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WIND TURBINES FOR ELECTRIC UTILITIES: DEVELOPMENT STATUS AND ECONOMICS‡

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E-035

Abstract

The technology and economics of the large, horizontal-axis wind turbines currently in the Federal Wind Energy Program are presented. Wind turbine technology advancements made in the last several years are discussed. It is shown that, based on current projections of the costs of these machines when produced in quantity, they should be attractive for utility application. The cost of electricity (COE) produced at the busbar is shown to be a strong function of the mean wind speed at the installation site. The breakeven COE as a "fuel saver" is discussed and the COE range that would be generally attractive to utilities is indicated.

Summary

The technology for large, horizontal-axis wind turbines (100 kW - 2500 kW) has been under development since 1973 as a major part of the Federal Wind Energy Program which is sponsored by the U.S. Department of Energy. Specific projects are being managed for the Department of Energy by the Lewis Research Center of the National Aeronautics and Space Administration.

The objective of the Federal Wind Energy Program is to accelerate the development of reliable and economically viable wind energy systems and enable the earliest possible commercialization of wind power. To achieve this objective requires advancing the technology, developing a sound industrial technology base, and addressing the non-technological issues which could deter the use of wind energy.

Significant advances have been made in the technology of large, horizontal-axis wind turbines since 1973. Technical feasibility has been demonstrated in utility service for systems with a rated power of up to 200 kW and a rotor diameter of 125 feet (Mod-0A). There appear to be no major feasibility issues to be resolved. The activation of larger prototype units in utility service in 1979 (Mod-1; 2000 kW, 200-foot diameter rotor) and in 1980 (Mod-2; 2500 kW, 300-foot diameter rotor) are expected to confirm this assessment.

The long term reliability of wind turbine systems is yet to be demonstrated. This will require time to accumulate service experience. In addition, machine capital costs must be further reduced through a combination of continued research and technology development and quantity production.

The "second-unit" capital costs† for large, horizontal-axis wind turbines currently range from about \$8000/kW for operational prototype units in the 200 kW class down to a little over \$1000/kW for advanced design prototype units in the multi-megawatt range.

The 100th production unit of Mod-2 is projected to have a capital cost of about \$750/kW and produce electricity at a cost of about \$.035/kWh at sites with mean annual wind speeds of about 15 mph. As large, horizontal-axis wind turbines reach a mature product status their costs are expected to be even lower. This should make them increasingly attractive to utilities. In addition, further technology advancements should permit additional capital cost reductions which, in turn, will make them more cost competitive at lower wind sites or, alternatively, further reduce their COE at the better wind sites.

In addition to the projected favorable economics, wind turbines appear to have no significant environmental impacts and use a replenishable, non-polluting source of energy. These features make wind turbines today one of the most attractive potential solar options for widespread utility application.

Background

Since 1973, the Lewis Research Center of the National Aeronautics and Space Administration (NASA) has managed the technology development for large, horizontal-axis wind turbines. This technology development effort is a major part of the Federal Wind Energy Program for which the U.S. Department of Energy (DOE) has overall responsibility.

Four wind turbine projects designated the Mod-0, Mod-0A, Mod-1, and Mod-2 are part of the current development program for large, horizontal-axis wind turbines in the U.S. The machine configurations are illustrated in fig. 1.

The Federal Wind Energy Program had its beginning in 1972 when a joint Solar Energy Panel of the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) recommended that wind energy be developed to broaden the Nation's options for new energy sources. In 1973, the NSF was given the responsibility for the Federal Solar Energy Program and the NASA-Lewis Research Center was designated by NSF to manage the technology development and initial implementation of large wind turbines. In the fall of 1973, a comprehensive government study[1] of the Nation's energy future recommended that a 5-year program be undertaken to develop wind turbines. Early in 1974, NASA was funded by NSF to:

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**Systems Analysis Engineer.
†All costs in this paper are in 1977 dollars.
‡Second printing. Minor modifications were made to the Summary for clarification.

(1) design, build, and operate a wind turbine for research purposes, designated Mod-0;

(2) initiate studies of wind turbines for utility application (this eventually led to undertaking the development of the Mod-1, to be installed and operated in utility service);

(3) undertake a program of supporting research and technology development for wind turbines.

By 1975, the responsibility within the Federal government for wind turbine development had been assigned to the newly created Energy Research and Development Administration (ERDA). Under ERDA's direction (and subsequently the Department of Energy in 1977) additional technology development projects were initiated and placed under the management of the NASA Lewis Research Center. These included:

(1) Mod-OA, aimed at placing several prototype units of the Mod-0 class into utilities to gain some early in-service experience;

(2) Mod-2, aimed at developing a MW-class wind turbine that is more advanced and generates lower cost electricity than Mod-1.

Four Mod-OA machines and three Mod-2 machines are to be placed in utility service.

The machine design and technology development projects have been supported by substantial analysis and hardware/material testing. These include efforts to improve the methods of structural dynamic analysis, assessment of utility interface problems, testing of component materials and evaluation of new blade concepts by analysis, laboratory testing of blade sections and operational testing of full-scale blades.

In addition to the configurations currently under development for testing, efforts aimed at achieving lower machine costs will be initiated in 1979. These will include an advanced, multi-megawatt wind turbine project and an advanced, multi-purpose, medium-scale wind turbine project.

Significant advances in the technology of large, horizontal-axis wind turbines have been made in the last several years. On the basis of cost projections for production units, these machines should be cost competitive for utility application. This cost competitiveness will require further advancements in technology leading to basic cost reductions and the development of designs to fully realize the economies and cost reductions that are expected to come from producing them in quantity.

Development Status of Large Wind Turbines

Mod-0

The current program of research and technology development on large, horizontal-axis wind turbines was initiated with the Mod-0. The Mod-0 is a 2-bladed, 125-foot diameter, research wind turbine rated at 100 kW. This machine was designed by the Lewis Research Center. The Mod-0 has aluminum blades. The rotor is located downwind of the tower. However, Mod-0 has also been operated with the rotor upwind of the tower to assess the effects on system structural loads and machine control requirements. The rotor speed is maintained at a constant RPM by rotating or pitching the blades about their lengthwise (spanwise) axes to control the aerodynamic torque imparted to the rotor as the wind speed varies. This type of speed control is referred to as full-span pitch control.

The nominal rotational speed of the Mod-0 is 40 RPM, but a belt drive incorporated in the drive train system (see fig. 2) has permitted the machine to be run at several different speeds for test purposes. Power is transmitted from the rotor through a speed increasing gearbox to a synchronous generator operating at 1800 rpm to produce 60-hertz power.

The entire assembly illustrated in fig. 2 is mounted on a steel, open-truss tower. This assembly is oriented to the wind by a yaw control mechanism. With a change in wind direction, the yaw control system orients the entire assembly using a hydraulic yaw drive connected to a large diameter ring gear.

The Mod-0 is installed at NASA's Plumbrook facility near Sandusky, Ohio. It became operational in the fall of 1975. It is being run in an automatic, unattended mode and synchronizes routinely with the Ohio Edison utility network. It has proved to be a valuable engineering test bed for evaluating advanced design concepts and validating the analytical methods and computer codes which are being used to design advanced machines. Some of the tests that have been conducted and those planned in the near future are discussed under "Technology Development".

Mod-OA

The Mod-OA Project will place four prototype units of the Mod-0 class into utilities to gain some early in-service experience. The Mod-OA is essentially the same design as the Mod-0 except for a larger generator (200 kW) and larger gearbox. The Westinghouse Electric Corporation of Pittsburgh, Pennsylvania is the prime contractor responsible for assembly and installation. The blades are built by the Lockheed California Company of Burbank, California.

The first Mod-OA was installed at Clayton, New Mexico; first rotation occurred in November of 1977. Following a checkout period, Lewis turned the machine over to the city of Clayton in March of 1978 to operate as an integral part of their utility system. The machine has operated successfully; it is operationally compatible with the utility grid and has generated 2 to 3 percent of the energy at Clayton since the machine was activated. As expected of the first machine in service, machine hardware problems have been encountered and have been corrected as they occur.

A second Mod-OA was installed at Culebra, Puerto Rico for the Puerto Rico Water Resources Authority and was activated in July, 1978. A third Mod-OA was installed at Block Island, Rhode Island for the Block Island Power Company and was activated in May, 1979. The fourth Mod-OA is planned for Hawaii and will be activated in 1980 on the island of Oahu for the Hawaiian Electric Company.

The Mod-OA project has demonstrated the technical feasibility of wind turbines in utility application. It has also provided valuable in-service testing of hardware and operations to help guide technology development.

Mod-1

The Mod-1 project was started in 1974. The Mod-1 is a 2-bladed, 200-foot diameter wind turbine with a rated power of 2000 kW. The blades are steel and the rotor is located downwind of the tower. Full-span pitch is used to control the rotor speed at a constant 35 RPM. The gearbox and generator are similar in design to the Mod-OA but, of course, are much larger. The tower is a steel, tubular truss design. The General Electric Company, Space Division of Philadelphia, Pennsylvania is the prime contractor for designing, fabricating and installing the Mod-1. The Boeing Engineering and Construction Company of Seattle, Washington, manufactured the two steel blades.

The Mod-1 is scheduled to be operational by mid-1979. A single prototype will be installed at Boone, North Carolina and will supply power to the Blue Ridge Electrical Membership Corporation.

Mod-2

The Mod-2 project was initiated in 1976. The machine is currently in final design and is to be a 2-bladed, 300-foot diameter wind turbine with a 2500 kW rating. This machine is being designed with a new technology base developed as a result of research and development efforts on Mod-0, Mod-OA, and Mod-1. Because of this, the Mod-2 is referred to as a second generation machine.

The Mod-2 rotor will be upwind of the tower. Rotor speed will be controlled at a constant 17.5 RPM. In order to simplify the configuration and achieve a lower weight and cost (the cost of these machines is closely tied to weight and complexity), the use of partial-span pitch control is being incorporated rather than full-span pitch. In this concept, only a portion of the blade near the tip (the outer 30% of the span) is rotated or pitched to control rotor speed and power. To reduce the loads on the system caused by wind gusts and wind shear, the rotor is designed to allow teeter of up to 5 degrees in and out of the plane of rotation. This reduction in loads saves weight and, therefore, cost in the rotor, nacelle and tower.

The Mod-2 tower is designed to be "soft" (flexible) rather than "stiff" (rigid). The softness of the tower refers to the first mode natural frequency of the tower in bending relative to the operating frequency of the system. For a two-bladed rotor, the tower is "excited" twice per revolution (2P) of the rotor. If the resonant frequency of the tower is greater than 2P it is referred to as "stiff". Between 1P and 2P it is generally characterized as "soft" and below 1P as "very soft". The stiffer the tower, the heavier and more costly it will be. The tower's first mode natural frequency must be selected to be sufficiently displaced from the primary forcing frequency (2P) so as not to resonate. Care must also be taken to avoid higher mode resonances.

The tower is a welded steel, cylindrical shell design. This design is more cost-effective than the stiff, open-truss tower. The gearbox is a compact, epicyclic design which is lighter weight than a parallel-shaft gearbox such as used on Mod-1. The nacelle configuration of the Mod-2 is illustrated in fig. 3.

The Boeing Engineering and Construction Company is the prime contractor for designing, fabricating, and installing the Mod-2. Current plans call for 3 prototype units to be installed at a single site during 1980-81. The site has not yet been selected.

Second Generation Designs

Second generation machines such as the Mod-2, will incorporate advanced design features for reducing machine weight and cost below first generation designs (Mod-OA and Mod-1).

The improvement that is anticipated in the Mod-2 is illustrated below:

	"Stiff" Designs		"Soft" Design
	Mod-OA	Mod-1	Mod-2
Rated Power (kW)	200	2000	2500
Weight* (k lbs)	90	655	600
Lbs/kW	450	328	240

* Weight on the tower foundation

This design evolution is based, in part, on a 1977 study for Lewis, by the General Electric Space Division, of an advanced concept called Mod-1A.

As the Mod-1 design effort progressed, it became clear that the Mod-1 would be relatively heavy and costly and could not lead to a cost competitive production unit. Weight and cost were being driven by a number of factors, the most significant of which were the "stiff" design criteria, the full-span pitch which required complicated, heavy mechanisms and excessive space in the hub area, and a heavy bedplate supporting the weight on top of the tower. At the same time, the analytical methods and computer codes required to analyze wind turbine dynamics and loads and the Project Team's understanding of the system's interactions advanced markedly, thus enabling the team to identify a number of configurational and design concepts which could be highly beneficial. These could not be incorporated into the Mod-1 without substantially redirecting and delaying the project. Consequently, General Electric was asked in 1977 to develop a conceptual design of a Mod-1 class machine incorporating these concepts for weight and cost savings. The resulting configuration called Mod-1A, reflected a projected weight reduction of more than 50 percent and a projected cost reduction of more than 40 percent from Mod-1.

A comparison of the Mod-1 and Mod-1A configurations is shown in fig. 4 illustrating the reduced size of the Mod-1A nacelle and tower. Like Mod-1, Mod-1A is a 2-bladed, 200-foot diameter wind turbine with a rated power of 2000 kW. However, it is a "soft" design like Mod-2, uses partial-span pitch control and a teetering rotor to reduce loads and uses the gearbox as an integral load carrying structure. Together, these features eliminate the need for a bedplate. The tower is a welded steel, cylindrical shell design (the Mod-2 tower concept is simlar to this design). Substantial economies in weight and cost were also realized in the yaw system's structure and control mechanisms relative to the Mod-1 due to the reduced top weight, smaller diameter yaw bearing and simplified yaw mechanisms.

It is anticipated that further weight and cost reductions in future machines will be possible through additional technology development.

Technology Development

As noted earlier, significant strides in large wind turbine technology have been made in the last several years. Analytic methods and computer codes have been developed, enabling the designer to analyze, in detail, the dynamics and loads of large wind turbine systems. These analytic methods and computer codes have been validated by comparing the analytical results to the operational data obtained from the Mod-0 research wind turbine. The Mod-0 has been used extensively to test system controls and various configurational changes and design features which have helped to confirm contemplated design improvements. Some examples are:

1) Various concepts have been tested for providing a sufficiently soft drive train to prevent variations in rotor input torque from being fed through the rest of the system. One result of these tests was verifying that a fluid coupling between the rotor and the gearbox could provide adequate attenuation of torque variations. This approach was incorporated in the Mod-0A machines.

2) Mod-0 has also been used to test the operational and control requirements of synchronous and induction generators.

3) Tests of the effects of a soft tower on system dynamics and loads have been performed by fitting the Mod-0 tower with a flexible base permitting different degrees of tower softness to be simulated.

Some of the areas to be examined in future tests include:

1) partial-span (tip) rotor speed control,

2) teetered hub,

3) passive yaw control using a downwind rotor with a teetered hub,

4) microprocessor control strategies to increase energy production,

5) fixed pitch blades,

6) different airfoil designs and shapes to improve aerodynamic performance,

7) multi-speed generators to permit multi-speed rotor operation and increase energy production.

A technology development effort on blades is being conducted. A 150-foot fiberglass blade has been fabricated and tested, and shows promise of providing a cost-effective design approach. Fiberglass blades of this nature will be tested on the Mod-1 in 1980. The design of a wood blade is also being pursued and appears attractive from a cost standpoint.

Further technology development is required to reduce the cost and improve the performance of future machines. Areas for potential improvement include:

(1) Improved rotor aerodynamic efficiency and energy capture;

(2) Improved component arrangements in the nacelle to optimize structural load paths and reduce overall structure weight;

(3) Reduced blade and overall rotor weight with attendant weight reductions throughout the system;

(4) More flexible ("very soft") tower;

(5) Improved drive train efficiency and reduced weight;

(6) System designs to simplify erection and installation;

(7) System designs for high reliability and ease of maintenance to reduce operating and maintenance costs.

Wind Turbine Costs

Elements of Capital Cost

The total capital investment for a wind turbine consists of the following elements:

Installed equipment cost
Land cost
Intra-cluster costs (for clusters of machines)
Contingency
Allowance for funds during construction (AFDC)

Capital Cost of Prototype Units

The installed equipment costs of the prototypes of the large, horizontal-axis wind turbines currently under development are (1977$):

	Mod-0A	Mod-1	Mod-2
Cost ($M)	1.61	5.40	3.37
($/kW)	8050	2700	1350

Second-unit costs are quoted so as not to include the nonrecurring costs associated with the first prototype unit.

The Mod-0A second-unit prototype cost represents Lewis' estimate of the cost that would be required to build a second unit identical to the first unit at the Clayton, New Mexico site and reflects the knowledge and experience gained as well as the actual costs incurred in that first installation. The costs for the Culebra, Puerta Rico machine (2nd Mod-0A installed) were not used because of the unusual costs associated with the transportation of equipment, materials and personnel to this island site and the site preparation and installation costs.

For the Mod-1, the second-unit prototype cost is based upon an estimate made by the General Electric Space Division. Although only a single prototype unit for the Mod-1 is to be built, this estimate for the second prototype unit is judged to be a reasonable estimate for the second-unit installed equipment cost.

The Mod-2 second-unit prototype cost is based upon the current estimate of the installed equipment for the second prototype unit to be built by the Boeing Engineering and Construction Company.

It should be remembered that the second-unit prototype cost estimates for the Mod-OA, Mod-1 and Mod-2 do not include land, intra-cluster costs, contingency and AFDC. Inclusion of these elements, however, is somewhat academic for the prototype units since these second-unit prototype costs would not be generally competitive as a utility powerplant.

Capital Cost of Production Units

When wind turbines are designed for quantity production and subsequently produced in quantity, their capital costs are expected to decrease substantially. Substantial economies are expected when production rates are large enough to benefit from greater degrees of automation. Additional reduction will result from discounts on quantity buys of purchased materials and components. The distribution of engineering and management costs over a larger number of units will also reduce the per-unit cost. Finally, the cost of production wind turbines will not include the extensive test and checkout costs associated with prototype units.

Current estimates for the capital costs of large horizontal-axis wind turbines, when produced in quantity, are based on:

(1) projections of the 100th unit cost of Mod-2 by the Boeing Engineering and Construction Company (BEC),

(2) projections for the 100th unit cost of an advanced, 200 kW wind turbine based on an in-house conceptual design study by the Lewis Research Center in 1978[2].

These projections are based on second-generation technology. As will be indicated later, further cost reductions are feasible and will result in competitive wind turbine systems for a broad segment of the market.

The current estimate of the installed equipment costs (1977$) for the 100th production unit of Mod-2 is shown below along with a current estimate of weights.

	Weight on Foundation, lbs	100th Unit Cost, $K
Machine	(588204)	(1163)
Rotor Subassy.	169567	329
Drive Train Subassy.	103892	379
Nacelle Subassy.	63279	184
Tower Subassy.	251466	271
Transp. & Install.		(328)
Transportation		29
Site Preparation		162
Erection & Checkout		137
Initial Spares & Maint. Equip.		(35)
Production Facility Depreciation		(35)
Subtotal		1561
Fee (10%)		156
Total Capital for Installed Equip.		1717

These costs are per-unit costs assuming a 25-unit cluster.

The overall configuration resulting from Lewis' conceptual design study is shown in fig. 5. A breakdown of the estimated installed equipment costs (1977$) for the 100th production unit is shown below along with a weight breakdown[2].

	Weight on Foundation, lbs.	100th Unit Cost, $
Machine	(72920)	(153650)
Rotor Subassy.	9200	53840
Drive Train Subassy.	17600	38880
Elect. & Control Subassy.	3120	17140
Tower Subassy.	43000	43790
Transp. & Install.		(22710)
Transportation		3450
Site Preparation		14090
Erection & Checkout		5170
Subtotal		176360
Fee (15%)		26450
		202810

These cost estimates were based on a combination of vendor quotes and Mod-0/OA experience.

Operating and Maintenance Costs of Production Units

The operating and maintenance (O&M) costs for a large wind turbine will depend on the reliability and maintainability of the system. They will also depend on whether a single machine or a wind turbine cluster is to be operated and maintained. In the latter case, the fixed O&M expenses can be allocated to a number of wind turbines thus reducing the O&M costs per machine.

In the Mod-OA project, data are currently being collected on actual O&M costs at Clayton, New Mexico and Culebra, Puerto Rico. Data will also be collected at Block Island, Rhode Island and at Hawaii when these machines are fully operational. From these data, an estimate will be made of current and projected O&M costs for this size machine.

In the analysis conducted by Lewis of an advanced, 200kW wind turbine[2], the machine was designed with a view to minimizing O&M costs. An average annual O&M cost of $4,000 (1977$) was estimated. This estimate assumed that the machine was located in close proximity to an existing utility plant and benefited from having existing O&M personnel cross-trained to operate, service and maintain the wind turbine. It assumed a machine availability of 0.9, i.e., the wind turbine was assumed to be available for service 90 percent of the time when the wind speed was in the range where it could operate and produce power.

An estimate of $4,000/year for the average annual O&M cost for an advanced 200 kW wind turbine may be optimistic. However, until a more detailed estimate is made or operational data become available, the $4,000 estimate will be used for computing the cost of electricity produced by intermediate-size wind turbines (hundreds of kW).

BEC has conducted a detailed analysis of the O&M requirements of the Mod-2 in a 25-unit cluster. The baseline maintenance concept includes:

(1) 25 wind turbines per cluster;

(2) 2-shifts, 2-man crews, 6 days per week;

(3) Use of outside services for shop repair, special tasks and heavy equipment rental;

(4) 100% spares availability with small items in panel truck; large items stored at utility substation.

Crew requirements were based upon a detailed analysis of scheduled and unscheduled actions, mean time to failure and mean time to repair, crew queing and crew availability.

In the case of a single-unit Mod-2 installation, it has been assumed that it would be necessary to have effectively one full-time employee for O&M. The resulting estimates of the average annual O&M costs for both a 25-unit cluster and a single-unit installation are (1977$):

	25-Unit Cluster	Single-Unit
Labor (pro rata)	$8,000	$41,600
Parts and Outside Service	7,000	7,000
Total	$15,000	$48,600

It can be seen that the major difference between a single-unit installation and a 25-unit cluster is the labor cost. The single unit case assumes it is necessary to have one full-time employee for O&M (2080 hours/year X $20/hour). The 25-unit cluster case is based on 2 shifts with 2-man crews, 6 days per week. The labor cost is based on the same fully burdened labor rate ($20/hour) and prorating the cost over the 25 wind turbines.

Wind Turbine Annual Energy Production

The annual energy produced by a wind turbine depends on the machine design and the available wind energy at the wind turbine site. The design of the wind turbine determines the output power for any wind speed. The available wind energy must be determined for any given site. However, for planning purposes, the wind speed characteristics are often represented by a "nominal" wind model. This will be discussed later.

Wind Turbine Power Output

The power output (P) of a wind turbine is related to the effective wind speed, W, by the following relationship:

$$P = \rho\eta C_p W^3$$

Where P = the electrical output power of the wind turbine at the busbar, typically expressed in kilowatts. Electrical power is nominally limited to the rated power of the generator.

W = the effective wind speed, often assumed to be the wind speed at hub height and typically expressed in meters/second or miles/hour.

C_p = the coefficient of performance of the rotor. This is the aerodynamic efficiency of the rotor and is usually expressed as a function of the ratio of rotor tip speed to wind speed at the hub.

η = the throughput energy efficiency from the rotor output to the busbar. It includes the efficiencies of the gearbox, generator, accessories, and step-up transformer. The efficiencies of the rotating machinery tend to decrease at operation below rated power.

ρ = the air density at the elevation of the hub.

The machine produces power whenever the wind speed falls within the operating range. Fig. 6 illustrates the power produced by a wind turbine as a function of wind speed. Various wind speeds of importance to the design of a wind turbine are indicated in fig. 6. There are two values for cutin and cutout wind speeds as well as a wind speed at which the machine reaches rated power. The selection of these wind speeds involves a number of trade-offs.

The wind turbine cuts in at low wind speeds (low cutin) when the average wind speed is sufficient to provide the required starting torque and to bring the machine to its operating RPM for synchronization with the grid. The wind turbine cuts out at low wind speeds (low cutout) when the average wind speed can no longer sustain normal RPM at net power. The low cutout wind speed is lower than the low cutin wind speed (typically about 1-3 mph less) to avoid excessive starts and stops in light, variable winds.

The wind turbine cuts out at high wind speeds (high cutout) when the average wind speed reaches a level determined by design loads. Cutin at high wind speeds (high cutin) occurs when the wind speed has decreased sufficiently below the cutout point (high cutout) to avoid excessive stops and starts in variable winds. Typically, the high cutin wind speed is about 1-3 mph less than the high cutout wind speed.

To generate the maximum amount of energy, the cutin and cutout wind speeds are selected to provide as broad an operating range as possible subject to the constraints noted above.

The rated wind speed is that wind speed at which the machine develops its rated power. Rated power is selected to minimize the cost of electricity.

The cutin, rated and cutout wind speeds (measured at hub height in mph) for the Mod-OA, Mod-1, and Mod-2 are:

	Mod-OA	Mod-1	Mod-2
Low Cutout	10.0	15.6	13.0
Low Cutin	12.0	15.6	14.0
Rated	21.7	32.6	27.7
High Cutin	35.0	42.6	42.0
High Cutout	40.0	42.6	45.0

Wind Model

The model for steady wind speeds used to compute the annual energy production is based on ref. 3. The annual distribution of steady wind speeds is given by the following Weibull distribution:

$$P\ (V_S \geq V) = \exp\ [-(V/C)^K]$$

where $P(V_S \geq V)$ = probability that $V_S \geq V$

V_S = steady wind speed, m/s

V = prescribed value of V_S, m/s

K = constant $\approx 1.09 + 0.20\ \overline{V}$

C = constant $= \overline{V}/\ \Gamma\ (1 + 1/K)$, m/s

Γ = Gamma Function

$\overline{V}$ = mean wind speed, m/s

Fig. 7 shows steady wind speed exceedance curves for wind speeds measured at a 9.1m (30 ft) height for several mean wind speeds. These curves display the number of hours per year that a wind speed is exceeded for a given site.

Basic properties of the Weibull distribution are discussed in ref. 3. This distribution model has been found useful and appropriate by a number of investigators for wind turbine performance analyses.

Wind turbine performance is calculated using the wind speed computed at the hub height. The relationship between the wind speed at a reference elevation such as 9.1 m and the wind speed at the hub is given by a wind shear model. For nominal performance calculations, wind speeds at elevations other than the reference elevation are given by the following equations:

$$V = V_r\ (h/h_r)^{\alpha}$$

where V = steady wind speed at elevation of interest, m/s

V_r = steady wind speed at reference elevation, m/s

h = elevation of interest, m

h_r = reference elevation = 9.1m (30 ft.)

and

$$\alpha = \alpha_o(1 - \log V_r/\log V_o)$$

$$\alpha_o = (Z_o/h_r)^{0.20}$$

Z_o = surface roughness length = 0.06m (0.20 ft.)

V_o = 67.1 m/s (150 mph)

The above wind shear relationship is a reformulation of the wind shear model of ref. 3 to include Z_o (surface roughness) explicitly. This permits a more straightforward evaluation of the effects of wind shear for a variety of topographical features which can be characterized by the surface roughness length, Z_o. Typical values[4] of surface roughness length range from 10^{-5}m to 4m. The selected roughness length (0.06 m) gives results consistent with the empirical values cited in ref. 3.

The annual wind speed distribution for the reference elevation of 9.1 m was defined above. At other elevations, the wind gradient power law is used to modify the Weibull parameters as follows:

$$K_h = K_r/[1 - \alpha_o(\log(h/h_r)/\log V_o)]$$

$$C_h = C_r(h/h_r)^{\alpha_h}$$

where

$$\alpha_h = \alpha_o(1 - \log C_r/\log V_o)$$

C_r and K_r are the Weibull parameters at the reference elevation (9.1 m) and C_h and K_h are the corrsponding parameters at elevation, h, above natural grade.

Wind Turbine Energy Output

The annual energy output for any horizontal-axis wind turbine can be computed for a specific wind speed duration curve by computing the power output at each wind speed and integrating it over the appropriate time duration for each wind speed.

The annual energy produced by the Mod-OA, Mod-1, and Mod-2 are illustrated in fig. 8 as a function of the mean wind speed at 30 feet above the ground. These annual electrical energy production curves account for the aerodynamic, electrical, and mechanical losses up to the busbar (output side of wind turbine's step-up transformer). They also include a 90% availability factor, i.e., the wind turbine is assumed to be available for service 90% of the time that the wind speed is in its operating range.

Cost of Electricity from Large Wind Turbines

The cost of electricity (COE) produced by wind turbines is computed as follows:

$$\text{COE (cents/kWh)} = \frac{(\text{Capital Cost},\$)\ (\text{Fixed Charge Rate},\ \%)}{(\text{Annual Energy, kWh})} + \frac{(\text{Annual O\&M costs},\$)\ (\text{Levelizing Factor})\ (100)}{(\text{Annual Energy, kWh})}$$

The cost of electricity is taken to be at the output of the installation's step-up transformer. Capital cost, O&M costs and annual energy production were discussed in previous sections. The two economic factors, fixed charge rate and levelizing factor, are briefly discussed in the following paragraphs.

Fixed Charge Rate

The fixed charge rate (FCR) is a capital levelizing or annualizing factor which accounts for the return to investors, depreciation, allowance for retirement dispersion, income and other taxes, and other items such as insurance and working capital. It is a function of the design life of the unit, the general inflation rate, the debt/equity ratio of the utility and other financial parameters such as the weighted average cost of capital. Methods for computing the FCR are described in refs. 5-7.

A fixed charge rate of 18% has been assumed in computing the COE for large, horizontal-axis wind turbines. This is a representative value for investor-owned utilities, assuming a general inflation rate of 6%, no allowance for tax preferences, an after-tax weighted average cost of capital of 8.0% (10% before tax) and a 30-year life.

Levelizing Factor

In order to correctly compute the total levelized revenue requirement or COE of a wind turbine (or any utility powerplant for that matter), expenses such as O&M costs which will tend to increase with time due to inflation (and thus result in a variable stream of annual costs) must be levelized before adding them to the levelized capital investment.

Levelization of expenses can be accomplished by multiplying the first year's expense by a levelizing factor[6]. The levelizing factor is a function of the general inflation rate, the cost of capital and any real escalation (above inflation) to which the expense may be subject. Using the assumed values of economic parameters described above and a 0% real escalation rate on O&M costs, the coresponding levelization factor is 2.0.

Cost of Electricity

The cost of electricity (COE) for the second prototype units of Mod-0A, Mod-1, and Mod-2 is shown in fig. 9 versus the site mean wind speed. The installed equipment costs shown earlier for the second prototype units were used in computing these COEs.

Sufficient operational data is not yet available to determine an appropriate O&M cost for these prototype units. Furthermore, because the prototype units are aimed at providing in-service testing and hardware qualifications, larger O&M costs will be experienced in these early prototypes than are expected from production units. Based on the estimates made for production units, the annual, levelized O&M cost for the prototypes was assumed to equal 2% of the total capital investment. A total fixed charge rate of 20% (18% on capital plus 2% for O&M) was therefore applied to the total capital investment to compute the COEs in fig. 9.

As noted in fig. 9, the reduction in COE from Mod-0A to Mod-1 is mainly attributable to economy of scale. The COE reduction from Mod-1 to Mod-2 is mainly the result of improved technology, i.e., moving from a rather stiff and heavy design to a relatively soft and lighter weight design.

The COEs of the prototype units displayed in fig. 9 are not low enough to be generally attractive to utilities. However, in quantity production the capital costs are expected to decrease substantially, as was discussed in the section, "Wind Turbine Costs".

A comparison of large wind turbines with products that have reached a mature status and that have similar functional requirements and design complexities (fig. 10) suggests that it is reasonable to expect that wind turbines can achieve a price of \$2/lb to \$3/lb. At this price level, wind turbines should be economical for a substantial number of utilities.

Applying this range of anticipated mature product costs to the Mod-2 gives the COEs shown in fig. 11. The mature product cost was applied to the estimated weight for Mod-2 (600,000 lbs). To this was added the cost of site preparation which is a cost that is peculiar to wind turbines and not accounted for in the mature product \$/lb figures.

The COEs in fig. 11 assume a 25-unit cluster which is estimated to have a per-machine availability of 0.96. This is higher than the availability estimated for a single-unit installation (0.90). This is due to a more efficient use of maintenance personnel and equipment and being able to economically maintain a larger inventory of spare parts thereby reducing the waiting time for parts. An average annual O&M cost of \$15,000/unit was assumed which is the current estimate for a 25-unit cluster of Mod-2 machines. A levelizing factor of 2.0 was applied to this estimate.

The current estimate of COE for the Mod-2 100th production unit falls within this range. For a site mean wind speed of 14 mph, for which the Mod-2 is optimized, the COE of the Mod-2 100th production unit ranges from \$.035/kWh considering only the installed equipment cost to about \$.040/kWh where nominal costs for land, contingency, intra-cluster costs and AFDC are included. The total cost including these adders would be more representative of the total cost to a utility.

The range of \$2/lb to \$3/lb represents a reasonable target for large, mature wind turbines. To achieve this, however, will require that further reductions in COE come from further weight reductions while maintaining simplicity in design and manufacturability. This will require further improvements in technology. Areas where further technology improvements are expected were discussed under "Technology Development" in the section, "Development Status of Large Wind Turbines".

The question of what COE is required for wind turbines to be generally attractive to utilities is addressed in the following section.

Wind Turbine Breakeven Costs for Utility Application

Wind turbines in utility application can save fuel and for some utilities may be counted as a capacity addition similar to the way in which conventional powerplants are considered.

Fuel Saver Mode

As a fuel saver, the power produced by a wind turbine in a utility system will enable the utility to reduce or shut down the generation from conventional, fuel-burning powerplants that would otherwise be required. The fuel thus saved can be credited to the wind turbine. In this mode, wind turbine power would be used whenever it is generated.

The ability of wind turbines to save fuel will, in part, depend on how readily a utility's conventional powerplants can respond to changes in the wind power being produced. For modest amounts of wind power, the wind power variations are expected to be of the same order as normal load variations and will appear to be a negative load to the rest of the system. At some level of wind power contribution (perhaps greater than 10% of system peak load), the wind variability may adversely affect system stability in the absence of short term storage. This level must be determined by each individual utility because it depends on the conventional mix, the characteristics of the load, the variability of the wind at the wind turbine site, etc.

Most utilities use economic dispatch. Units with the lowest operational cost are dispatched first and those with the highest operational cost are dispatched last. With this strategy, wind turbines will tend to save the most costly fuel being burned at any particular instant of time. At times, the fuel saved will be relatively expensive gas turbine fuel (oil or gas) while at other times, relatively inexpensive baseload coal (it is assumed that nuclear plants would not be throttled to save nuclear fuel). Thus, the first increment of wind turbine power added by a utility will be the most attractive. As more wind turbines are added to a system, they will tend to save less costly fuel as they meet more of the system load. Here again, each utility's fuel savings per kWh of wind turbine energy produced will be different depending on its generation mix, its price of fuels, etc.

Ultimately, fuel savings attributable to wind turbines must be determined on an individual utility basis. The Department of Energy (DOE) has supported a number of studies[8-11] aimed at developing generic analytical techniques and approaches that may be used by utilities in this determination.

To obtain some overall feel for the COE requirements of wind turbines, one can examine the price of fuels paid by utilities. As noted above, the first increment of wind turbine power added by a utility will tend to save the most expensive fuel being used at any instant of time when the wind turbine produces power. Successive additions will save fuels that are decreasingly costly. Thus, for modest amounts of wind turbine power the average price of fossil fuels paid by a utility affords a conservative measure of the COE that wind turbines must achieve to be generally attractive to a utility. This is a conservative approach in that the average price of fossil fuels for most utilities will be heavily weighted to their baseload fuel prices because of the predominance of baseload generation.

The estimated average price of fossil fuels paid by each of some 310 utilities in 1977 is illustrated in fig. 12. The utilities included represent nearly 98% of all U.S. fossil generation. Fig. 12 is based upon an analysis of data from refs. 12-14.

In order to assess whether a wind turbine would be an attractive investment as a fuel saver, the total life-cycle fuel savings over the lifetime of the wind turbine must be compared to the total life-cycle cost of the wind turbine. This approach, of course, determines the so-called breakeven cost at which point any investor would be indifferent (theoretically at least) to whether he made the investment or not. In any investment decision, the perceived risks and uncertainties will play a major role. Thus, it is prudent to be conservative in assessing the breakeven costs of wind turbines to minimize the perceived risks and uncertainties.

One method commonly used in breakeven analyses is to compare the present value of all savings to the present value of all costs or, alternatively, to compare the annual levelized savings and costs. The latter is convenient and easily understood since the annual levelized cost of a wind turbine divided by its annual energy output is the COE. Thus a wind turbine that has a COE of \$.02/kWh would breakeven if its annual levelized savings also equalled \$.02/kWh.

Fuel costs (and therefore savings) will tend to increase with time due to inflation. They may also increase faster than inflation, i.e., escalate in real terms. The annual fuel savings attributed to the wind turbine at the beginning of its life may be multiplied by a levelization factor to find the annual levelized fuel savings over the life of the wind turbine. This is analogous to the way in which average annual O&M expenses are levelized to determine their contribution to COE. Thus, if we assume a 6% general inflation rate and assume that fuel prices will not escalate in real terms, the appropriate levelization factor is 2.0. The assumption that fuel prices (and therefore savings) will increase only at the general inflation rate is generally thought to be conservative.

Based on the range of fuel prices paid by utilities in 1977 and assuming that fuel prices will increase at the rate of general inflation, it appears that a COE range of \$.02/kWh to \$.03/kWh for mature wind turbines will make them attractive to a significant number of utilities. Achieving COEs in this range is contingent, of course, on utilities having sufficiently good wind sites. If we compare the COE range of the second generation Mod-2 from fig. 11 with this target range we see that a mature Mod-2 would be generally competitive at sites having mean wind speeds of 15 mph or greater. Anticipated weight and cost reductions in advanced machines are expected to bring the COE within the target range at more sites, thus significantly increasing the potential market.

Capacity Credit

In addition to fuel savings, "capacity credit" may increase the breakeven COE beyond that of a "fuel saver". Capacity credit is defined as the amount of conventional capacity that may be displaced by wind turbines divided by the amount of wind turbine capacity added to the system while maintaining the same system reliability. Determination of capacity credit is very dependent on the variability of the wind at a specific site (which determines the effective forced outage rate of the wind turbine), the makeup of the utility's generation mix and the nature of its load profile. Consequently, capacity credit can only be adequately determined by examining individual utilities in some detail. Based on a recent General Electric study[15] of wind turbine economics conducted for EPRI, and several studies supported by DOE[8-10], the contribution of capacity credit to a wind turbine's value will be generally modest.

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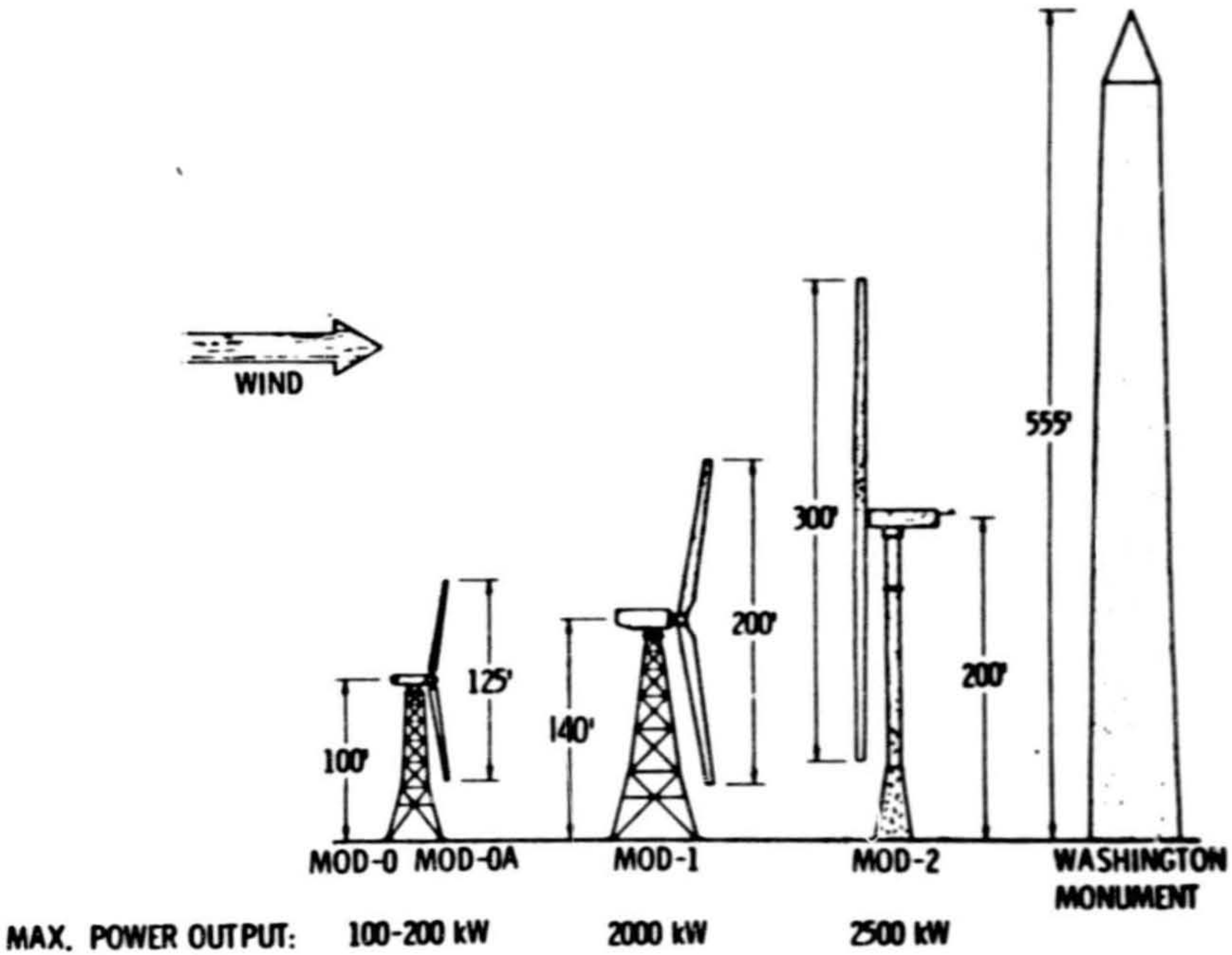

Figure 1. - Large wind turbines

CS-79-1109

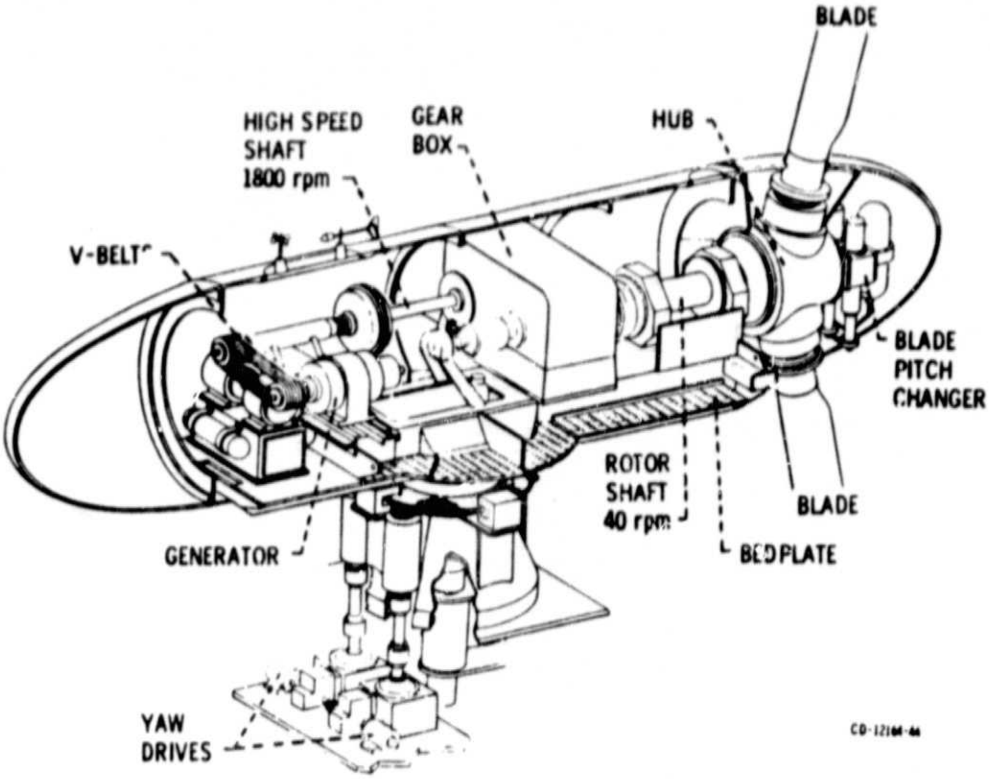

Figure 2. - Mod-0/0A drive train assembly and yaw system.

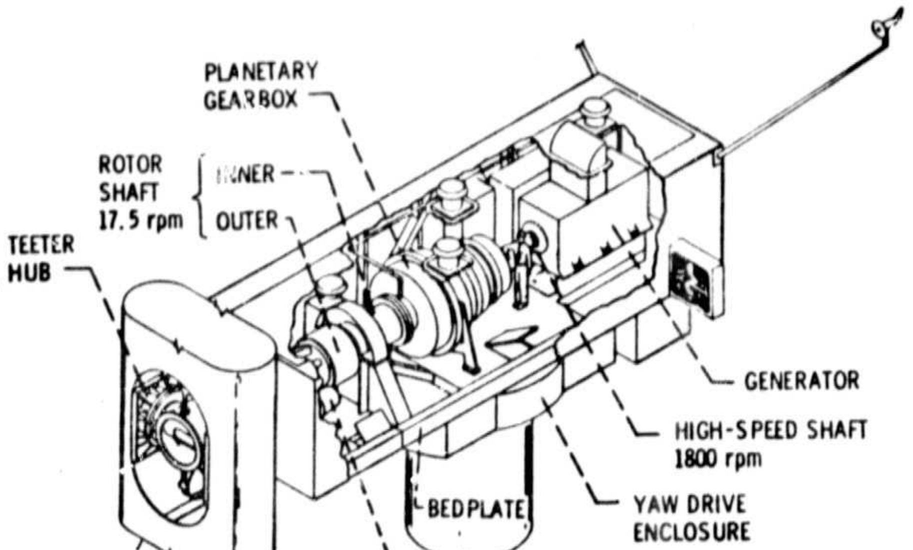

Figure 3. - Mod-2 nacelle.

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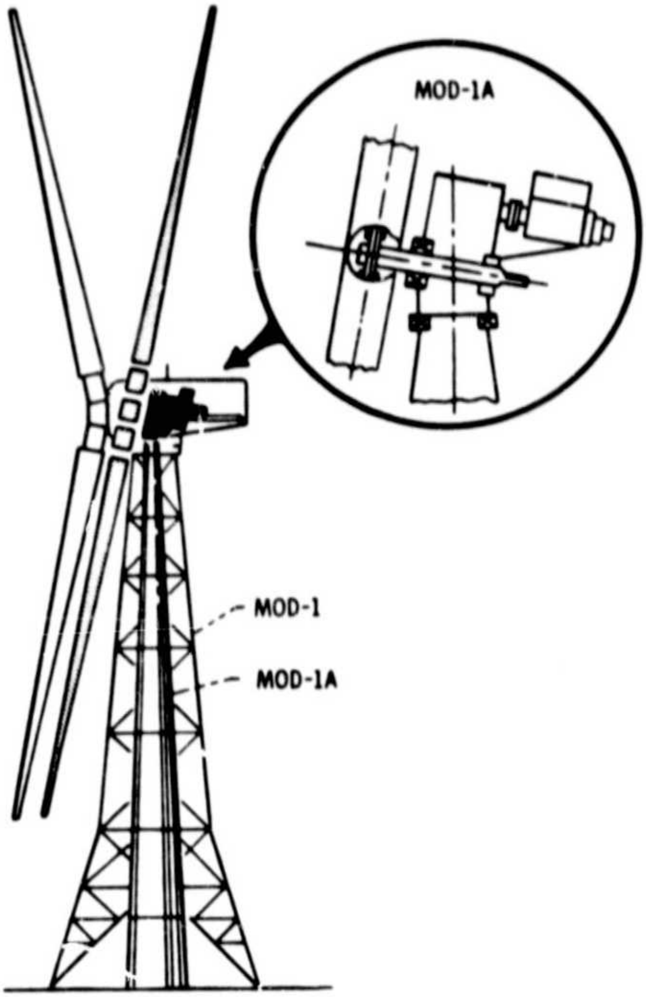

Figure 4. - Mod-1/Mod-1A comparison.

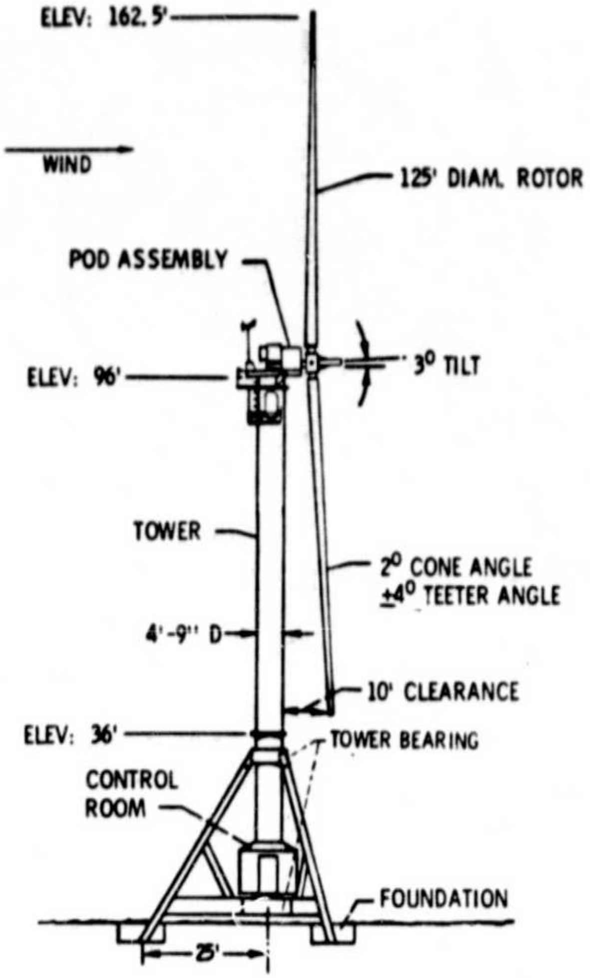

Figure 5. - 200 kW advanced conceptual design.

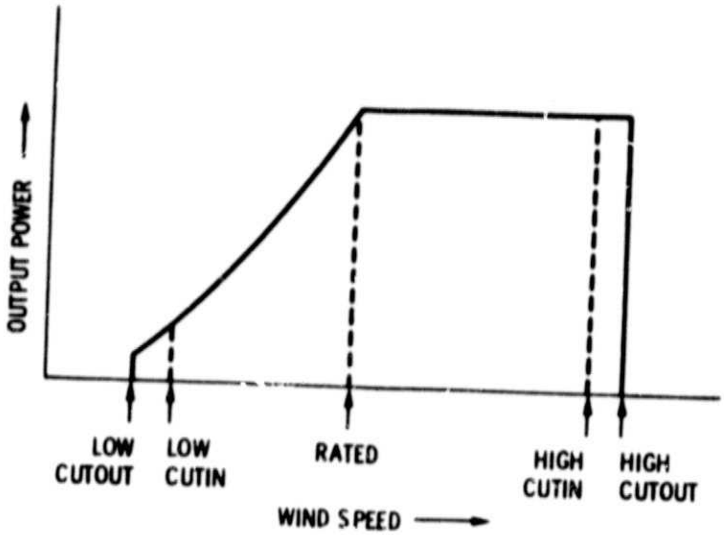

Figure 6. - Wind turbine output power vs wind speed.

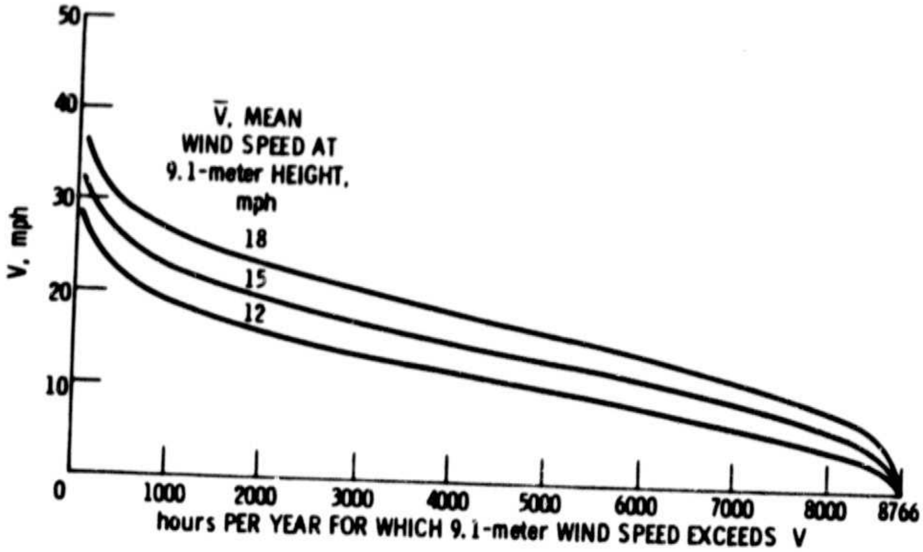

Figure 7. - Wind speed exceedance curves.

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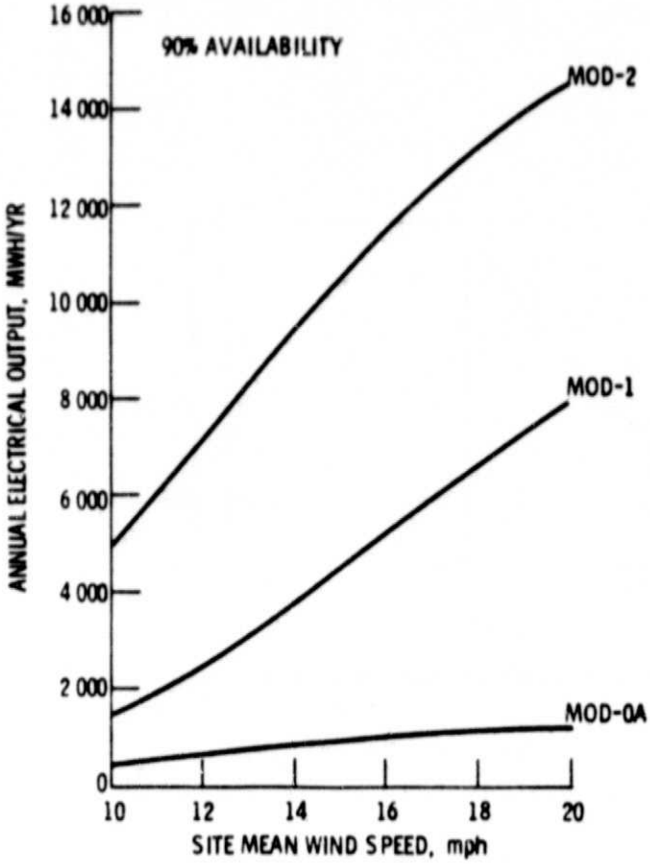

Figure 8. - Wind turbine annual output.

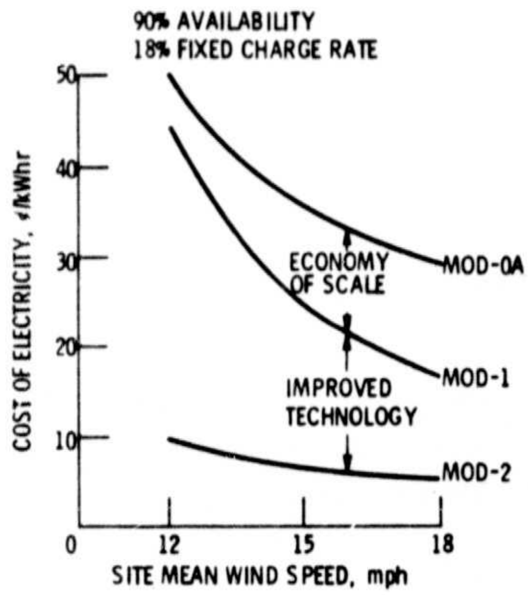

Figure 9. - Cost of electricity for 2nd prototype units.

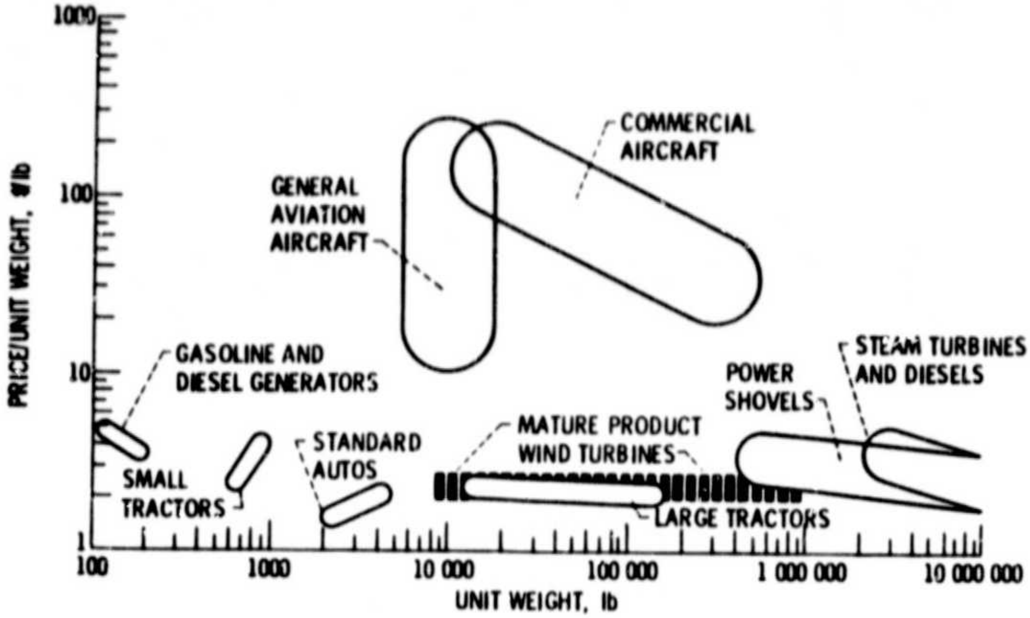

Figure 10. - Retail price of mature products (1977 $).

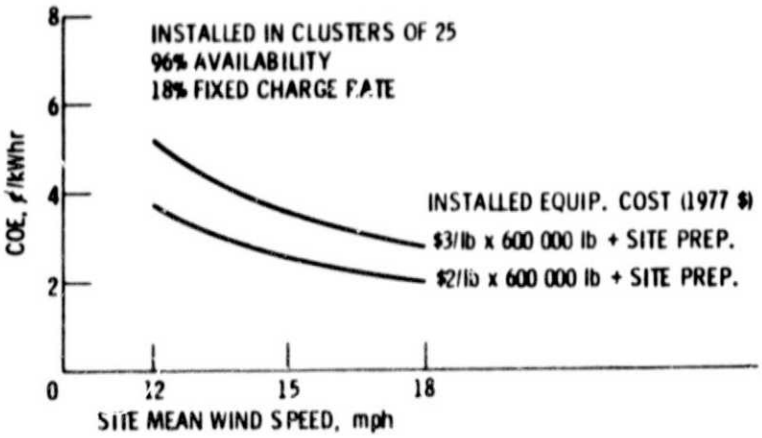

Figure 11. - COE of mature Mod-2.

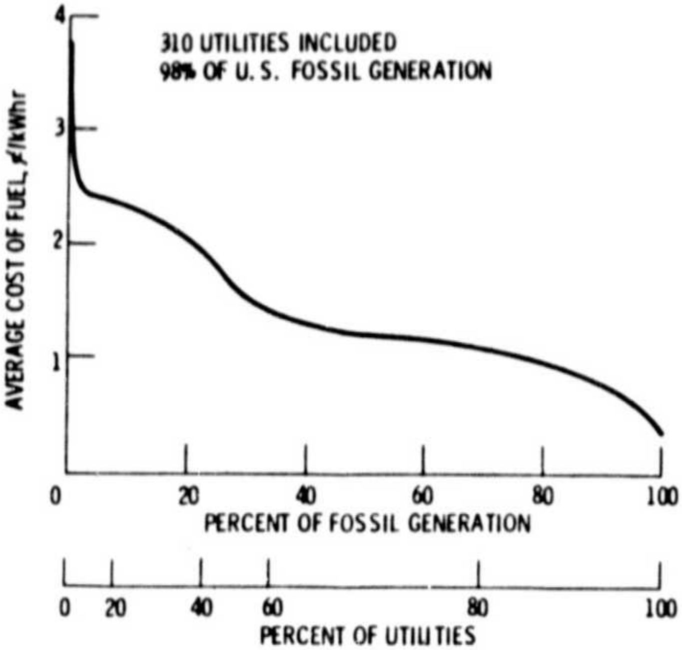

Figure 12. - Average fossil fuel costs to utilities in 1977*.