

# WIND ENERGY – A RENEWABLE ENERGY OPTION

by

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## BACKGROUND

As part of the solar energy developments, the Federal Government is sponsoring a five-year program to determine the feasibility of wind energy as an alternate energy source. This program is being sponsored by the Energy Research and Development Administration (ERDA), and assisted by several governmental agencies and ERDA laboratories. NASA-Lewis Research Center has been designated as the cognizant government agency to develop certain research and technology activities associated with large horizontal axis systems. After a brief background description of previous wind turbine systems that have evolved over the centuries, ERDA's Five Year Development Plan, certain aspects of the national and regional assessment of wind availability and potential applications, and the NASA/ERDA hardware programs will be discussed, as well as a brief description of what can be expected in the future.

The capture and conversion of wind power has played a vital and important role in the history of mankind, from very simple devices, categorized as vertical axis systems, used for pumping water and milling grain (Fig. 1). These devices have evolved through to the typical wind-mill dominant in the farm scene in the early 20th century. One of the first large experimental machines which can be considered in today's class of electric generating systems was a 100 kW wind turbine built in 1931 by the Russians. It was located at Balaclava near Yalta on the Black Sea. Although primitive in its construction, it provided power to Sevastopol about 20 miles away. Based on the technology pioneered in this time frame, we expect that the Russians have further pursued the implementation of similar wind turbine generators for farm and other applications. As a commercial R&D activity started in 1934, the S. Morgan Smith Company of York, Pennsylvania, began the pioneering of the largest system known at that time, the Smith-Putnam Machine. Its capacity was 1.25 MW, operated intermittently over a period of 4 years until in 1945 an overstressed blade failed. Some serious consideration was given to a multirotor system in 1951, but because it could not be proven to be economical, the idea was scrapped.

Several other successes have been achieved in Europe, primarily with two and three bladed machines in the 100 to 200 kW sized range (Fig. 2). Most of these systems similarly have been abandoned because of lack of economics with the low-cost of competing electricity.

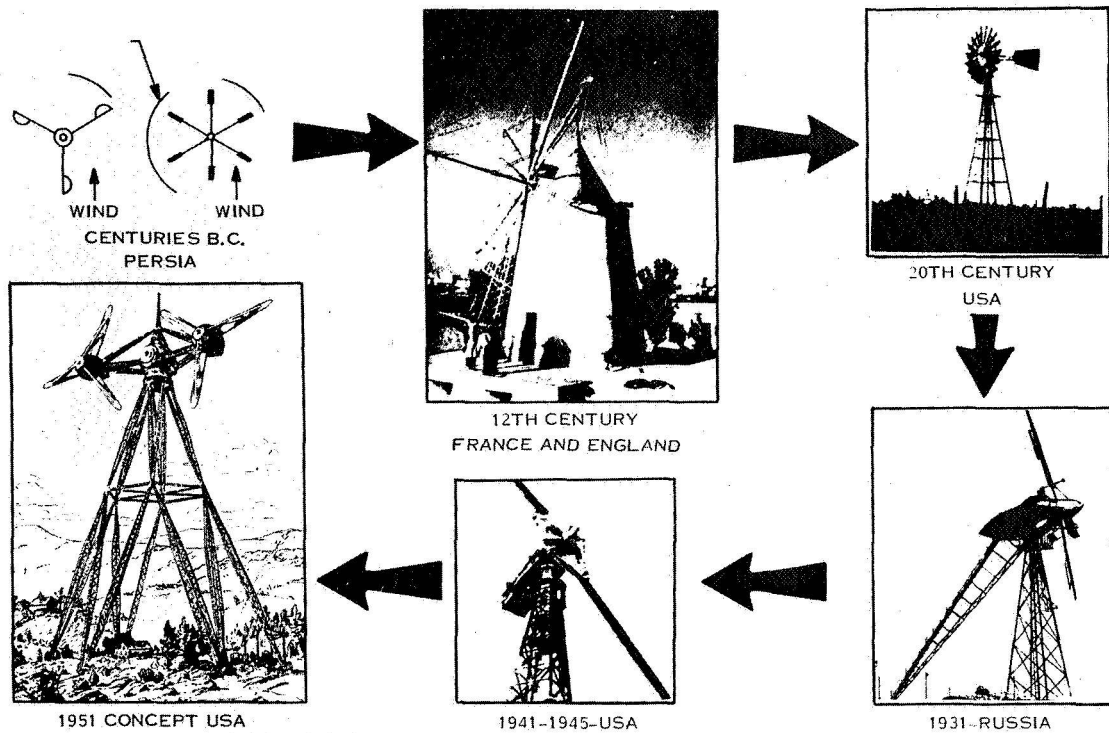


Figure 1. Wind power evolution.

<u>PERIOD</u>	<u>LOCATION</u>	<u>TYPE</u>
CENTURIES B.C.	PERSIA	VERTICAL AXIS
12TH CENTURY	FRANCE/ENGLAND	HORIZONTAL AXIS
18TH CENTURY	USA	HORIZONTAL AXIS
1890	DENMARK	HORIZONTAL (5-25 kW)
20TH CENTURY	USA	HORIZONTAL – FARM TYPE (5-25 kW)
1931	RUSSIA	HORIZONTAL – 2 BLADE (100 kW)
1941-45	USA	HORIZONTAL – 2 BLADE (1250 kW)
1950's	ENGLAND	HORIZONTAL – 2 BLADE (AIR) (100 kW)
1957	DENMARK	HORIZONTAL – 3 BLADE (200 kW)
1950's	FRANCE	HORIZONTAL – 3 BLADE (130-300 kW)
1960's	GERMANY	HORIZONTAL – 2 BLADE (100 kW)
1975	USA	HORIZONTAL – 2 BLADE (200 kW)

Figure 2. Successful wind conversion devices.

Although the Smith-Putnam machine (Fig. 3) located at Grandpa's Knob near Rutland, Vermont, was considered a technical success, it was not successful economically. Much of the development, however, and the findings achieved on this large system provided a good base for ERDA and NASA engineers. To this period, it was physically the largest machine ever built and tested. The tower was 110 ft high and the rotor was 107 ft in diameter and had an 11 ft 4 in. cord. Blade pitch was adjustable so that constant generator speed could be maintained. This rotational speed was maintained in winds as high as 70 to 75 mph. The rotor turned an ac synchronous generator that produced 1250 kW of power at wind speeds greater than 30 mph. This power was fed into the power company network.



Figure 3. Smith-Putnam machine located at Grandpa's Knob near Rutland, Vermont.

## ERDA WIND DEVELOPMENT PROGRAM

The Federal Wind Energy Program was initiated in FY74 as a modestly funded activity under the auspices of the National Science Foundation. The program has grown rapidly and in January 1975 was transferred to the then newly formed Energy Research and Development Administration (ERDA). To pursue the development of wind energy, a number of parallel activities were initiated to address the many questions existing at the initiation of the program. These activities were developed to address certain areas of more than one project in order to provide comparative results and to furnish a measure of uncertainty. The major highlights of the ERDA Five Year Development Plan (Fig. 4) were covered, including economic assessment, technology, and system studies that are leading to hardware development programs.

To establish a solid base for pursuing the technical and economic feasibility of developing wind energy, the steps of pursuit are carefully segregated but yet interrelated. The early studies and technology developments are now evolving through hardware development and demonstration systems. These systems will be tested to assure performance acceptability within the applications for which they are being developed. Following the successful demonstration and test phase, ERDA will assist industry in developing the tools necessary to fulfill commercialization and marketing goals.

Several studies regarding the national and regional applications of wind turbine generators are projected to continue through mid-1978 (Fig. 5). Because of the high investment required at the early stages of the developmental program, an incentives investigation is underway to determine such aspects as tax refunds, capital investment incentives, etc., for consideration by Congress for ultimate implementation of wind energy systems. Technology studies which include better understanding of wind characteristics (gusting and wind availability), as well as hardware (mechanical and electrical), are being studied. The hardware demonstration program also currently underway is designed to prove the feasibility of certain system sizes and will hopefully culminate in the definition and design of systems that will be available for commercial implementation in the early to mid-1980's. Within each of these large-scale demonstration program categories, advanced systems such as a vortex machine, diffuser augmentation, and vertical axis rotors are continuing at a fairly low level. It is possible that these systems could be developed as hardware in the early 1990's.

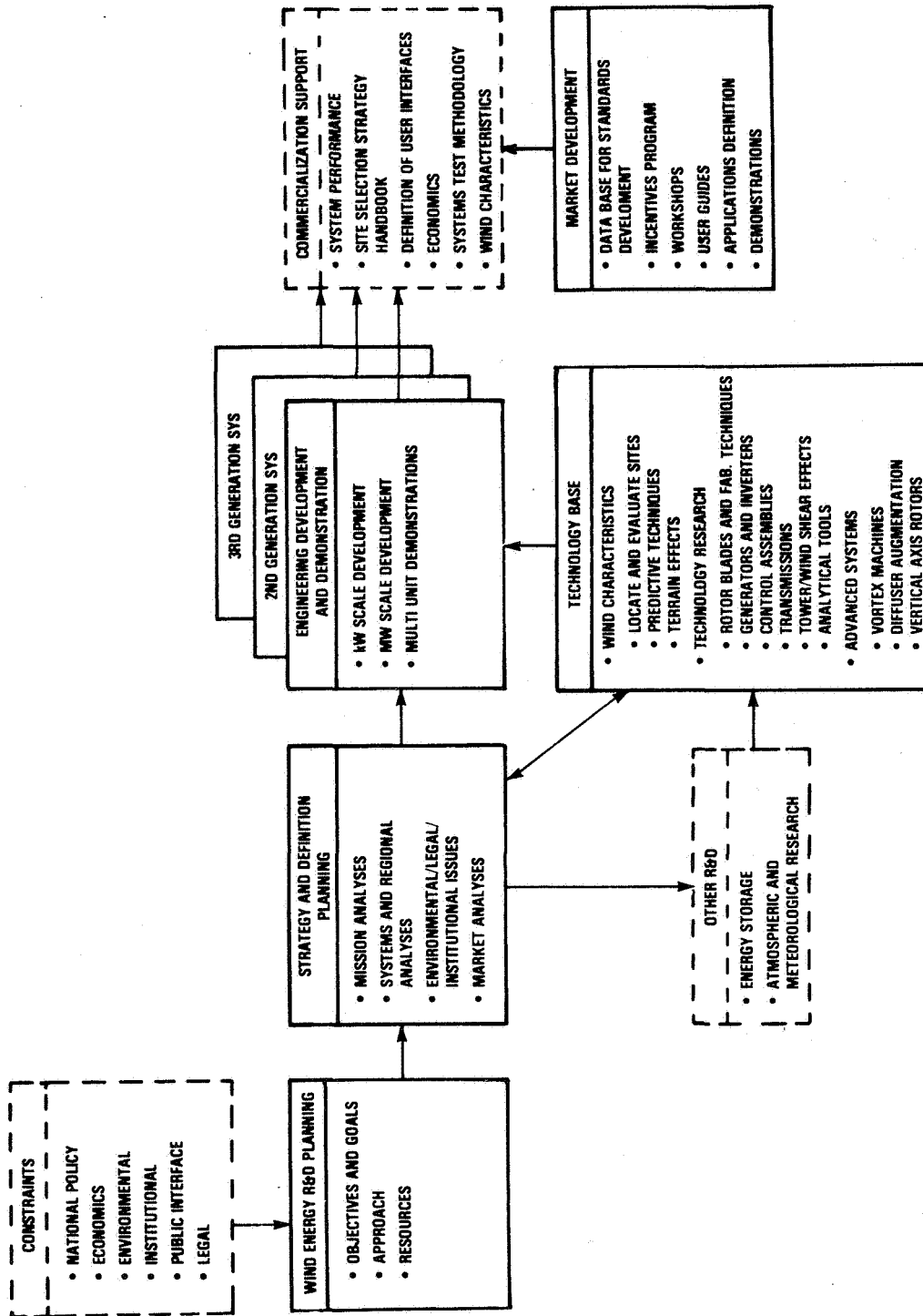


Figure 4. The ERDA wind development program.

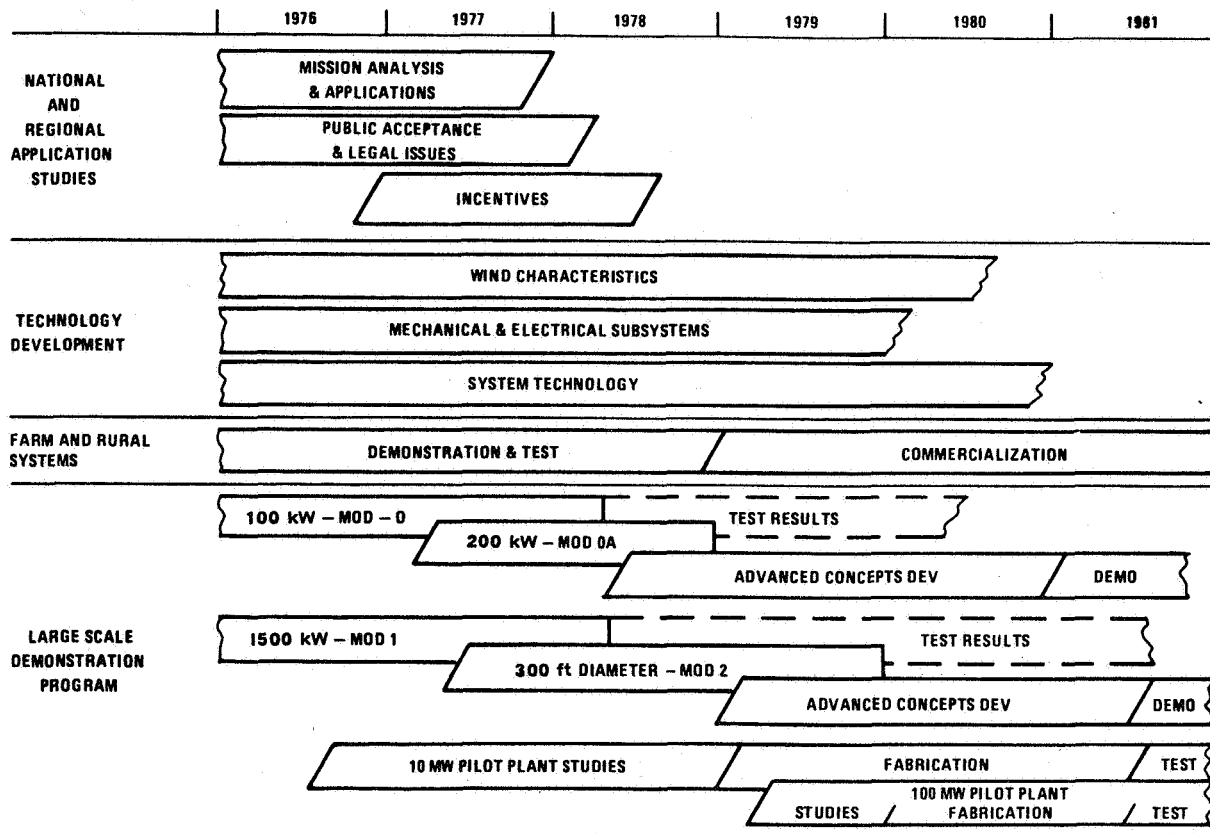


Figure 5. The ERDA Development Program.

Figure 6 shows a comparison of current wind turbine generator program developmental activities [such as MOD-OA (200 kW), MOD-1 (1500 kW), and MOD-2 (2000 to 3000 kW)] with respect to the current state-of-the-art in aircraft development. It's interesting to note that the MOD-2 blade span is almost as large as the "Spruce-Goose" developed by Hughes several years ago.

In anticipation of the hardware demonstration programs being developed, ERDA has selected 17 utilities in sites located throughout the U.S. for initial demonstration system installations (Fig. 7). The first 200 kW MOD-OA uprated versions of the first NASA installed unit at Plumbrook will be sited at two of these locations. The site at Clayton, New Mexico, has already been selected for the first installation of MOD-OA. The next two units, 1500 kW MOD-1 systems being developed by the General Electric Company at their Valley Force Space Division, will be installed at two of the other locations yet to be selected.

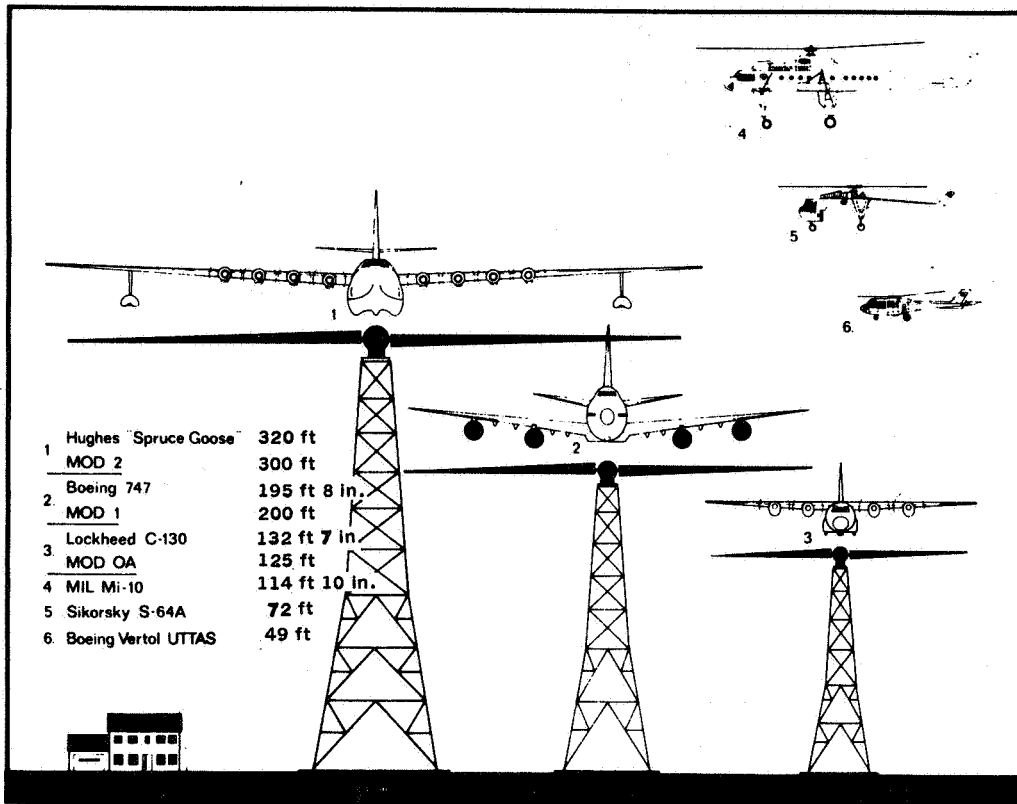


Figure 6. Wind turbine size comparison.

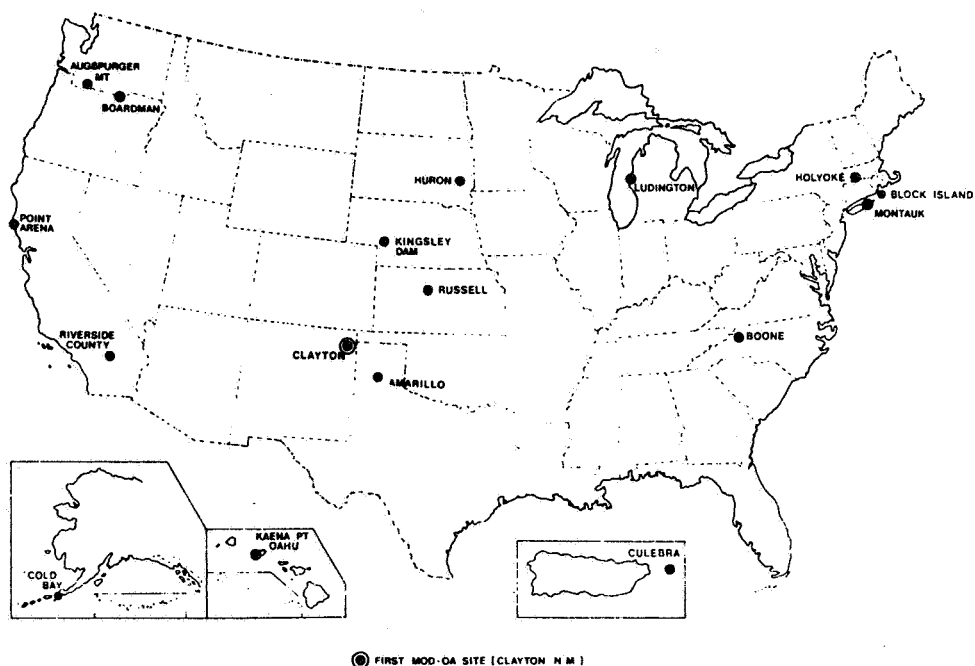


Figure 7. Seventeen candidate wind turbine generator field-test sites.



These sites selected by ERDA for further wind evaluation and test will be instrumented with towers and instruments for the purpose of collecting wind data prior to final system configuration (Fig. 8). Data will be collected on wind velocity, gusting, shifts, and lulls, which will ultimately be used to determine value of each site for wind energy conversion effectiveness. Meteorological towers 160 ft high have been erected at the sites and instrumented at two levels to sense wind direction and speed. These towers will define wind gusts (wind direction and velocity). Instruments will be located at two levels, 30 ft and 150 ft above the ground. The data will be collected and reduced for analysis and distributed to interested centers on a monthly basis. These data will be compared with existing records of wind data collected over a 20 year period by local weather stations to determine relative consistency. Each site will be independently evaluated as to its suitability for types and sizes of wind turbine generator test installations. Additional evaluation factors include topography (to determine ease of installing large wind turbine generators), the nature of the utility power grid interconnection and loads, and the overall capability and value of the wind turbine test and evaluation program following installation of the system. Sites will be selected sometime this year for installation of the remaining MOD-OA and the MOD-1 wind turbine generators.

- WIND DATA COLLECTION
  - 160 FT METEOROLOGICAL TOWERS
  - WIND SPEED AND DIRECTION SENSORS
  - DATA REDUCTION AND DISTRIBUTION
  - DATA COMPARISON - 20 YEAR WEATHER STATION DATA
  
- OVERALL EVALUATION
  - WIND CHARACTERISTICS SUITABILITY
  - TOPOGRAPHY
  - POWER INTEGRATION
  - WIND TURBINE TEST AND EVALUATION

Figure 8. Test site instrumentation and evaluation.

## NATIONAL AND REGIONAL WIND ASSESSMENT STUDIES

General Electric Company's Space Division has been a major participant in ERDA's Wind Energy Development Program since its inception early in 1975. A comprehensive assessment of wind availability and potential applications on a national scale was conducted in parallel with a similar study performed by the

Lockheed-California Company in Burbank, California. These studies (Fig. 9) are being augmented by additional, more in-depth determination of the economic and technical impact of large scale implementation of wind energy conversion systems into utility sectors.

- WIND CHARACTERISTICS AND AVAILABILITY
- WIND ENERGY APPLICATIONS
- ECONOMICS
- PUBLIC ACCEPTANCE
- RESOURCE BARRIERS
- STORAGE CONSIDERATIONS
- TECHNICAL BARRIERS
- IMPLEMENTATION SCENARIOS

Figure 9. National and regional wind assessment studies.

The purpose of these studies is to ultimately prove the wind energy potential as an economic, viable, alternate energy source. These factors are being investigated both at the national scale and in more depth for individual regional applications. To identify a clear path for economic implementation once the technology problems have been resolved, selected results of some of these studies which indicate the direction in which the wind development program is proceeding will be discussed. No major concern has been established with public acceptance and availability of raw materials and resources to implement at an appropriate rate. Storage, unless in the form of already existing hydroelectric dams, has not been considered economic through and beyond the year 2000.

For purposes of convenience, wind availability has been categorized at three different levels (Fig. 10): high — measuring annual mean wind power availability of 7 MW hr/m<sup>2</sup>/yr and above; moderate — 4 to 7 MW hr/m<sup>2</sup>/yr; and low — 2 to 4 MW hr/m<sup>2</sup>/yr. These categories generally have relative commonality with average annual mean wind speeds of: high — 18 mph and above; moderate — 14 to 18 mph mean wind speed; and low — 14 mph and below.

The wind availability map (Fig. 10) was prepared by using several sources of wind data (Fig. 11). The basic source was the Sandia surface wind data which exists for the entire U.S., collected from the weather stations and similar sources. To provide meaningful power potential measured at a 50 m height (which is the elevation of the hub center line above the ground), additional

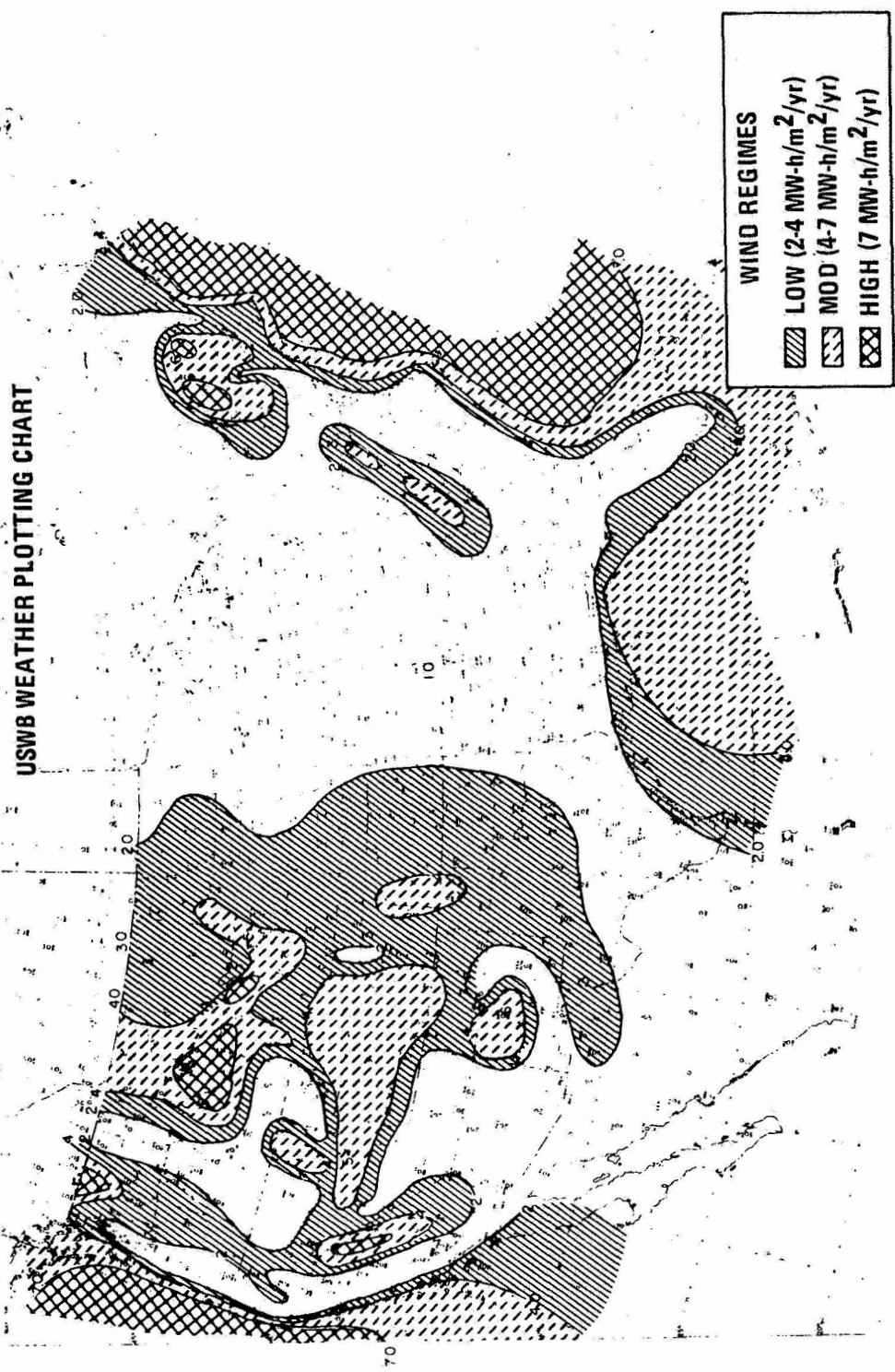


Figure 10. Wind energy regimes (at 50 m).

- |  |
|--|
| <p><b>NATIONAL</b></p> <ul style="list-style-type: none"> <li>● SOURCES <ul style="list-style-type: none"> <li>– SANDIA SURFACE WIND DATA</li> <li>– METEOROLOGICAL RAWINDSONDE DATA</li> <li>– UPPER WIND DATA</li> </ul> </li> <li>● INTEGRATION AND INTERPOLATION</li> <li>● CORRELATION WITH MEASURED DATA</li> </ul> <p><b>SITE RELATED</b></p> <ul style="list-style-type: none"> <li>● DECENNIAL CENSUS DATA</li> <li>● TOPOGRAPHIC SITE SURVEYS</li> <li>● INSTRUMENTATION ON TOWERS</li> <li>● CORRELATION WITH MEASURED AVERAGED DATA</li> </ul> |
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Figure 11. Wind availability assessment.

source data were required. All source materials were integrated to interpret the high, moderate, and low wind areas shown on this map. Certain high elevation locations were correlated with actual measured data. This map, therefore, shows those geographical areas with high probability of having wind conditions within the high, moderate, and low regimes. The regional studies are further taking into consideration the topography of land and additional more detailed decennial census data. Because of varying local conditions, certain wind characteristics may vary from the national assessment. These data will be measured on towers and correlated with measured average data to provide specific regional wind characteristics.

Since the power density of wind (Fig. 12) that can be derived from the wind increases by the cube of the wind speed, it is important that those sites having a high annual mean wind speed be considered first for economic reasons. Power is measured in watts, kilowatts, or megawatts per area of the swept wing-span and is directly related to the area of the wind-disc or the area measured by the blade diameter.

Once a site or region has been selected as a candidate, wind characterization and wind data will describe the "footprint" of that particular site. This "foot-print" is described by a power duration curve (Fig. 13) specific to that site. The shaded area within a typical high wind regime represents the available power for electrical conversion over a 1 year period of time. The large area below the shaded area represents lost power because the wind machine is not capable of producing power at velocities below that level and is turned off. The system designer of wind turbine generators uses this curve to determine the

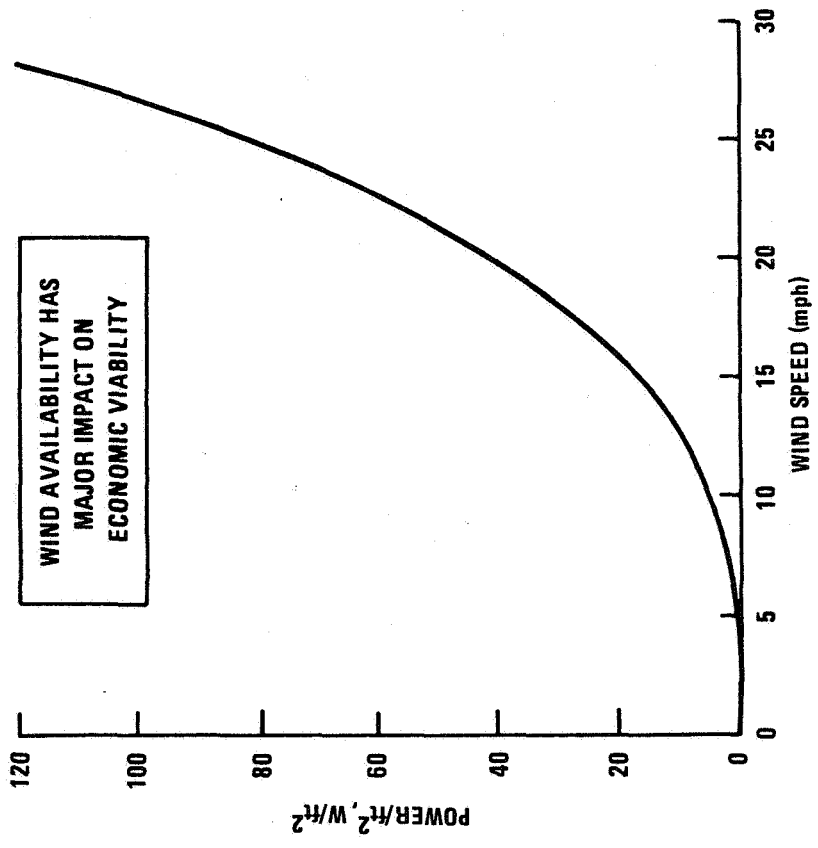
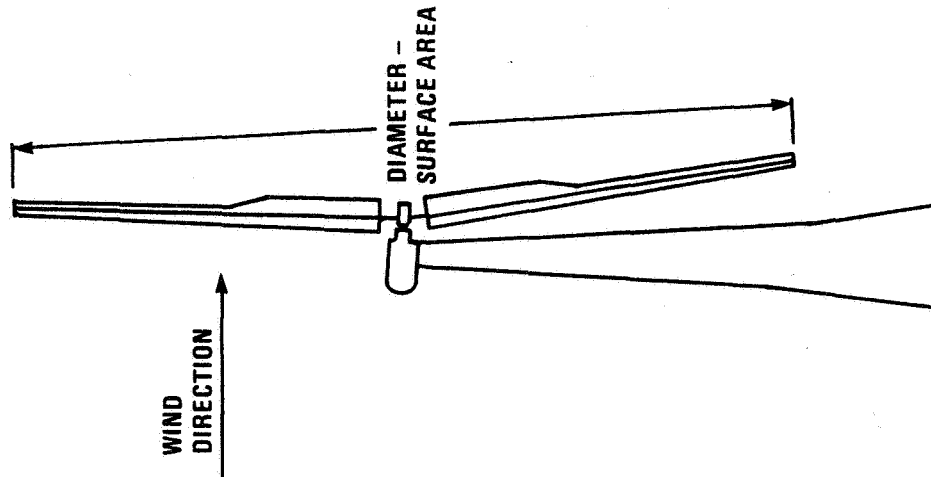


Figure 12. Power density of wind.

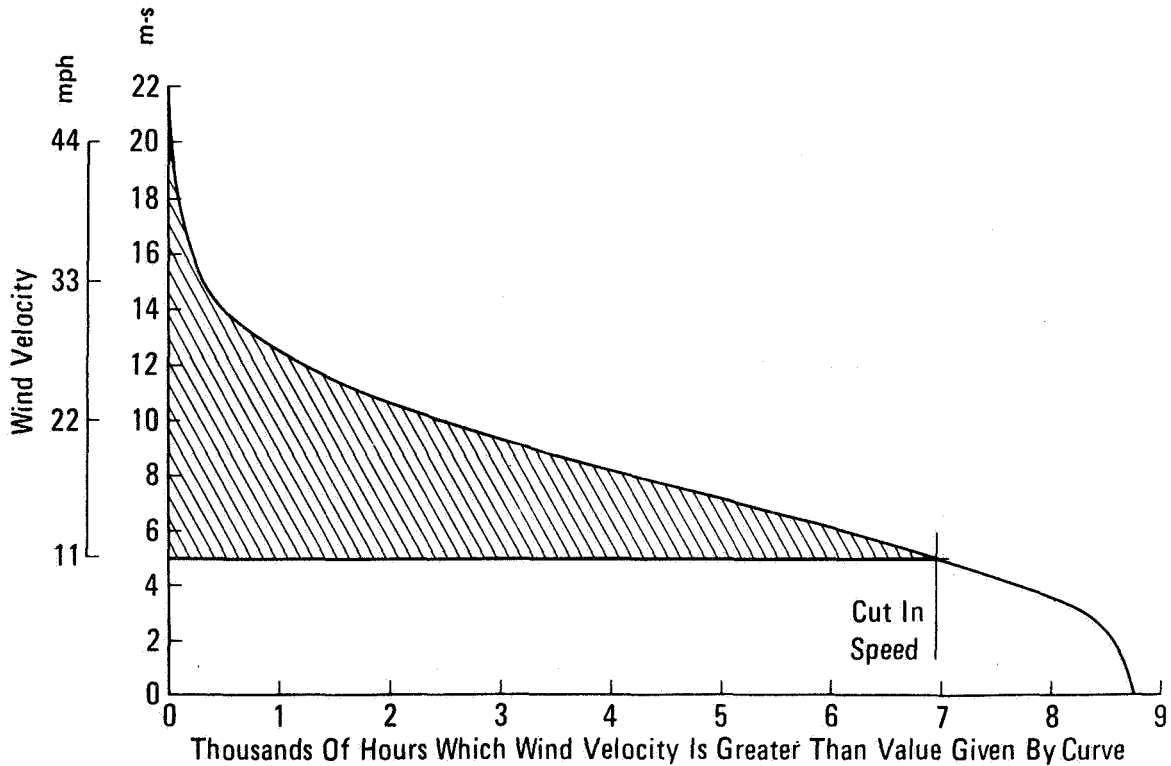


Figure 13. Typical power duration curve high wind regime.

cut-in and cut-out speeds which describes the envelope within which the wind turbine generator will operate most economically. This particular curve shows cut-in at 11 mph and although the particular site does not show winds in excess of 45 mph, the system being designed for this application will cut out at 50 mph. This will provide an advantage of using this system design at a site having wind higher than 45 mph for some periods of time.

The area integrated in the shaded portion of Figure 13 is dependent upon several factors. One of the most important of which is variation in the winds at particular sites at different times of the day. This is important to utilities, since a most economic wind turbine generator has a diurnal — that is an hourly — variation that coincides with peak loads of the utility. Notice the difference in peaks between the high and the moderate/low wind regimes in Figure 14. This is generally a characteristic resulting from the fact that most high wind regimes are located in mountainous or high elevation areas and there is a reverse energy flow at these elevations compared to the moderate and low regimes, generally located in flat or plain areas.

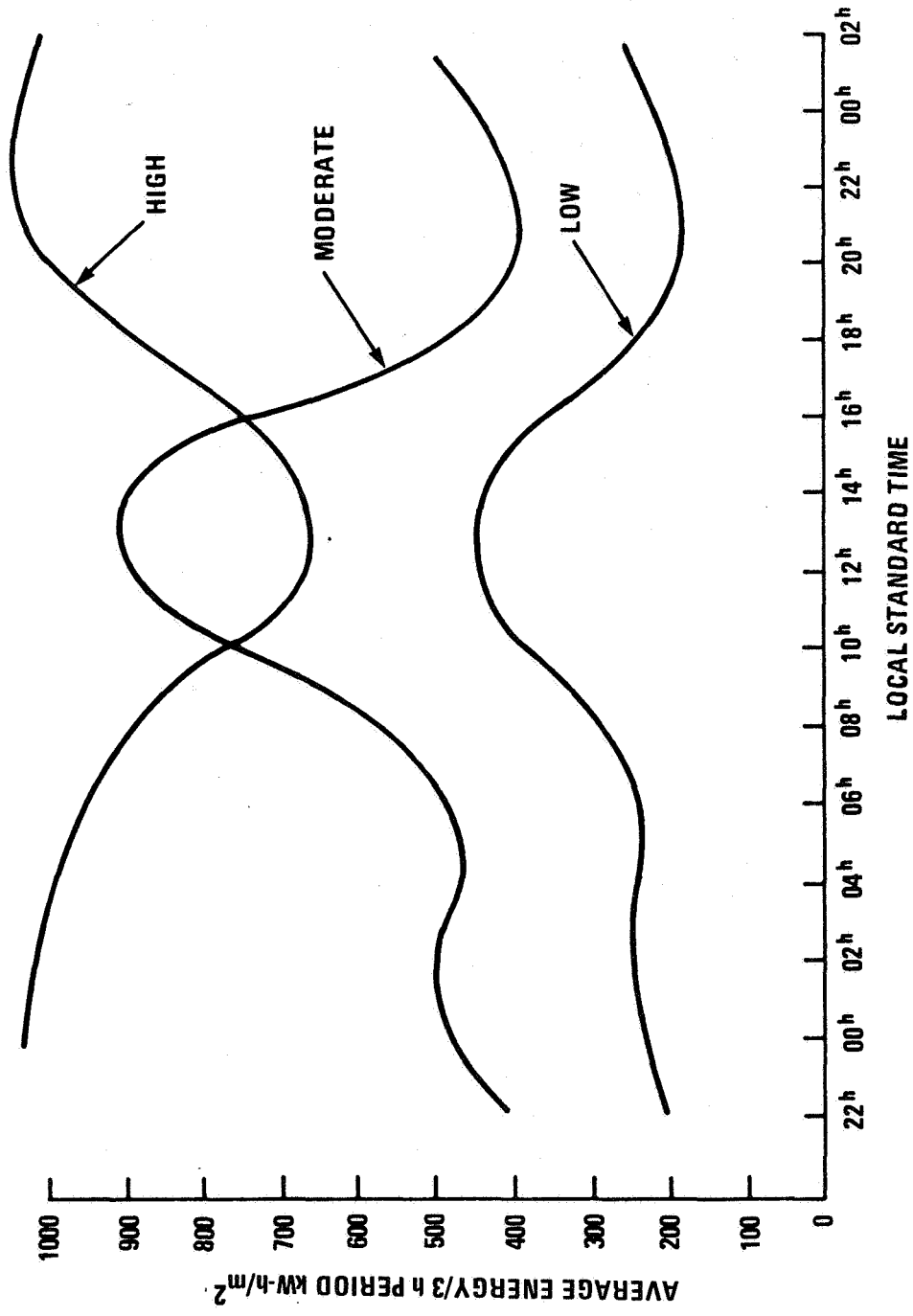


Figure 14. Diurnal variation model.

Another important consideration of interest to the utilities is the seasonal variation of the wind (Fig. 15). Again, the utilities are faced with peak and low demands relative to different times of the year. For instance, in the Midwest, large farming areas are heavily dependent on irrigation systems and the utilities find their peaking requirements in the June–July time frames. As can be seen from Figure 15, the national wind availability is not a good match for this peak loading requirement. Other areas, however, with a high incidence of electric heating will cause utility peaking to occur in the winter months which is compatible with the national high wind regime data. Although the diurnal and seasonal variations appear to place a severe penalty on the potential economic viability of wind turbine generators, it has been determined that wind energy must be considered base-load capacity. That is when the wind is blowing, the utilities will use the energy being produced. Either existing capacity or storage must therefore be available for those peaking conditions previously described.

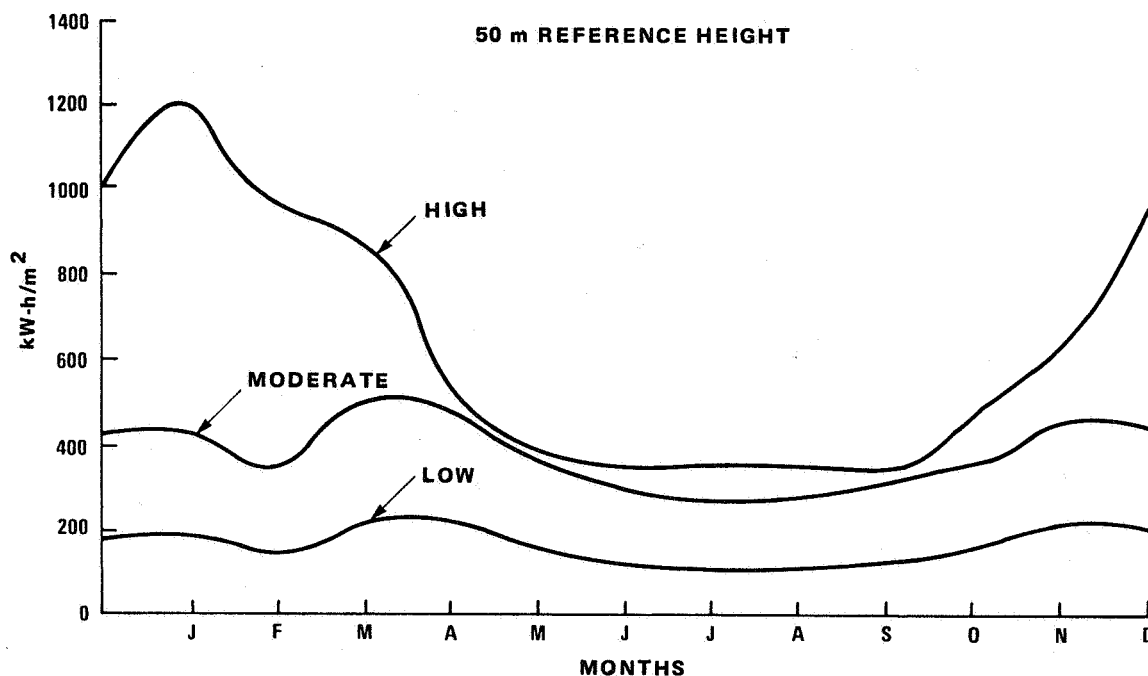


Figure 15. Seasonal variation model.

In GE's National Wind Energy Assessment Study, the total area of the United States, Guam, Puerto Rico, Hawaii, and Alaska were considered for potential wind turbine generator installations. Allowing for unavailability of typical areas such as highly urbanized and lands reserved for park areas, etc., it was determined that this total number of units (313 500) spaced appropriately for efficient wind energy capture could be installed to service the utilities in the



United States. This total capacity, called saturation (Fig. 16), would amount to 470 GW of installed capacity which could represent, operating at a nominal efficiency rate, 1070 billion kW/h/yr. Using an accepted growth rate (2.8 percent per year) of energy consumption through the year 2000, this generating capacity would represent approximately 28 percent of total utility installations and approximately 14 percent of the energy demand for the year 2000.

REGIME	AVAILABLE AREA (THOUSANDS OF MILES <sup>2</sup> )	NUMBER OF INSTALLED UNITS	INSTALLED ELECTRICAL CAPACITY (GW)	ENERGY OUTPUT (BILLIONS OF (kW-h/yr)
HIGH	3.0	8,960	13.4	45
MODERATE	53.9	99,800	150.0	433
LOW	156.8	204,800	307.0	592
<b>TOTAL</b>	<b>214.0</b>	<b>313,500</b>	<b>470.0</b>	<b>1070</b>

**CAPACITY - IF INSTALLED IN YEAR 2000 -**  
 ≅ 28% UTILITY INSTALLED CAPACITY  
 ≅ 14% UTILITY ENERGY DEMAND

Figure 16. Available wind energy at saturation (utility sector).

Based on electric demand and capacity growth rate projected to the year 2000, the tremendous need for filling the capacity requirements can be seen (Fig. 17). At the bottom of the curve, the 470 GW capacity represents wind saturation as defined in Figure 16. GE investigated the feasibility of implementing wind machines between 1980 and 2000 at three varying rates of implementation — rapid, medium, and slow. A fourth rate called very rapid was investigated which would achieve the 470 GW saturation point by the year 2000. This became such an overwhelming burden to industry in terms of building up plant capacity that it was discarded as not being realistic. Even the rapid rate posed serious questions as to the feasibility of reaching approximately 150 000 installed units by the year 2000. The medium and slow rates of implementation were therefore considered as being more realistic and more probable, unless the government initiated a crash program shortly after the hardware demonstration and test phase. It is reasonable then that 14 percent of demand at saturation cannot be achieved in the year 2000, but could likely happen sometime beyond that point in time.

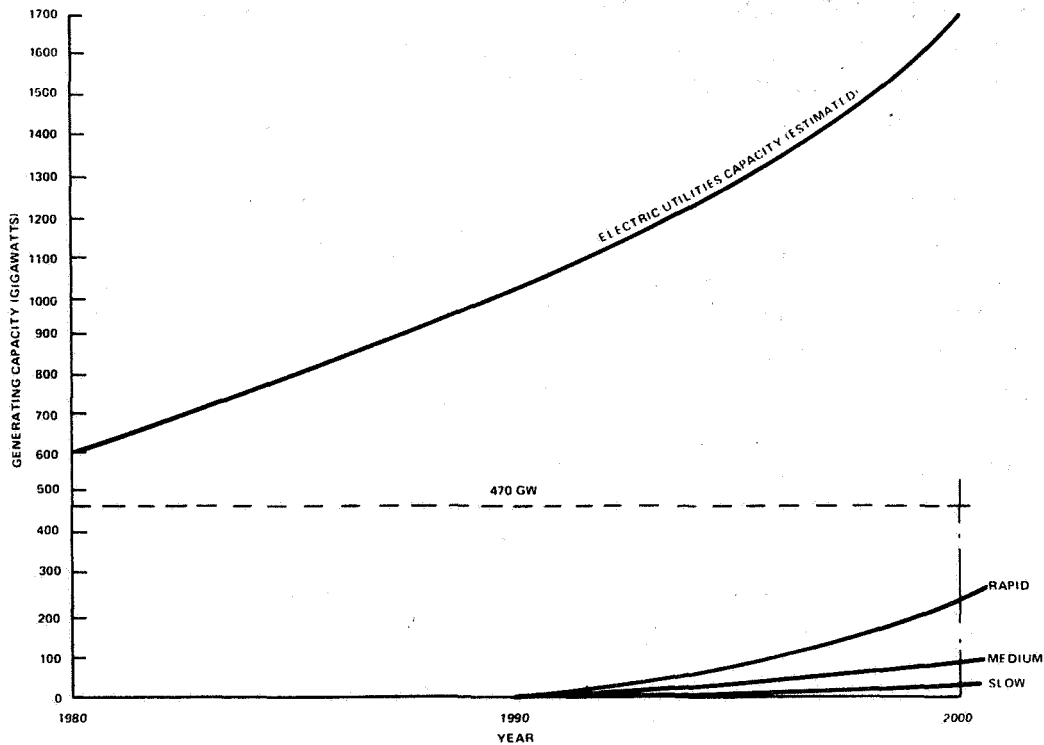


Figure 17. Wind energy systems implementation rates and protected utility capacity.

In a comprehensive regional study GE is performing for EPRI, a specific utility is being studied to determine the economic implications and value of wind turbine systems on a regional scale. This kind of planning with conventional power generation equipment is being conducted on a regular basis for all utilities individually to determine their requirements and their approach to solving their future requirements. Figure 18 shows a typical plan that could be achievable by the year 1990 and that show wind representing 10 percent of a utility's conventional generation capacity.

Although the largest single sector utilizing electrical power through the year 2000 and beyond is the utility sector, other applications were investigated and the summary results are shown in Figure 19. Similar guidelines and bases for the total number of units installed were used to reach saturation for each of these other applications. If some of these applications were considered economically feasible, some additional percentage of total demand (over 14 percent) of the U.S. requirements could be provided by wind turbine generators.

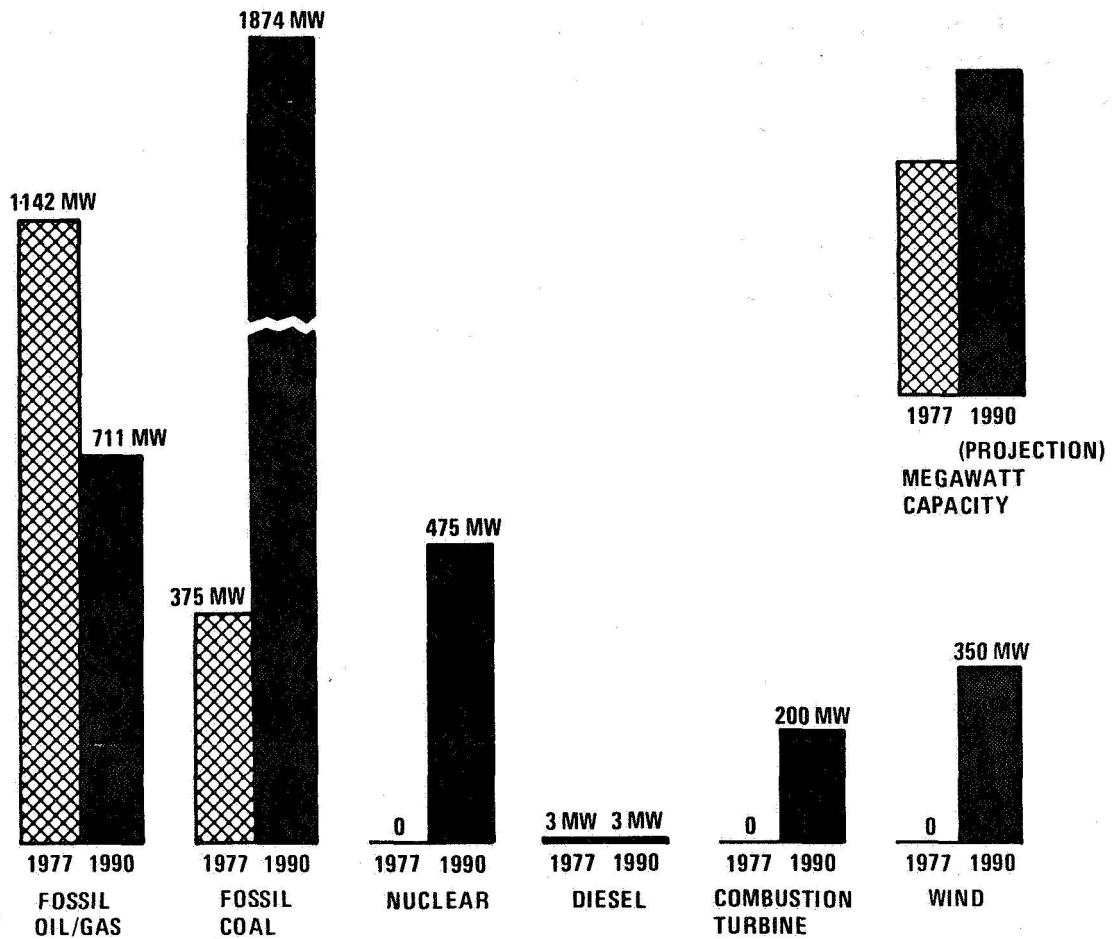


Figure 18. Typical gas and electric utility generation mix — 1977-1990.

APPLICATION	WECS UNIT SIZE (kW)	MARKET SIZE (SATURATION)			PROTOTYPE COST OF WECS (\$/kW)	BREAKEVEN COST (\$/kW)	COMPETING WITH (¢/kWh)
		TOTAL NUMBER OF WECS UNITS	CAPACITY (GW)	ANNUAL ENERGY OUTPUT (BILLION kWh)			
ELECTRIC UTILITIES	1500	313,500	470	1070	2398**	239**	1.9
RESIDENCES	10	9,300,000	93	207	3947	533	3
AGRICULTURE	35	780,000	27	43	2187	367	2.77
PAPER MILLS	1500	1,000	1.9	2.9	2292	186**	1.7
REMOTE COMMUNITIES	1500	1,000	1.0	2.5	2671	626	3.9

\*\* EFFECTIVE VALUES FOR APPLICATION, FOR COMPARISON PURPOSES ONLY, NUMBERS REPRESENT MIXTURES OF WECS IN DIFFERENT WIND REGIMES.

Figure 19. Summary of key application characteristics.

In another regional study underway at GE, technical considerations effecting the utility system's control and stability with regard to large numbers of wind units being installed within that utility are being investigated (Fig. 20). In this case, the utilities are located in the state of Vermont, located where good wind conditions exist.

- WHAT ARE THE EFFECTS OF WIND VARIABILITY ON AN ELECTRICAL POWER SYSTEM CONTAINING A SIGNIFICANT NUMBER OF UNITS?
- WHAT ENGINEERING INFORMATION DO THE UTILITY AND WIND TURBINE GENERATOR DESIGNERS NEED TO KNOW?
- ARE THERE ANY UNIQUE OPERATIONAL CHARACTERISTICS OR INTERFACES ASSOCIATED WITH THE UTILIZATION OF WIND ENERGY CONVERSION SYSTEMS?

Figure 20. System dynamics of multiple wind turbine units.

Several conditions including numbers and sizes of wind turbine generators, main and feeder distribution line tie-ins, and different characteristics of load and peaking conditions (all including peaking profile and reactance and resistive load characteristics) are being modeled within that area.

Although the results of the VELCO Transmission Expansion Study (Fig. 21) are not complete, the chart shown in Figure 22 represents the ultimate desired findings in order to be assured that there will be no technical problems associated with introducing large scale numbers of wind turbine generators into utilities. By carefully selecting representative utilities and equally representative potential wind turbine generator system characteristics, GE is fairly certain that the results will be achieved. That is, the results of the study are generally applicable to the range of utilities and the range of systems under consideration, and that no significant impact will result to the utilities from the standpoint of system dynamics.

Since in-depth modeling of the utilities stability and control systems just began, GE does not have results yet that establish the conditions hoped for by the end of the study. They are, however, fairly confident that the results will provide sufficient data to be able to solve any problems that might be uncovered.

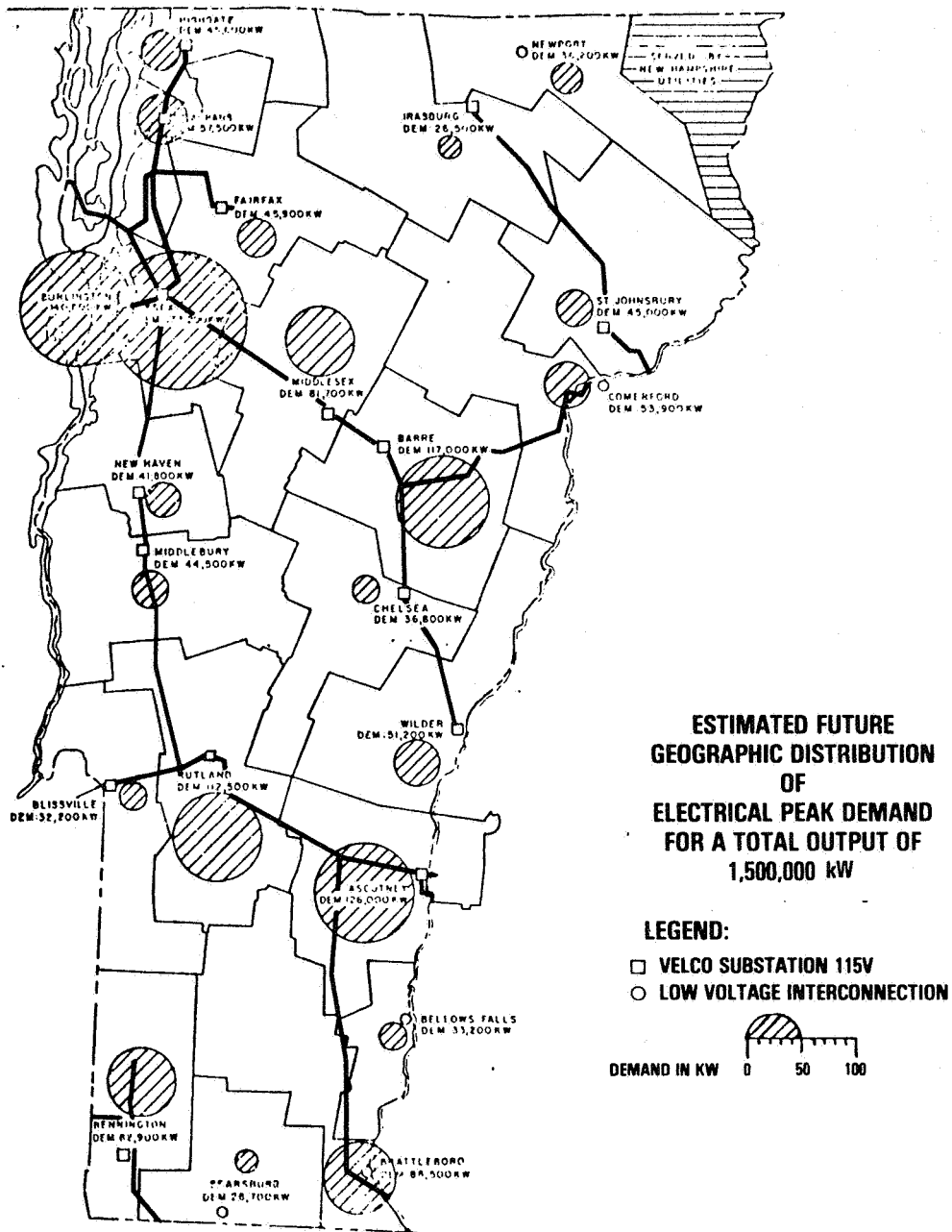


Figure 21. VELCO Transmission Expansion Study.

- RESULTS APPLICABLE TO UTILITY RANGE OF WECS 1500 kW AND 3000 kW – BOTH SYNCHRONOUS AND INDUCTION
- RESULTS REPRESENTATIVE FOR MOST U.S. UTILITIES – RESULTS APPLICABLE TO GRID-INTERCONNECTED UTILITIES
- USE OF ENERGY STORAGE FOR STABILITY – NO REQUIREMENT
- LOGICAL AND REGIONAL WIND VARIABILITY – NO SIGNIFICANT IMPACT ON UTILITY DYNAMIC STABILITY
- FAULT SUSCEPTABILITY AND RECOVERY – SIMILAR TO OTHER GENERATING SOURCES OF THIS SIZE
- WECS STABILITY SENSITIVITY TO LOADS – INSENSITIVE TO VARIOUS TYPE LOADS AND GENERATING SOURCES
- WECS STABILITY SENSITIVITY TO DISTRIBUTION – INSENSITIVE TO VARIOUS POWER GRID DISTRIBUTIONS AND SINGLE/CLUSTERED WECS
- HIGH LEVEL WECS PENETRATION – NO STABILITY PROBLEMS IN IMPLEMENTATION OF UP TO 50 PERCENT OF PEAK LOAD

Figure 22. Desired results of VELCO Transmission Expansion Study.

## HARDWARE DEMONSTRATION PROGRAMS

The hardware demonstration programs currently underway range from systems in the small category that satisfy residential and farm uses through the first demonstration unit installed at Plumbrook (a 1000 kW unit now in operation) to the MOD-1 System (a 1500 kW WTG currently under development at GE) shown in Figure 23.

GE, in parallel with the Kaman Aerospace Corporation, conducted parametric design studies which examined the various parameters associated with designing large wind turbine generators (Fig. 24). It was determined early in the study that GE would concentrate on 500 kW and 1500 kW rated machines in various wind regimes. The basis of some of these requirements emanated from the early design of the Smith-Putnam machine at Grandpa's Knob, Vermont. Later European machines were studied from the standpoint of being compatible with utility requirements whose equipment life is at least 30 years.

# HARDWARE PROGRAMS

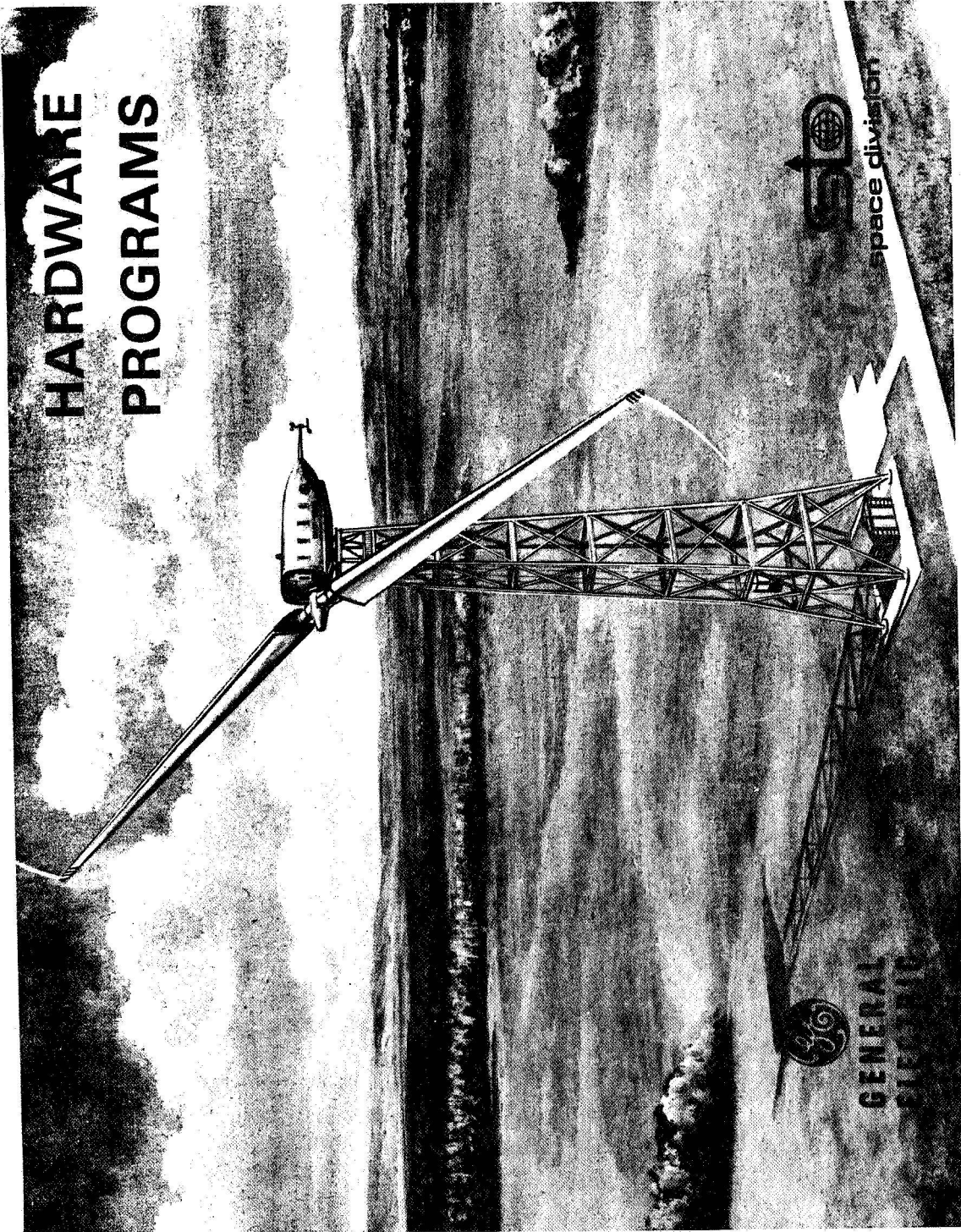


Figure 23. The MOD-1 system.

<p><b>POWER LEVEL</b></p> <p>RATED 500 kW ac IN 12 mph <math>V_M</math> WITH <math>V_R = 16.3</math> mph  1500 kW ac IN 18 mph <math>V_M</math> WITH <math>V_R = 22.7</math> mph</p> <p><b>CONFIGURATION</b></p> <ul style="list-style-type: none"> <li>● HORIZONTAL AXIS 2 BLADE PROPELLER TYPE ROTOR ATOP SUPPORTING TOWER</li> <li>● 50 ft GROUND CLEARANCE</li> <li>● ROTOR DOWN WIND OF TOWER</li> </ul> <p><b>OPERATIONAL ENVIRONMENT</b></p> <ul style="list-style-type: none"> <li>● LIFE – 30 YEARS DYNAMIC COMPONENTS; 50 YEARS STATIC COMPONENTS</li> <li>● TEMPERATURE – 60°F TO 120°F</li> <li>● HAIL, RAIN, SNOW, SAND, LIGHTNING, SALT SPRAY, SUN, ICE</li> </ul> <p>THE DYNAMIC COMPONENTS OF THE SYSTEM MUST BE DESIGNED TO WITHSTAND THE FOLLOWING LOAD CONDITIONS:</p> <ul style="list-style-type: none"> <li>● NORMAL CONDITION OF BREAKAWAY, CUT IN, RATED, CUT OUT <ul style="list-style-type: none"> <li>– TORQUE</li> <li>– THRUST</li> <li>– MOMENTS</li> <li>– HORIZONTAL AND VERTICAL INPLANE FORCES</li> <li>– CYCLIC EXCITATION</li> <li>– GYROSCOPIC</li> </ul> </li> <li>● WIND DIRECTION CHANGES <ul style="list-style-type: none"> <li>– <math>\pm 15^\circ</math> FOR <math>V_W \leq V_R</math>; PROPORTIONAL FOR <math>V_W &gt; V_R</math></li> <li>– <math>180^\circ</math> IN 30 s</li> </ul> </li> <li>● WIND SHEAR <ul style="list-style-type: none"> <li>– <math>V/V_0 = (H/H_0)^N</math> WHEN <math>N = 1/6</math> AND <math>H_0 = 30</math> ft</li> </ul> </li> <li>● TOWER SHADOWING</li> </ul>
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Figure 24. System design requirements.

GE found early in the study that the most demanding conditions involved system dynamics both during operation and during shut-down in severe weather conditions. It was also determined that to assure reasonable economics, the system must operate in wind conditions having high variability in wind direction and wind speeds caused by gusting. Therefore, the design had to be able to operate, react to, and seek the wind from various directions quickly and to accommodate changes in wind conditions. Similarly, it was found that the tower creates a "wall" that limits the wind behind the tower and causes blade deflection and difficult dynamics problems on the blades, tower, and other subassemblies.



Therefore, the study took on the problem of determining the mechanical design and subsystems that would operate acceptably under the nominal operating conditions (Fig. 25).

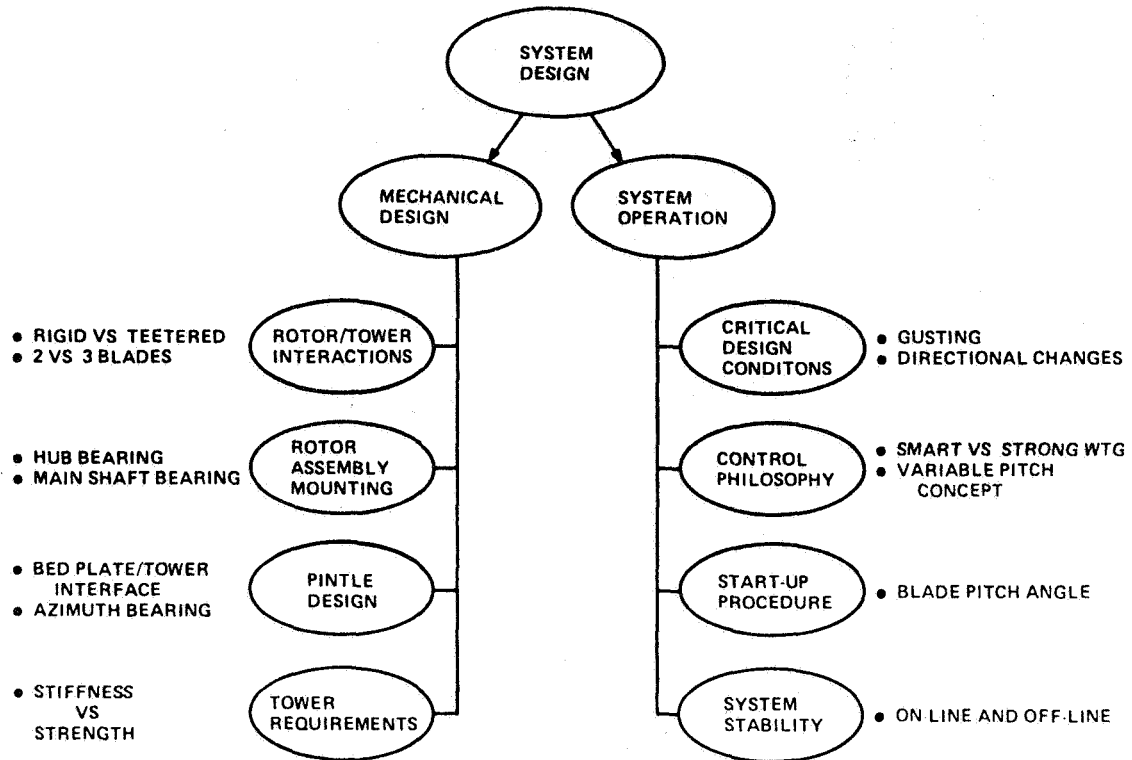


Figure 25. Key system design areas.

The curves in Figure 26 represents a typical operating sequence of the 1500 kW constant speed system. Velocity ratio is top speed to wind speed and power ratio is the percentage of power extracted from the power available in the wind stream. Depending upon the wind speed, GE will try to operate as close to the peak power ratio as is possible. This is shown by the increasing sized curves labeled 40, 30, 10, 5, 2, -5 degrees. The degree factor represents the pitch angle of the blade. At high wind speeds the air foil operates inefficiently at 40 and 30 degrees, dumping some of the excess load. At the minimum operational wind speed the system is actually operating at a slightly negative angle-of-attack to gain most lift. Both the control system sensitivity and the specific air-foil characteristics are equally important to the successful design configuration once the wind envelope has been determined.

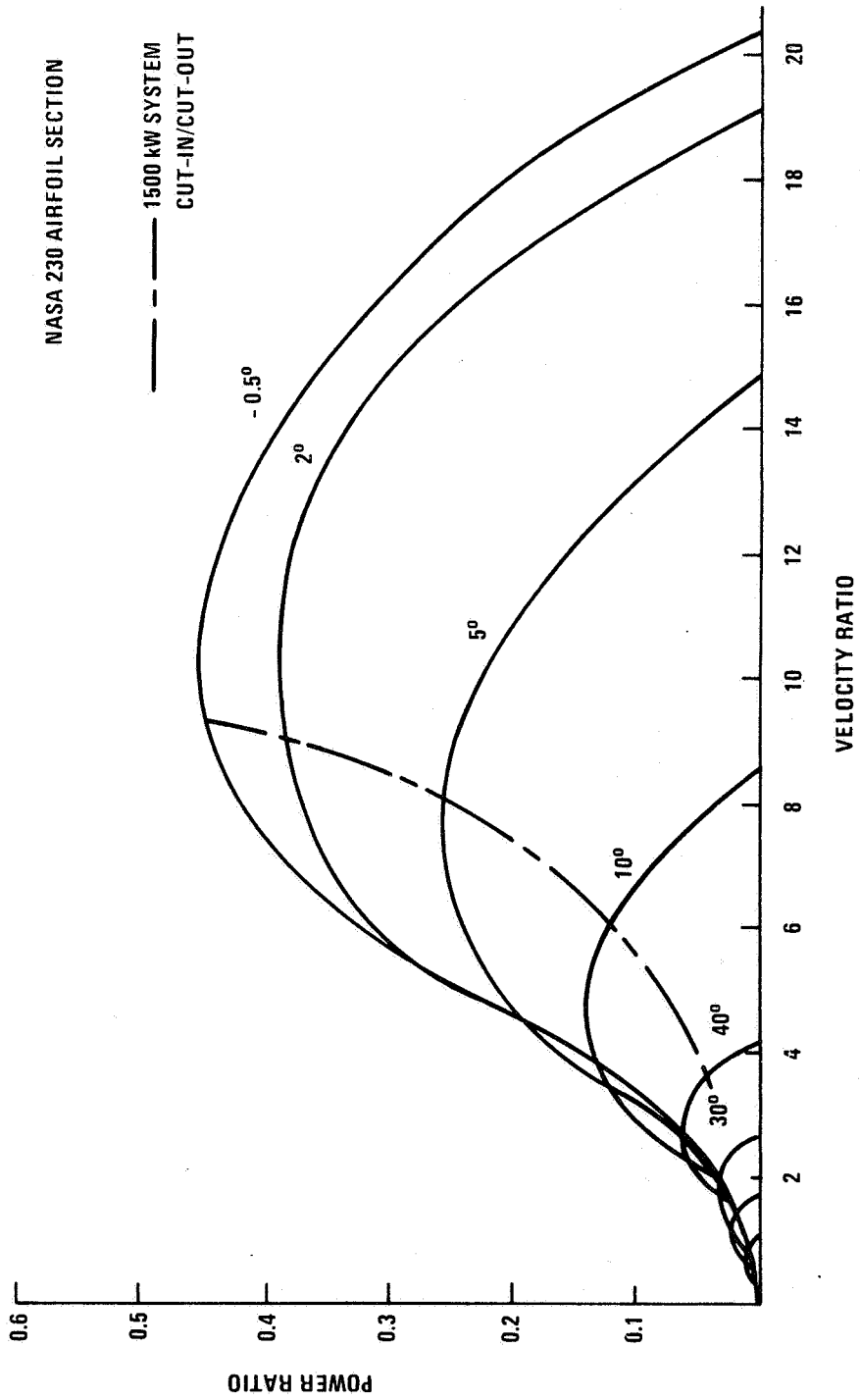


Figure 26. System operation.

The 23 000 series airfoil was selected early in the design study because it was simple to manufacture and had good operation and stall characteristics. To be cost competitive with other energy sources it is necessary to get as close to the flat portion of the low cost per kilowatt hour curve as possible. Figure 27 shows that as the wind speed or the rotor diameter is increased, the probability of achieving lower costs is increased. Since good wind cannot be assured for every potential site, larger rotor diameter machines in the moderate and low wind regimes will provide the potential for cost competitive power.

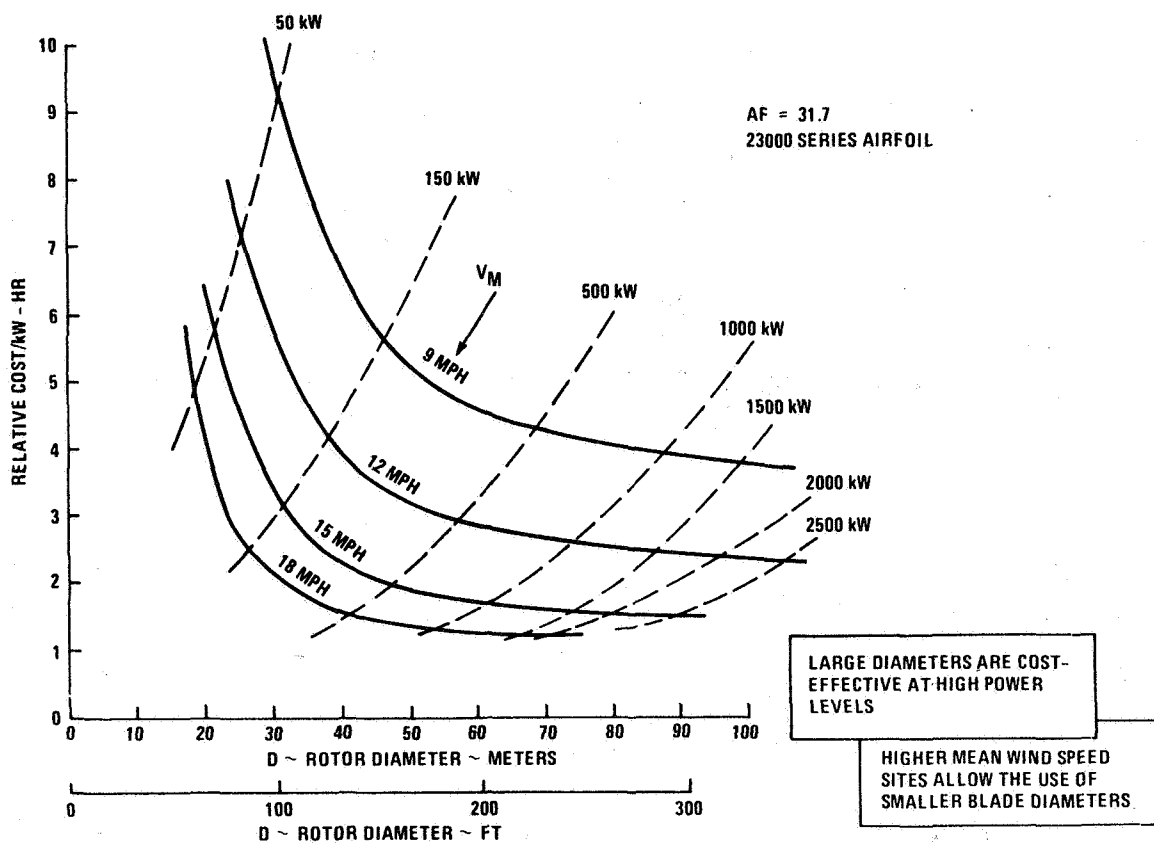


Figure 27. Cost sensitivity to rotor diameter.

The optimum 1500 kW system for various wind regimes is shown in Figure 28. By maintaining a desired 1500 kW power output, the relative wind turbine generator size with increasing annual median wind speeds ( $V_M$ ) can be seen.  $V_R$  is the rated wind velocity at which the 1500 kW power level is generated.

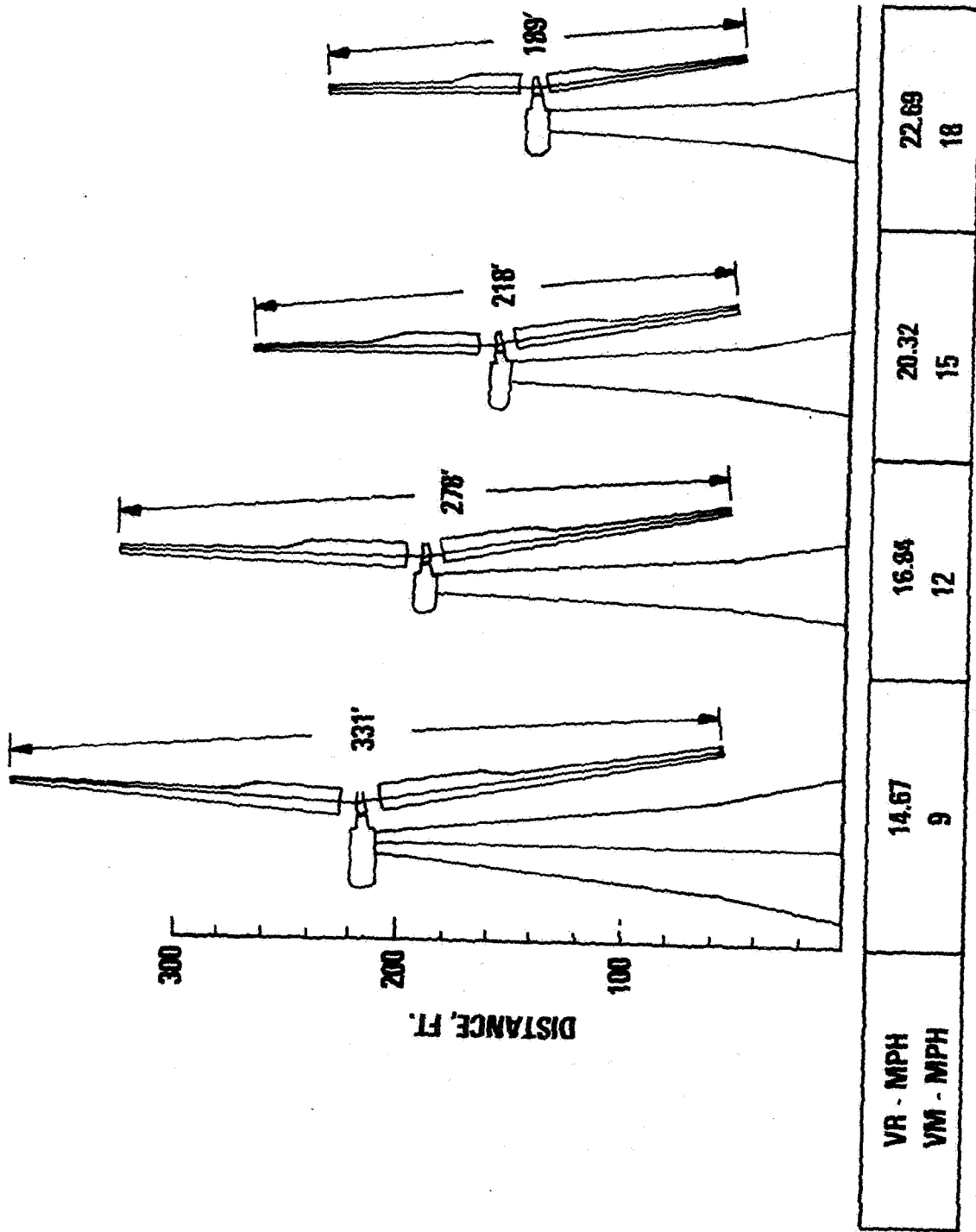


Figure 28. Optimum 1500 kW system for various wind regimes.

The system configuration selected for competitive hardware procurement for the MOD-1 demonstration program was the 1500 kW wind turbine generator (Fig. 29) operating in the high wind regime (i.e., annual mean wind speed of 19 mph). This is the device that is now on contract with GE. Two units will be built and installed at two sites described earlier. The schedule for completion and operation is mid-1978.

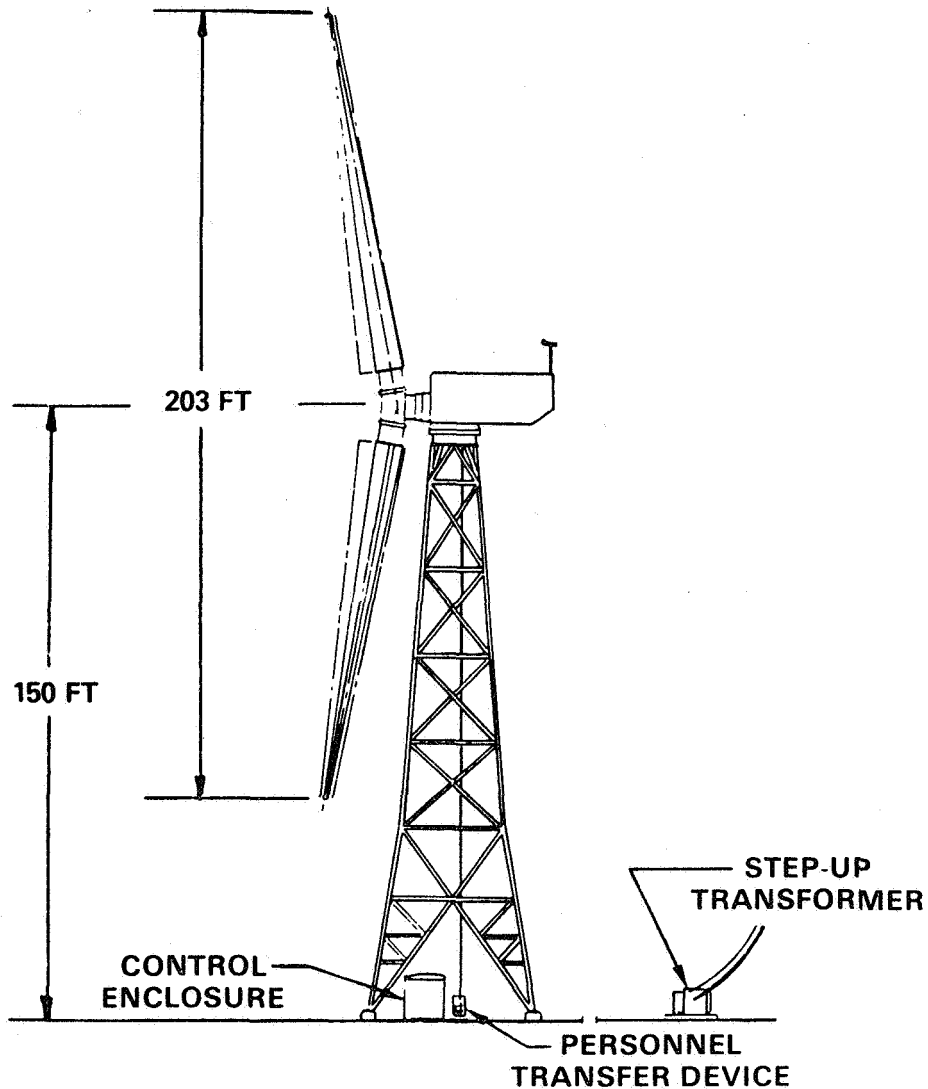


Figure 29. 1500 kW wind turbine generator.

The characteristics of the MOD-1 1500 kW Wind Turbine Generator System are shown in Figure 30. It is interesting to note that the characteristics of this system resulted from those parametric design studies that were performed

<b>RATED POWER</b>	<b>1500 kW</b>
<b>RATED WIND SPEED</b>	<b>22 mph</b>
<b>CUT IN CUT OUT WIND SPEED</b>	<b>11/50 mph</b>
<b>MAXIMUM WIND SPEED (SURVIVAL)</b>	<b>150 mph</b>
<b>ROTOR</b>	<b>TWO BLADED DOWN-WIND OF TOWER</b>
<b>BLADE DIAMETER</b>	<b>203 ft</b>
<b>CONE ANGLE</b>	<b>10°</b>
<b>AIR FOIL</b>	<b>23,000</b>
<b>ROTOR SPEED</b>	<b>35 rpm</b>
<b>YAW RATE</b>	<b>0.5° /s</b>
<b>TOWER HEIGHT</b>	<b>145 ft</b>
<b>DESIGN LIFE</b>	<b>30 YEARS</b>
<b>OVERALL CHARACTERISTICS SIMILAR TO ORIGINAL CONFIGURATION</b>	

Figure 30. 1500 kW Wind Turbine Generator System Characteristics.

by both GE and Kaman Aerospace. The driving parameter which led to this design configuration was the lowest cost kilowatt hour of energy produced with a system that would not require substantial developmental challenges.

The housing at the top of the tower is called the "nacelle" and contains most of the power generation equipment (Fig. 31). From left to right, it consists of the rotor and the blade, pitch change mechanism (a derivation from helicopter technology), single main bearing, main shaft, and the low speed flex coupling, which connects the main shaft to the speed increased. Since the nacelle is operated at 35 rpm and the generator is an off-the-shelf 1800 rpm synchronous generator, a rather large speed increased (transmission) is needed. It is a three-stage transmission provided by Philadelphia Gear Corporation based on designs used for commercial off-the-shelf equipment. There is a high speed brake at the end of the transmission, connected to a high-speed flexible coupling and then to the generator. At the bottom of the system, the yaw-bearing and yaw-drive which drives the nacelle laterally into the wind is actuated by a hydraulic system that also actuates the pitch-change mechanism. The control system which senses wind-gusting and wind variability conditions is housed in a building located below the tower. The central heart of the control system is a mini-computer.

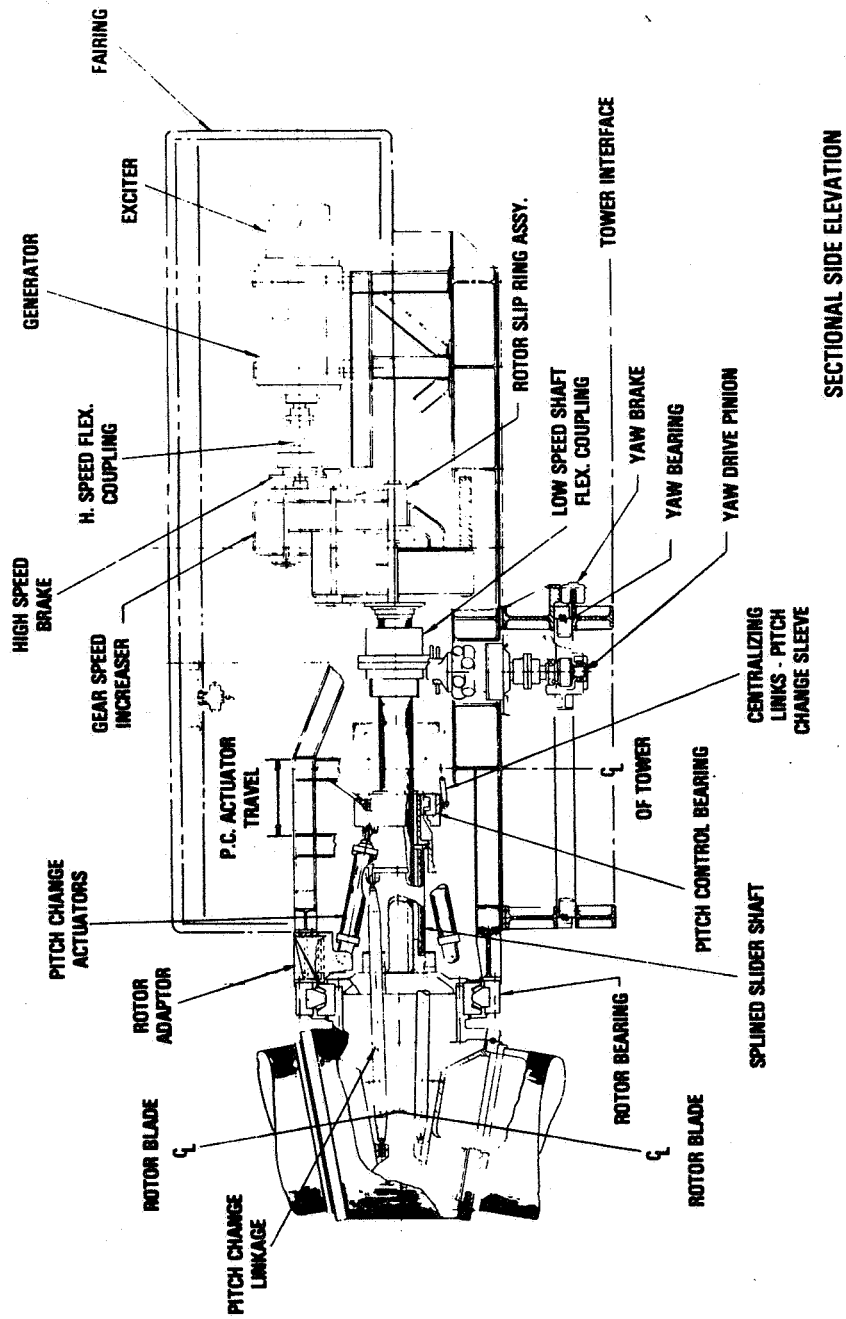


Figure 31. Internal view of nacelle.

The basic design philosophy requirement was to satisfy steady power to a utility with a system made up of equipments mostly off-the-shelf (Fig. 32).

- UTILITY TYPE WIND POWER GENERATOR
  - SIMPLE AND COST EFFECTIVE DESIGN
    - USE OF STANDARD UTILITY PRACTICES, AS FAR AS POSSIBLE
    - COMMERCIALY AVAILABLE COMPONENTS
    - ELIMINATION OF NON-ESSENTIAL PARTS
    - REDUCE REQUIREMENTS TO NECESSARY MINIMUM
    - REDUCE FIELD ASSEMBLY AND CHECKOUT TIME
    - REDUNDANCIES FOR SAFETY ONLY
    - EASE OF MAINTENANCE
- EMPHASIS IS ON COMPONENT SIMPLICITY AND OFF-SHELF EQUIPMENT**

Figure 32. System design approach/philosophy.

To arrive at a design compatible with the requirements listed in Figure 32, an extensive amount of structural dynamics was required and special mathematical tools were developed to prove the design. The mathematical models were tested with actual measured data taken from the MOD-0 system located at Plumbrook. The MOD-1 program status is that the preliminary design phase has just been concluded and long-lead items have been ordered. Fabrication will begin later this year.

- STRUCTURAL DYNAMICS
    - RESONANT FREQUENCY PLACEMENT
    - ADEQUATE DESIGN LOADS (NO OVER DESIGN)
    - MINIMUM SENSITIVITY TO VARIATIONS
  - SYSTEM STABILITY FOR ON AND OFF-LINE OPERATION
    - SELECTION OF GENERATOR CHARACTERISTICS
    - DRIVE TRAIN TORSIONAL CHARACTERISTICS
    - CONTROL SYSTEM RESPONSE
    - UTILITY CHARACTERISTIC
- DESIGN AND OPERATION GOALS REQUIRED IN-DEPTH TRADE-OFFS AND ANALYSES**

Figure 33. Key system considerations.



Another developmental program underway at Sandia Laboratories at Albuquerque, New Mexico is a vertical-axis "darrius" type of wind turbine generator (Fig. 34).

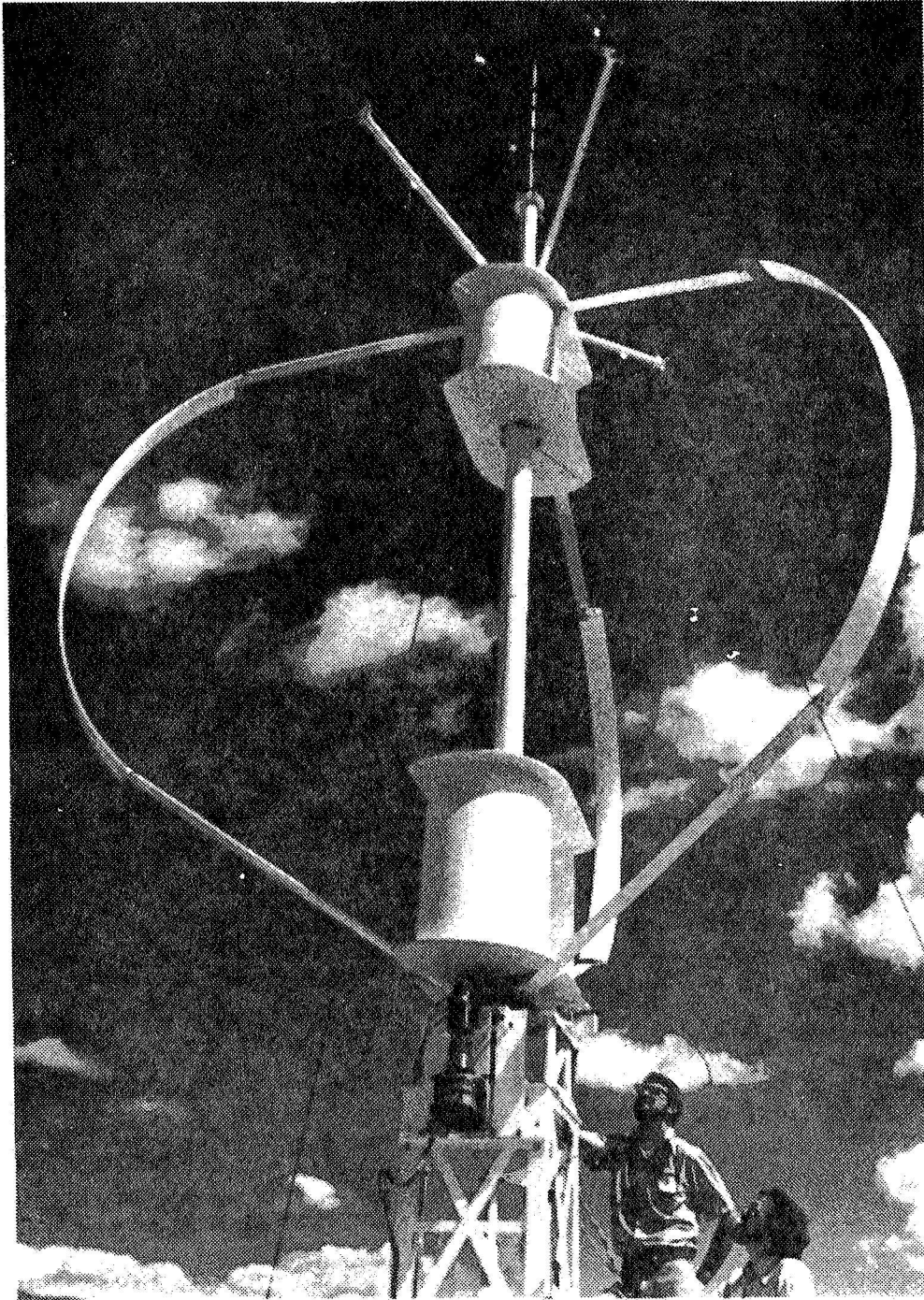


Figure 34. Darrius-type vertical-axis wind turbine.

Although the completed engineering design effort leading to economic optimization is not as extensive as that performed on the horizontal-axis MOD-1 type, the vertical axis wind turbine generator has significant advantages that must be weighed very carefully (Fig. 35). It is likely that the vertical-axis machine has good economic potential for certain applications. Both design and hardware development are being continued by Sandia for ERDA.

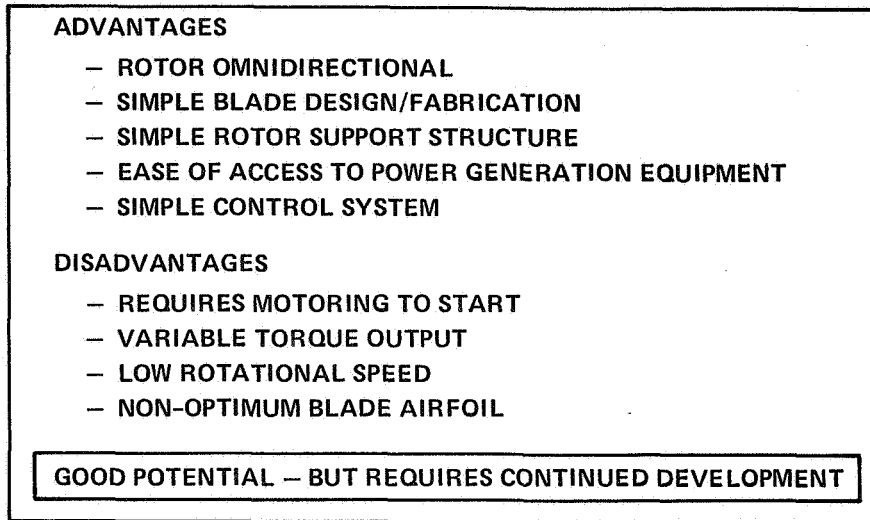


Figure 35. Vertical axis advantages/disadvantages.

## FUTURES

ERDA's development plan includes a significant degree of continuing development and demonstration.

Prior to formal commercialization of wind energy systems, demonstrations of larger and more comprehensive developments are in the planning stages (Fig. 36). The most imminent, not yet on the drawing-board but currently being completed, is the MOD-2 300 ft wind turbine system for the moderate wind regimes. GE has proposed to NASA-LeRC to design and build three of these systems, and the proposals are currently in the evaluation stage. Operation is scheduled for late 1979 or early 1980. The multiple MOD-1 and MOD-2 pilot plants represent demonstration with utilities to prove economic operation. Several units of MOD-1 and MOD-2 sizes will be clustered or strung along distribution lines to make up a 100 MW pilot plant. A well-developed operation

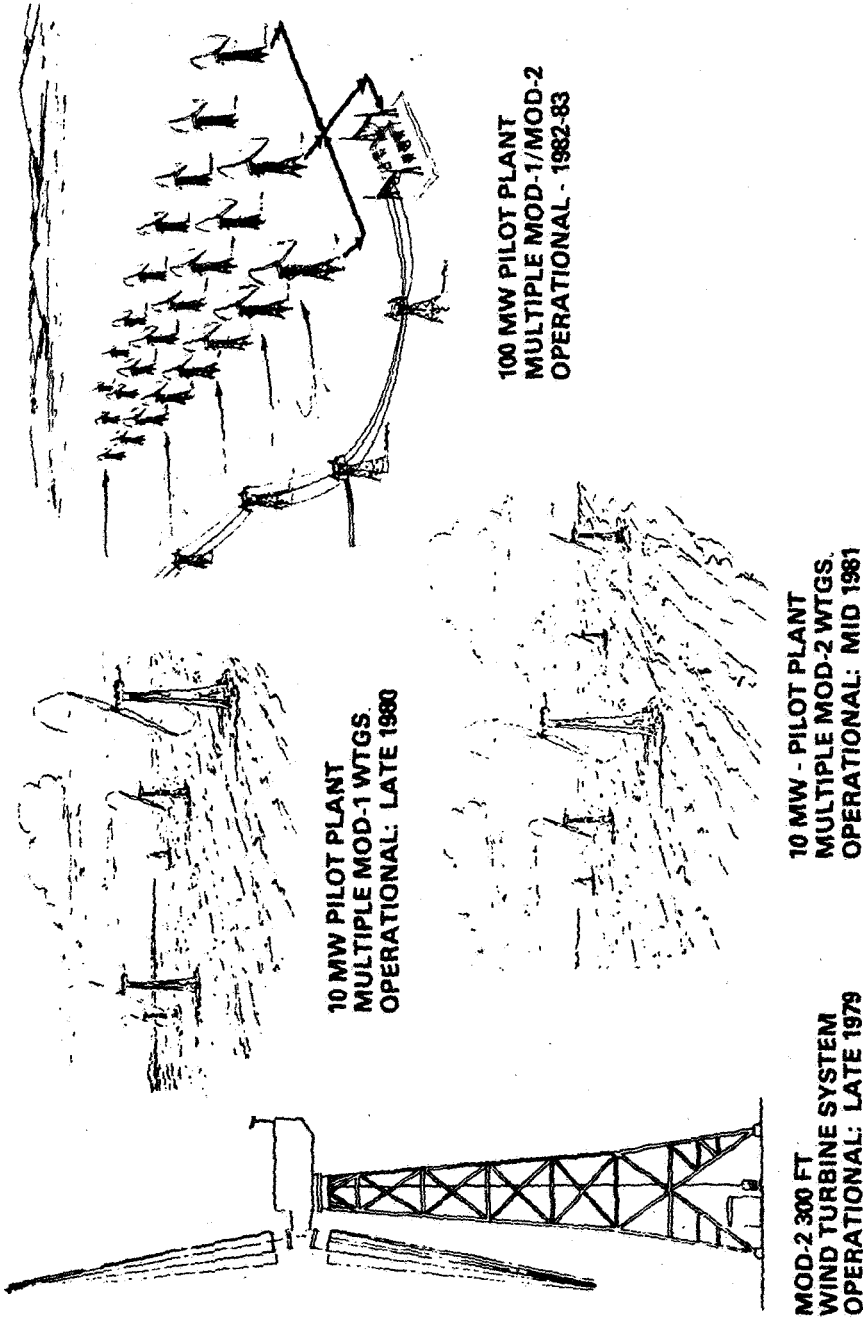


Figure 36. ERDA Large Scale Development Program.

and test program of these demonstrations is designed to prove the technologies and the wind power economics, thus paving the way for large scale commercial implementation in the kinds of numbers that would achieve a significant power generation capacity from the late 1980's through and beyond the year 2000.