTIME IN EXCESS OF 100 HOURS DURING TESTING OF ENERTECH 44, BUSHLAND, TX, 1982 - 1993.

DATE	MONTH	PROBLEM	HOURS
December 29, 1982	6	Broken control relay	130
February 11, 1983	8	Rotor rpm sensor failure	166
August 29, 1983	14	Rotor rpm sensor failure	204
February 27, 1984	20	Rotor shaft failure	530
November 5, 1984	29	Replaced 40 kW with 60 kW	192
August 20, 1985	38	Tip brake deployment	211
October 27, 1986	53	Cracked tower leg	2592
January 5, 1988	66	Ice on rotor blades	118
May 13, 1988	71	Gearbox seals leaking	1595
December 21, 1990	102	Ice on rotor blades	156
March 12, 1991	105	Tip brake deployment	151
June 29, 1992	120	Replacement of parking brake pads	168
January 8, 1993	127	Ice on rotor blades	122

change the turbines. Failure resulted from an improper lathe cut on the rotor shaft and all three prototype 25 kW wind turbines experienced similar failures. Unfortunately, we were not able to remove the unit before failure.

The original 40 kW unit ran for 8 months without any down-time except for service. It had an availability of 99.9% during the period (Clark and Vosper, 1984). The prototype 60 kW unit, installed immediately after the 40 kW unit, operated for 9 months before problems developed with the tip-brakes. The internal spring mechanism that controlled the tension on the tip-brake would not stay adjusted, thus allowing early deployment of one tip-brake. A new mechanism was installed in August 1985 on all three tip-brakes.

In October 1986, 4.5 years after installation, a 5-cm long crack developed in the up-wind tower leg just below the top mounting plate. Similar cracks were found on this manufacturer's wind turbines located in the wind parks in California. After careful study by several groups, it was concluded that the crack was caused by loads translated from the free yaw movement of the rotor. Several "fixes" were suggested and we chose to replace the top tower section legs (schedule 40 pipe) with schedule 80 pipe. This was done and the turbine was returned to service 4 months after locating the crack. There were 22,437 operating hours on the tower when failure occurred.

The turbine has been shut off for extended periods at three times because of ice on the rotor blades. Two of these occurred in January and one in December. Each occurrence involved a week-end when the ice thawed and no one was available to restart the machine until Monday. Ice often causes the rotor to loose its airfoil shape and the system operates as giant fan; using electricity rather than producing power. Other icing events have caused shut-downs of less than 100 hours.

The machine was removed from the tower to replace the leaking seals in the gearbox and while we were repairing the gearbox, the gear ratio was changed to the same one as used in the 40 kW systems to reduce the rotor speed. Since July 19, 1988, the wind turbine has operated as a 40 kW unit. An additional tip-brake mechanism modification was required to strengthen the spring to avoid unwanted releases. Also in June 1992, the parking brake pads were replaced after a broken brake wire in the twist cable caused the brake to engage while the machine was operating.

Overall availability for the wind turbine has been 97% during the total period. About one-third (1%) of this down-time is attributed to icing and other weather related events, another one-third (1%) to repair of component failures, and an estimated 1% of the time for routine maintenance and servicing. This machine has operated extremely well as a new technology prototype and has demonstrated manufacturers ability to choose good component products.

PERFORMANCE DATA

The annual average wind speed during the 11 years was 5.71 m/s measured at the 10-m height. The wind speed at hub height (25 m) was calculated to average 7.1 m/s, about 25% higher. The total run hours for each month are presented in Figure 1. During the 132 months reported by these data, the turbine was in operation for 125 complete months. The four dips in this curve show the time the turbine was removed from the tower, either to replace the generator with a different size, or to repair the tower. These replacement or repair dates are listed in Table 1. The other dips in the curve can be identified with significant off-times as listed in Table 3. It is interesting to note that the 60 kW ran fewer hours, months 29 to 71, than either the 25 or 40 kW units. The wind turbine averaged running about 5400 hours per year or 61% of the time. Total number of hours in operation during the 11 years was 55,716 hours.

The monthly energy generated by the wind turbine is shown in Figure 2. Again the four times the turbine was removed from the tower are clearly shown; however, other down-times show their impact in this chart. During the period 1 to 20 months, the results from using the smaller 25 kW generator is seen; however, the influence of the 60 kW generator is not clearly shown during months 29 to 71. The turbine produced 839,699 kWh during the 11 years and averaged 6,700 kWh per month or about 80,000 kWh per year.

As a comparison of the three generator configurations studied during the operation of this wind turbine, 20 months of similar data were selected for each generator type and the energy production and hours of operation were compared. The cumulative hours for 20 continuous months of operation for the three generator configurations are shown in Figure 3.

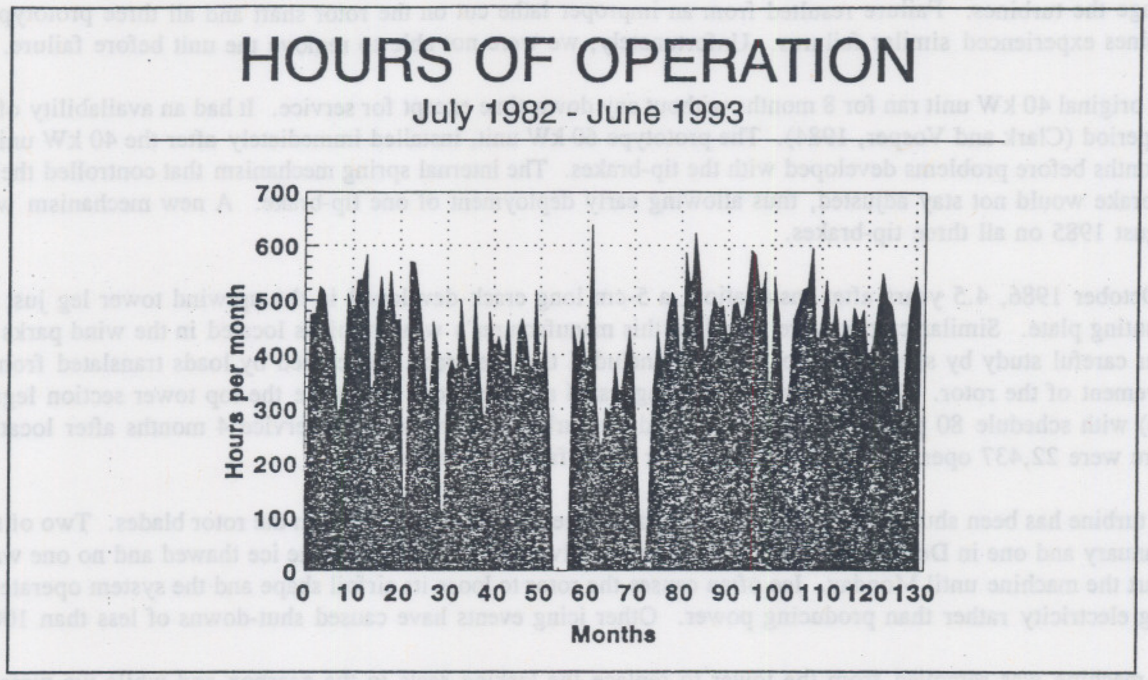

FIGURE 1. MONTHLY HOURS OF ACTUAL ON-LINE TURBINE OPERATION.

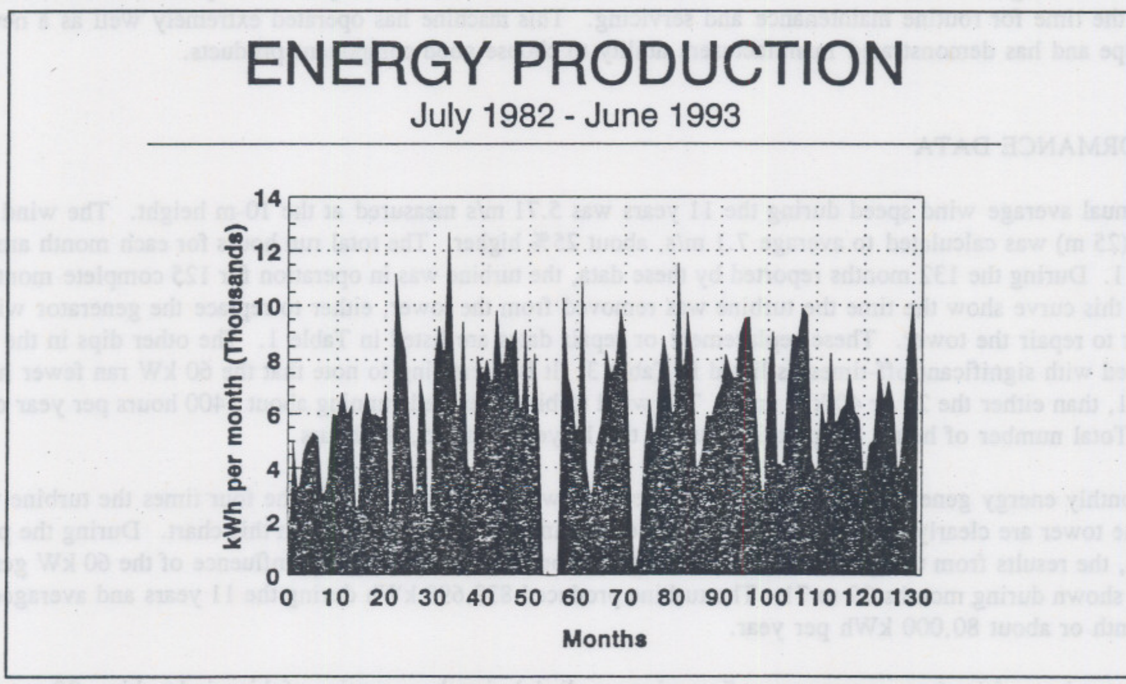

FIGURE 2. MONTHLY ENERGY (kWh) PRODUCED BY THE WIND TURBINE.

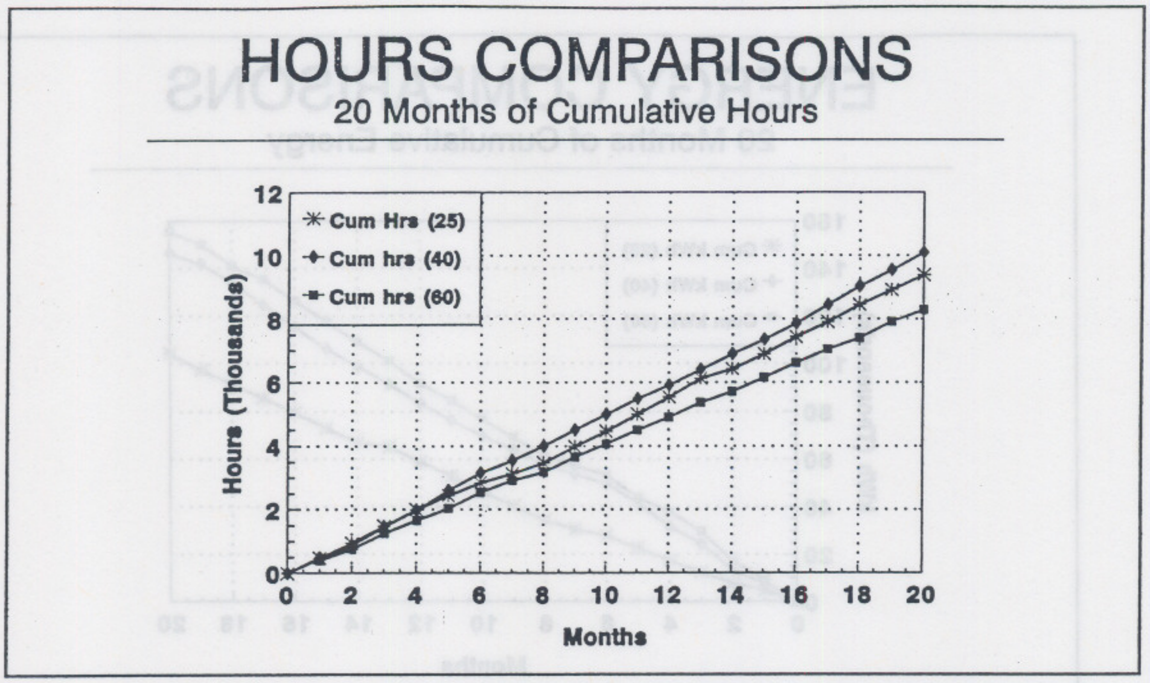

FIGURE 3. CUMULATIVE MONTHLY RUN-HOURS FOR 20 CONSECUTIVE MONTHS FOR EACH SIZE GENERATOR.

Notice that the 40 kW generator ran more total hours than either the 25 or 60 kW. When comparing the energy produced (Figure 4), the 40 and 60 kW generators clearly out produced the 25 kW, but the differences between the 40 and 60 kW were not significant. Since these data were collected at different times and the average wind speed were not exactly the same, the differences could have been reduced because of wind speed. However, all data presented show that the 60 kW generator does not exhibit a clear advantage over the 40 kW. Actually, an optimum generator for this 13.4-m rotor may be 50 kW rather than the 40 or 60 kW studied (Vosper and Clark, 1985b).

Power curves were determined for each configuration of the wind turbine during the 11 years using measured hub-height wind speeds. The three power curves for 25 kW, 40 kW, and 60 kW operation are shown in Figure 5. In each case, the machine reached or exceeded its rated power at a wind speed of 13.4 m/s. Two significant features of these power curves are the point where power is first produced, and how the 40 kW and 60 kW curves follow closely until they diverge when the wind speed exceeds 11 m/s. Although the 60 kW generator produced more power at high wind speeds, it didn't necessarily operate the same number of hours. The 25 and 40 kW generators both produced about 5 kW at a wind speed of 5.5 m/s while the 60 kW was just beginning to produce power. This feature becomes significant because of the large number of hours the wind blows at that speed. The effect of the difference in starting wind speed is clearly shown by the efficiency (power coefficient) curves (Figure 6). The power coefficient is the ratio of the actual power produced at a given wind speed to the theoretical power available at that wind speed. Although there is significant differences between the 40 and 60 kW power curves at higher wind speeds, these curves are not too different at wind speeds between 7 and 11 m/s; where most of the wind power is produced by turbines located in the US Great Plains.

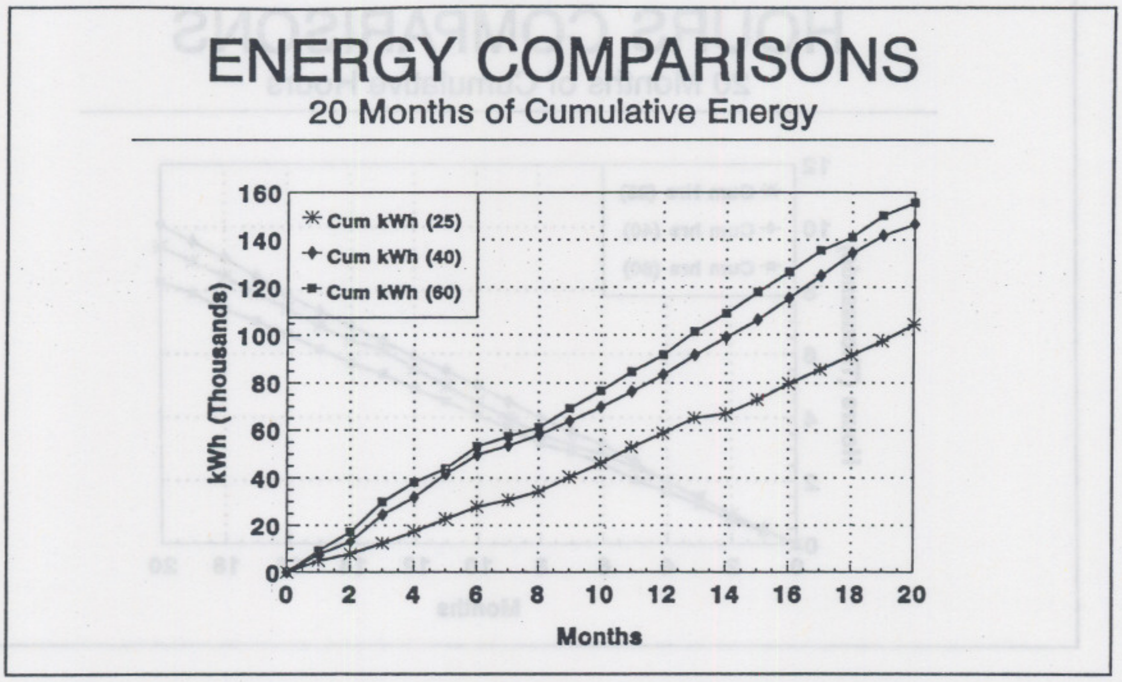

FIGURE 4. CUMULATIVE MONTHLY ENERGY (kWh) PRODUCED FOR 20 CONSECUTIVE MONTHS FOR EACH SIZE GENERATOR.

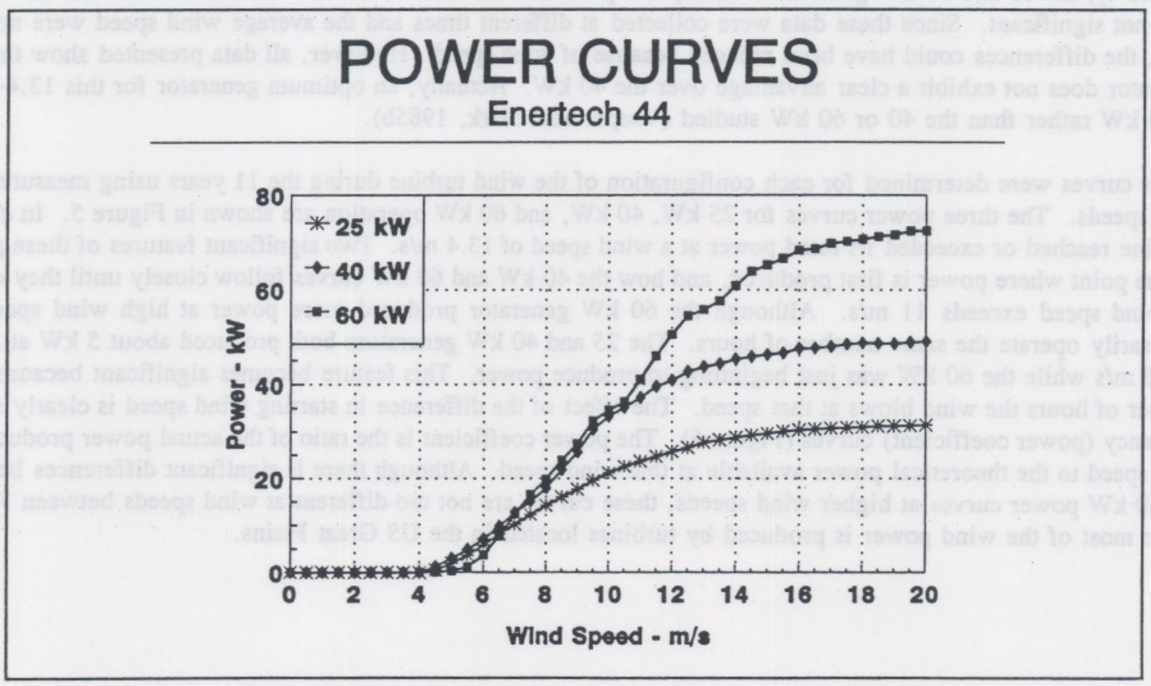

FIGURE 5. MEASURED POWER CURVES FOR EACH GENERATOR TESTED. THE POWER WAS CORRECTED TO STANDARD DENSITY AND THE WIND SPEED WAS MEASURED AT 25-m, HUB HEIGHT.

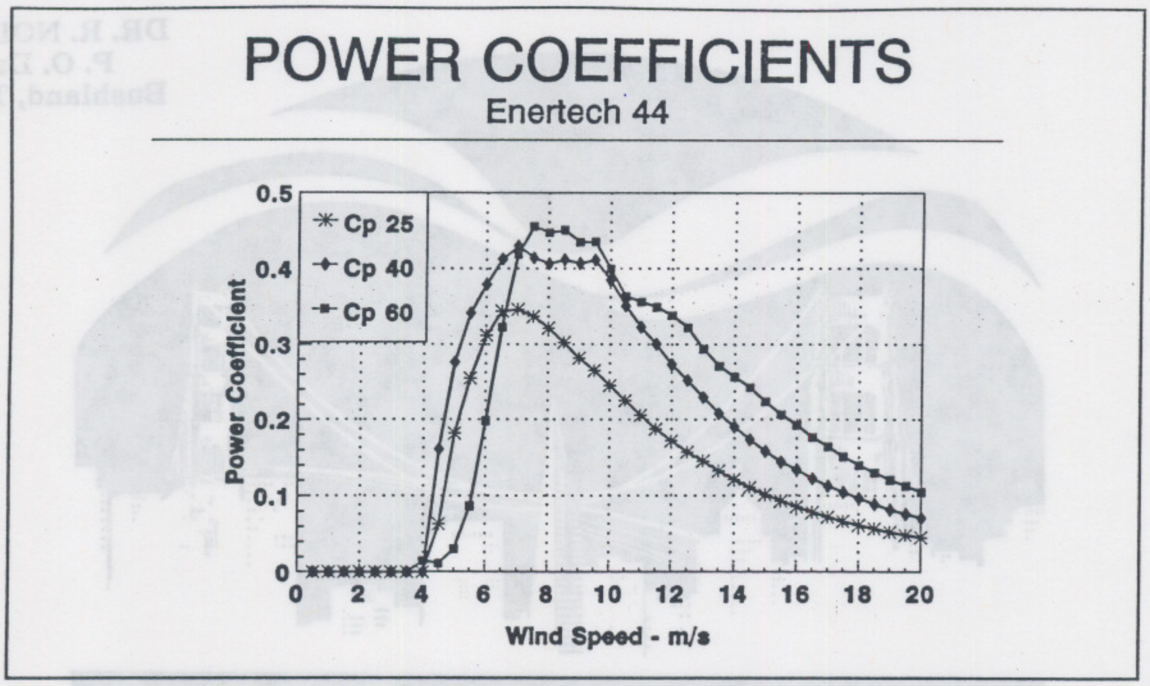

FIGURE 6. THE POWER COEFFICIENT OF THE WIND ELECTRIC GENERATORS AS DETERMINED BY THE RATIO OF ACTUAL POWER TO THEORETICAL POWER.

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