To minimize internal bending stresses during rotation, blades are shaped to approximate a *troposkien* (from the Greek for "turning rope"), a shape with zero bending stress. VAWT rotors contain two or three fixed-pitch blades, usually symmetrical in cross-section and without twist or taper. As with a HAWT, the *swept area* of a VAWT is defined by the projection on a vertical plane of the surface generated by the moving blades. *Rotor diameter* is the width of the swept area at its equator. *Rotor height* is the distance between upper and lower hubs and is usually 15% to 30% larger than the diameter.

Darrieus rotors are stall-controlled, because pitch-change mechanisms have not been found to be cost-effective. Motoring of the generator is the usual method for starting Darrieus rotors, since the blades develop lift and torque only through a superposition of rotational (forward) speed and the wind speed and, therefore, are not normally self-starting. VAWT rotors are usually stopped by applying a *rotor brake* in the power train, although trailing-edge flaps have also been used for this purpose.

The most common material for Darrieus blades is extruded aluminum alloy. Blades are bolted to the upper and lower hubs, each of which is rigidly connected to the rotor column. Thus, the rotor column collects torque from the two hubs and transmits it to the power train. Buckling strength is the principal structural requirement on the rotor column, since it must react the relatively high downward loads produced by the supporting cables.

The Power Train Subsystem

Comparison of Figure 2-7(b) and 2-4 shows that there are three major differences between HAWT and VAWT power trains. First, VAWT power-train components are located at or near the ground, which provides for easier maintenance and requires a relatively low support stand. Second, the VAWT turbine shaft assembly carries axial and torque loads only, with no bending loads like those on a HAWT turbine shaft. Third, the VAWT rotor brake is much larger than the parking brake typical of a HAWT, because it must be able to stop a Darrieus rotor operating at top speed. It may even be located on the turbine shaft for added reliability, so that the braking torque does not have to be transmitted through the gearbox.

VAWT gearboxes, generator-drive shafts, and generators have the same general configurations and functions as described previously for HAWT power-train components, except for their vertical rather than horizontal orientation.

The Support Structure Subsystem

The VAWT support structure consists of *upper and lower rotor bearings*, *structural cables with tensioning devices*, and a *support stand*. Darrieus rotors require three or four cables (or sets of cables) to support the upper end of the rotor in a horizontal plane. These cables stretch from the upper rotor bearing to ground anchors at an elevation angle of about 30 to 40 degrees. Cable tension causes a downward thrust load on the upper rotor bearing equal to one-half or more of the tensile loads in all cables. This thrust load passes downward through the rotor column, to the lower rotor bearing, the support stand, and finally to the foundation. Depending on the design, the upper and lower hubs may also be in the compressive load path.

The fundamental system frequency of a VAWT is determined by the size and tension of the cables, because they are the elastic springs which restrain motions of the center of mass of the VAWT rotor. Like a HAWT tower, cables can provide stiff, soft, or soft-soft support to the rotor. Cables are usually sized and tensioned to a soft condition, producing a fundamental system frequency greater than the rotor speed but less than the blade passing frequency (*i.e.*, the number of blades times the rotor speed).

The height of the support stand is equal to the ground clearance. The minimum ground clearance required for safety is usually much less for a VAWT than for a HAWT, because the speed of a VAWT blade near the ground is relatively low. Any increase in support-stand height above the minimum ground clearance again depends on a trade-off between the marginal increase in energy capture and the marginal increase in system cost. The latter is relatively high because many cable changes must be made in order to maintain the desired fundamental system frequency as the upper bearing is raised. These include larger cables, more cables, and higher cable tension, which in turn require more capacity in rotor bearings, more buckling strength in the rotor column and support stand, and more weight in the cable foundations.

All these cost factors combine to keep the elevation of the center of a typical Darrieus VAWT rotor lower than that of a HAWT with the same swept area. Because average wind speed generally increases with elevation, the annual average *wind power density* of a VAWT rotor (in watts of wind power per square meter of swept area) is usually lower than that of a comparable HAWT rotor at the same site.

The Foundation Subsystem

VAWT foundations include a *central foundation* under the support stand and a *cable foundation* at the lower end of each set of support cables. Because the central foundation is not subject to uplift or overturning loads, its weight is usually less than the combined weights of the cable foundations, and it is not as wide or as heavily reinforced as a HAWT tower foundation. VAWT cable foundations contain steel cable anchors, are heavily reinforced to resist tensile stresses, and are sized to prevent uplift or shifting which would result in loss of cable tension.

The Ground Equipment Station

The equipment on the ground that interfaces a VAWT with the electric utility system or other user is essentially the same as that required for a HAWT of the same power rating. This equipment may all be housed in an enclosure separate from the VAWT, or part of it may be located on the central foundation.

Wind Turbine System Performance

The principal measure of the performance of a wind turbine system is *annual energy output*, which is the *electrical energy* delivered to the customer during a complete year [ASME 1989]. *System power output* is often used as an intermediate measure of performance and is defined by electrical power output as a function of steady wind speed (graphed as the *power-versus-wind speed curve* or, simply, the *power curve*). Obviously, the net electrical energy produced by a wind turbine system will depend on the energy of the wind passing through its swept area, as well as on the efficiencies of its components.

A measure of the energy-conversion efficiency of a wind turbine system is its *coefficient of energy* or *energy recovery factor*, defined as the ratio of its electrical energy output to its wind energy input over the course of a year. Thus

$$C_E = \frac{\text{Annual Energy Output}}{\text{Annual Wind Energy Input}} = \frac{AEO}{E_W} = \frac{\int_{year} P_O \, dt}{\int_A \left(\int_{year} p_W \, dt \right) dA} \tag{2-1}$$

where
- C_E = coefficient of energy or energy recovery factor
- P_O = system output power (W)
- A = swept area of the turbine rotor; projection on a vertical plane (m^2)
- p_W = wind power density (W/m^2)

It is often convenient during the design process to calculate the coefficient of energy on the basis of a hypothetical *reference wind regime* that is representative of the wind speed distributions in time and space expected to be present during operations. The principal factors involved in determining reference values of annual energy production and annual wind energy will be introduced here and discussed in more detail in later chapters.

Reference Annual Wind Energy

Consider a horizontal *streamtube* of wind, which is air flowing in an imaginary pipe with all particles passing a given cross-section at the same speed. The *wind power density* at a point in this streamtube is the fluid-dynamic power per unit of cross-sectional area, given by the following equation:

$$p_W = 0.5 \, \rho \, U^3 \tag{2-2}$$

where
- ρ = air density (kg/m^3)
- U = horizontal component of the steady free-stream wind speed (m/s)

Thus, wind power density is directly proportional to the cube of the wind speed, and this fact is fundamental to both wind turbine design and site selection.

For purposes of calculating wind power density, wind speeds are usually averaged for about 0.1 hour to obtain the *steady wind speed*. This averaging process eliminates higher-frequency *turbulence* (instantaneous deviations from the average wind speed and direction) whose effects would be too rapid or too local to influence long-term energy conversion. The term "steady" is a relative one and relates only to a selected averaging period and elevation. The steady wind itself will vary over longer periods of time and with changes

in elevation, even at a specific geographic location. Because of these variations, a meaningful measure of the wind as a power source is the *annual wind energy density*, or

$$e_W(z) = \int_{year} p_W(z) \, dt = 0.5 \, \rho \int_0^\infty U^3 f_W(z) \, dU \tag{2-3}$$

where
- e_W = annual wind energy density at elevation z ($Wh/m^2/y$)
- t = elapsed time (h)
- f_W = frequency distribution function of U at elevation z [(h/y)/(m/s)]

Models of the Steady Wind

Two simple models are commonly used together to calculate the frequency distribution function f_W in terms of both wind speed and elevation. These are a *Weibull model* for the frequency distribution function of wind speed at a specified *reference elevation*, and a *power-law model* for the variation of wind speed with elevation (for details, see Chapter 8). The power-law equation for the vertical profile of the steady wind speed or *wind shear* is

$$U(z) = U_R \, (z/z_R)^\alpha \tag{2-4}$$

where
- z = elevation above level ground (m)
- z_R = reference elevation (m)
- U_R = steady wind speed at the reference elevation, at the same time as U (m/s)
- α = empirical wind shear exponent

The exponent α is not a constant, but varies with the roughness of the terrain, temperature gradients in the atmosphere over the site, and steady wind speed [Justus and Mikhail 1976, Spera and Richards 1979]. Equations (2-3) and (2-4) can be combined to give

$$e_W(z) = 0.5 \, \rho \int_0^\infty U_R^3 \, (z/z_R)^{3\alpha} f_W(z_R) \, dU \tag{2-5}$$

Placing α inside the integration permits it to vary with wind speed U.

The Weibull model for f_W at the reference elevation z_r is as follows:

$$f_W(z_R) = (8{,}760/C_R) \, k_R \, (U/C_R)^{k_R - 1} \exp[-(U/C_R)^{k_R}] \tag{2-6}$$

where
- C_R = empirical Weibull *scale factor* for winds at the reference elevation (m/s)
- k_R = empirical Weibull *shape factor* for winds at the reference elevation
- exp[ ] = exponential function of [ ]

The *annual average wind speed* can be expressed in terms of the Weibull factors as

$$U_{A,R} = C_R \, \Gamma(1 + 1/k_R) \approx (0.90 \pm 0.01) \, C_R \tag{2-7}$$

where
- $U_{A,R}$ = annual average wind speed at the reference elevation (m/s)
- $\Gamma(\,)$ = gamma function of ( )

DOE/NASA Reference Design Site and Reference Wind Regime

The characteristics of a *reference design site* were specified for the U. S. Federal Wind Energy Program (described in Chapter 3) in the 1970's in order to provide a uniform basis for research and development projects. This design site was one with level terrain and an annual average wind speed of 14 mph (6.24 m/s) at a reference elevation of 30 ft (9.1 m), and a wind shear exponent of 1/7. Early wind resource studies indicated that this site description was representative of large areas in the U. S. and around the world suitable for installation of wind turbines. In the early 1980's, during the development of megawatt-scale HAWTs for the U. S. Department of Energy, NASA engineers further defined the frequency distribution and vertical profile of a *reference wind regime* in the following terms:

$$z_R = 10.0\ m \qquad (2\text{-}8a)$$
$$\alpha_R = 0.351 - 0.192 \log(U_R) \qquad (2\text{-}8b)$$

$$C_R = 7.17\ m/s \qquad (2\text{-}8c)$$
$$k_R = 2.29 \qquad (2\text{-}8d)$$
$$\rho_R = 1.225\ kg/m^3 \quad (Sea\text{-}level\ Standard) \qquad (2\text{-}8e)$$

Figure 2-8 shows the reference frequency distributions of steady wind speed and wind power density at an elevation of 10 m. The area under the latter curve equals an annual wind energy density of 2,324 kWh/y/m^2. The wind speed at which the energy frequency is a maximum lies in the middle of the most energetic wind range at the design site. This speed is designated here as the *design wind speed*, U_D, because annual energy production is usually a maximum if a wind turbine is designed for maximum aerodynamic efficiency at $U \approx U_D$. With the specified model for the vertical profile of the wind speed, frequency distributions can be calculated for any given elevation [Spera and Richards 1979]. The parameters C, k, U_A, U_D, and e_W for the reference wind regime are given in Table 2-1 *vs*. elevation. It can be seen that the reference wind energy density increases significantly with elevation.

Referring to Equations (2-1) and (2-3), the reference annual wind energy becomes

$$E_W = \int_A e_W(z)\, dA = \int_H e_W(z)\, w(z)\, dz \qquad (2\text{-}9)$$

where E_W = reference annual wind energy input to the rotor swept area (W/y)
H = vertical height of the swept area; includes *tilt*, if any (m)
w = width of the swept area at elevation z (m)

For example, taking e_W from Table 2-1 and performing the integrations numerically, the reference annual wind energy inputs to the Mod-5B HAWT and the 34-m VAWT are

$$Mod\text{-}5B\ HAWT(\ 12.2\,m < z < 109.7\,m,\ A = 7{,}470\,m^2):$$
$$E_W = 41{,}710\ MWh/y \qquad (2\text{-}10a)$$

$$34\text{-}m\ VAWT(\ 7.1\ m < z < 49.0\,m,\ A = 955\,m^2):$$
$$E_W = 3{,}640\ MWh/y \qquad (2\text{-}10b)$$

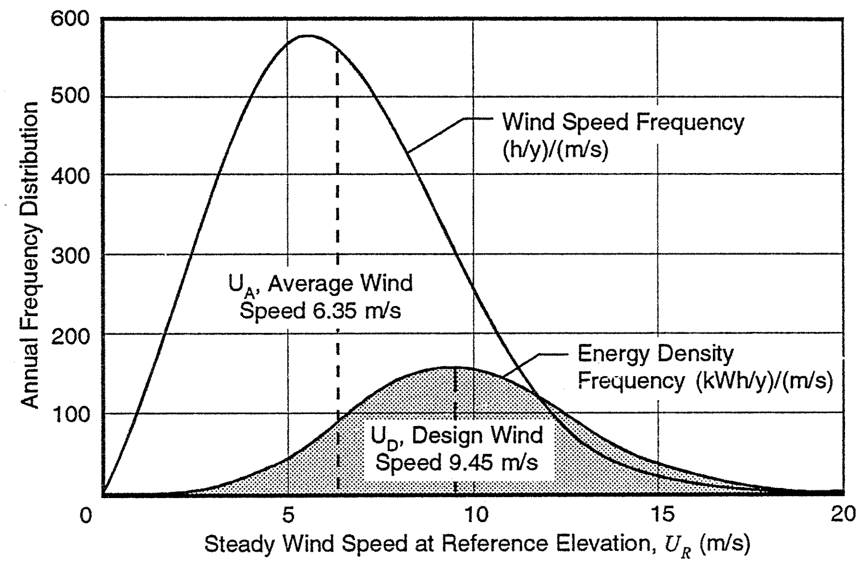


Figure 2-8. Frequency distribution functions for wind speed and wind energy density at the DOE/NASA Design Reference Site. Elevation = 10 m; air density = 1.225 kg/m^3.

Table 2-1. Parameters of the DOE/NASA Reference Wind Regime *vs* Elevation

Elevation z (m)	Scale C (m/s)	Shape k	Average Speed U_A (m/s)	Design Speed U_D (m/s)	Energy Density e_W (kWh/m^2/y)
5	6.30	2.16	5.58	8.55	1,656
10	7.17	2.29	6.35	9.45	2,324
15	7.73	2.37	6.85	10.05	2,836
20	8.16	2.43	7.24	10.50	3,276
25	8.51	2.48	7.54	10.85	3,664
30	8.80	2.52	7.80	11.15	4,009
35	9.06	2.56	8.04	11.40	4,331
40	9.28	2.59	8.24	11.65	4,621
45	9.49	2.62	8.44	11.85	4,907
50	9.68	2.64	8.60	12.00	5,183
55	9.85	2.67	8.76	12.20	5,425
60	10.01	2.69	8.90	12.35	5,669
65	10.16	2.71	9.03	12.50	5,902
70	10.30	2.73	9.16	12.65	6,123
75	10.44	2.75	9.29	12.77	6,350
80	10.56	2.77	9.40	12.90	6,545
85	10.68	2.79	9.51	13.00	6,744
90	10.80	2.80	9.61	13.10	6,958
95	10.91	2.82	9.72	13.22	7,145
100	11.01	2.83	9.81	13.30	7,327

Reference Annual Energy Output

The conventional measure of the aerodynamic performance of a wind turbine rotor (regardless of configuration) is its *rotor power coefficient*, which is the ratio of the rotor power density (mechanical power at the turbine shaft per unit of swept area) to the wind power density, or

$$C_{P,r} = \frac{P_r/A}{p_W} = \frac{P_r}{0.5\,\rho\,U^3 A} \qquad (2\text{-}11)$$

where $C_{P,r}$ = rotor power coefficient
P_r = mechanical power at the turbine rotor shaft (W)
A = swept area of the rotor (m/s)

A convenient scaling parameter which integrates the principal aerodynamic effects of wind speed, rotor speed, and rotor size on the rotor power coefficient is the *tip-speed ratio*:

$$\lambda = \Omega R / U \qquad (2\text{-}12)$$

where λ = tip-speed ratio
Ω = rotor speed (rad/s)
R = rotor radius, from axis to tip (m)

Two basic physical processes limit the *maximum rotor power coefficient* of an unducted wind turbine. First, a rotor increases the upwind static pressure, reducing the mass flow rate through its swept area and the wind energy available for conversion. Second, a rotor converts some of the linear kinetic energy of the wind to rotational kinetic energy in its wake, which is no longer available for conversion to mechanical energy. Figure 2-9 is a typical graph of rotor power coefficient *vs* tip-speed ratio and illustrates the effects of these two limiting processes. The first or *retardation* process limits the rotor power coefficient at all tip-speed ratios to 0.593 (16/27), which is referred to as the *Betz* or, more-accurately, the *Lanchester-Betz limit* [Bergey 1980]. The second or *wake rotation* process reduces the maximum rotor power coefficient further, but this is important only if the tip-speed ratio is less than about 3.

The design rotor power coefficients of the Mod-5B HAWT [Boeing 1988] and the 34-m VAWT [Dodd 1990] are also shown in Figure 2-9. These are typical of modern wind turbine rotors which have a small number of slender blades designed to operate at higher tip-speed ratios. As such, their power coefficients are not significantly affected by wake rotation losses.

For a HAWT with blade pitch control, when the wind speed exceeds the *rated wind speed* power is limited to the maximum permitted through the power train. In Figure 2-6, *above-rated operation* is indicated on the Mod-5B curve by the shaded region in which power coefficients are purposely reduced at lower tip-speed ratios. Rotor power coefficients have little significance in the above-rated regime. The power limit at above-rated wind speeds is determined by an economic trade-off study in which the value of the power lost is balanced by the reduced cost and maintenance expense of a smaller-capacity power train.

Figure 2-10 shows sample HAWT and VAWT *power output density curves* (power output per unit of swept area *vs* wind speed) calculated from rotor power coefficients, specified air density, schedules of rotor speed *vs* wind speed (for a variable-speed turbine), mechanical and electrical losses in the power trains, and power lost in transmission to the specified system output point. The calculation procedure is illustrated in Table 2-2.

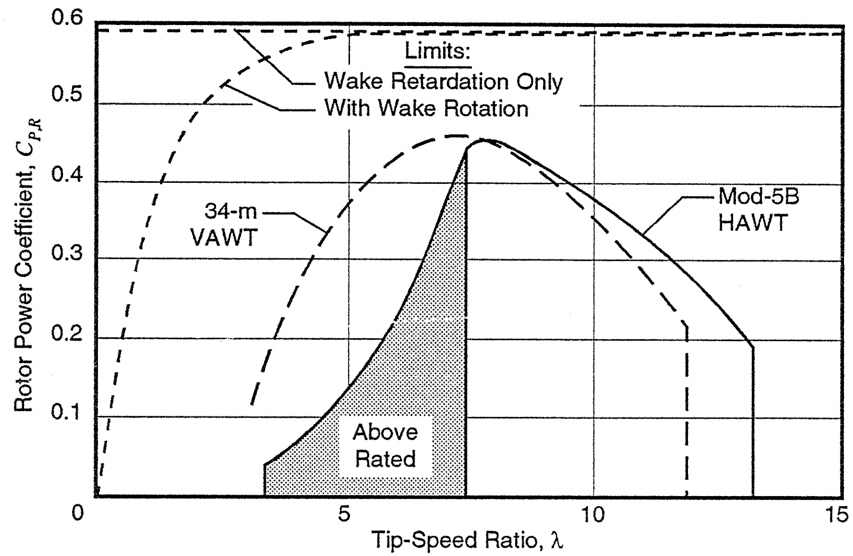


Figure 2-9. Sample variations of HAWT and VAWT rotor power coefficients with tip-speed ratio. Power coefficients are limited by retardation and wake rotation effects.

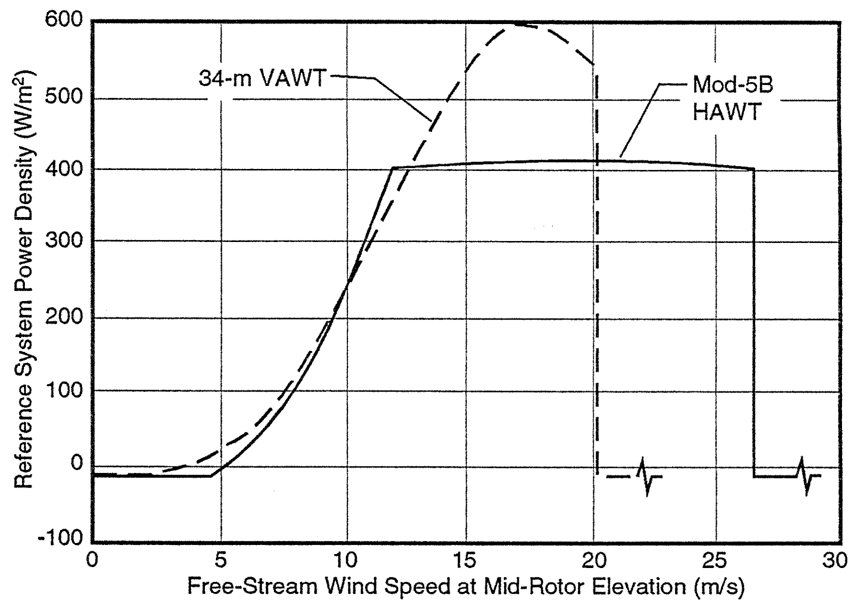


Figure 2-10. Sample HAWT and VAWT power output density curves. The HAWT power is limited by pitch control, while the VAWT power is limited by aerodynamic stall.

Table 2-2.
Power Output Density and Annual Energy Output of the Mod-5B HAWT

Wind speed bin U (m/s)	Rotor speed Ω (rad/s)	Tip-speed ratio λ	Rotor power coef. $C_{P,r}$ (a)	Rotor power density p_r (b) (W/m²)	Losses (W/m²): Gearbox and main bearings	Losses (W/m²): Generator and power electronics	Losses (W/m²): Auxiliary electrical (c)	Power output density p_O (W/m²)	Time in bin (Ref.) Δt (h/y)
< 4.8	0.00	0.00	0.000	0	0	0	10	-10	1,088
5.0	1.35	13.19	0.192	14	3	8	5	-2	309
5.5	1.35	11.99	0.273	27	3	8	6	10	348
6.0	1.35	10.99	0.332	43	3	9	6	25	382
6.5	1.35	10.15	0.376	62	3	10	6	43	413
7.0	1.35	9.42	0.407	84	3	10	7	63	437
7.5	1.35	8.79	0.429	108	4	11	8	86	455
8.0	1.35	8.24	0.450	137	4	12	8	114	465
8.5	1.43	8.20	0.455	167	4	13	9	141	469
9.0	1.50	8.15	0.455	199	5	14	10	170	464
9.5	1.58	8.12	0.455	233	5	16	10	202	453
10.0	1.66	8.08	0.455	272	6	17	11	238	435
10.5	1.73	8.05	0.455	315	6	18	12	279	411
11.0	1.81	8.02	0.455	363	7	20	13	323	382
11.5	1.81	7.67	0.455	415	7	22	15	371	350
12.0	1.81	7.35	0.432	446	8	23	15	401	316
12.5	1.81	7.06	0.383	448	8	23	15	402	281
13.0	1.81	6.54	0.341	448	8	23	15	402	245
13.5	1.81	6.30	0.305	449	8	23	15	403	211
14.0	1.81	6.09	0.274	450	8	23	15	404	178
14.5	1.81	5.88	0.247	451	8	23	15	404	148
15.0	1.81	5.69	0.223	452	8	23	15	405	121
15.5	1.81	5.52	0.203	452	8	23	16	406	98
16.0	1.81	5.52	0.185	453	8	23	16	407	77
16.5	1.81	5.35	0.169	454	8	23	16	407	60
17.0	1.81	5.19	0.155	455	8	23	16	408	46
17.5	1.81	5.04	0.142	455	8	23	16	409	34
18.0	1.81	4.90	0.131	456	8	23	16	410	25
18.5	1.81	4.77	0.121	457	8	23	16	411	18
19.0	1.81	4.65	0.111	458	8	23	16	412	13
19.5	1.81	4.53	0.103	459	8	23	16	412	9
20.0	1.81	4.41	0.096	459	8	23	16	412	6
20.5	1.81	4.31	0.089	459	8	23	16	411	4
21.0	1.81	4.20	0.083	458	8	23	16	411	3
21.5	1.81	4.10	0.077	457	8	23	16	410	2
22.0	1.81	4.01	0.071	456	8	23	16	409	1
22.5	1.81	3.92	0.067	455	8	23	16	408	0
26.5	1.81	3.33	0.040	448	8	23	16	402	0
									Total: 8,760

Reference Annual Energy Output: $AEO = A \times \Sigma\,(p_O\,\Delta t) = 12{,}040$ MWh/y

(a) Includes effects of wind shear and yaw heading error
(b) Air density = 1.225 kg/m³
(c) Includes transformer losses and power input for standby and starting operations

Before calculating the reference annual energy output of a wind turbine, it is necessary to determine the frequency distribution of free-stream winds at the *mid-elevation* of the area swept by the rotor. Weibull factors for this elevation are obtained by interpolation within Table 2-1. For the example wind turbines, these factors are

$$Mod\text{-}5B\ HAWT:\quad z_m = 61.0\,m \quad C_m = 10.04\,m/s \quad k_m = 2.70 \tag{2-13a}$$

$$34\text{-}m\ VAWT:\quad z_m = 28.0\,m \quad C_m = 8.68\,m/s \quad k_m = 2.50 \tag{2-13b}$$

The subscript m denotes a parameter at the mid-elevation of the rotor. The reference annual energy output in Equation (2-1) can now be expressed as

$$AEO = \int_{year} P_O(t)\,dt = A\int_0^\infty p_O(U)\,f_W(z_m)\,dU \tag{2-14}$$

where E_O = reference annual energy output (W/y)
p_O = system output power density (W/m²)

The integration is usually performed numerically, by summing the products of the last two columns in Table 2-2. The product $f_W\,dU$ is replaced by a *histogram* in which the duration in a wind speed interval or *bin* is calculated from the Weibull model as

$$\Delta t(U) = 8{,}760\left(\exp\left[-\left(\frac{U - \Delta U/2}{C_m}\right)^{k_m}\right] - \exp\left[-\left(\frac{U + \Delta U/2}{C_m}\right)^{k_m}\right]\right)$$

where Δt = duration of $(U - \Delta U/2) \le U \le (U + \Delta U/2)$ (h/y) (2-15)

Using the annual wind energy input data from Equations (2-10), the reference coefficients of energy for the example wind turbines are

$$Mod\text{-}5B\ HAWT:\quad C_E = \frac{12{,}040\ MWh/y}{41{,}710\ MWh/y} = 0.29 \tag{2-16a}$$

$$34\text{-}m\ VAWT:\quad C_E = \frac{1{,}240\ MWh/y}{3{,}640\ MWh/y} = 0.34 \tag{2-16b}$$

Wind tunnel testing of a scale-model rotor can be used to predict power coefficients if both the tip-speed ratio, λ, and the *Reynolds number* of the model are approximately equal to those of the prototype. For the same fluid properties, Reynolds number is proportional to $R^2\Omega$, which leads to the following scaling requirements:

$$\Omega_M \approx \Omega\,(R/R_M)^2 \qquad U_M \approx U\,(R/R_M) \tag{2-17}$$

where M = subscript denoting model parameters

Wind Turbine Economics

The economic *figure-of-merit* most often used as the basis for choosing the configuration of a wind power station -- including the type and size of turbines, number and location of units, electrical collection and distribution system, and operation and maintenance strategies -- is the *unit cost of energy*, or *COE*, delivered to the customer. The COE of a wind turbine system, like that of a conventional power plant, contains the following three general elements: (1) Capital cost, (2) operating and maintenance costs, and (3) energy output. The following simplified formula can be used for estimating the cost of energy:

$$COE = \frac{TIC \times FCR + AOM}{AF \times AEO} \qquad (2\text{-}18)$$

where COE = unit cost of energy delivered to the customer ($/kWh)
TIC = total initial cost of the wind turbine system; includes complete cost exposure for land, equipment, and start-up operations ($)
FCR = levelized fixed charge rate; includes return on capital, income tax, property tax, and insurance (1/y)
AOM = annual cost of operations and maintenance of the system ($/y)
AF = availability factor accounting for system downtime, partial or total
AEO = net annual energy output of the system without downtime (kWh/y)

Total Initial Cost

Items usually included in the total initial cost of a wind turbine system are listed in Table 2-3, together with an estimate of their relative sizes for a power station composed of 60 large-scale HAWTs [Boeing 1988]. Land costs are not included in this table because of their highly variable nature. For this type of wind power station, the cost of equipment "aloft" is about 60 percent of the total installed cost.

Fixed Charge Rate

The fixed charge rate in Equation (2-18) may be a composite of rates for different items in Table 2-3. It is sensitive to the cost of capital, method of capitalization, tax rates, tax incentives, and the lifetime of the wind turbine system. Wind turbine economic studies have been made with fixed charge rates from 0.10 to 0.20.

Annual Operations and Maintenance Cost

Operating and maintenance budgets for a wind power station are sensitive to such factors as the maturity and durability of the wind turbine equipment, the size and number of units in the system, ease of maintenance and availability of spare parts, and weather conditions. This subject is discussed in more detail in Chapter 4.

Availability Factor

On-line availability is closely related to operations and maintenance costs and is also sensitive to the maturity of the wind turbine equipment. Availability factors from 0.90 to 0.97 are usually assumed when estimating the cost of energy from a wind power station after several years of operation.

Table 2-3.
Items Included in the Total Initial Cost of a Wind Turbine System with Estimated Relative Contributions [Boeing 1988] (a)

Initial Cost Item	Contribution
Rotor Assemblies	23.2 %
Nacelle Structures and Auxiliary Equipment	15.1 %
Power Train Equipment	13.0 %
Site Preparation and Roads	10.3 %
Towers and Foundations	8.9 %
Profit	8.7 %
Ground Equipment Stations	8.2 %
Maintenance Equipment and Initial Spares	5.0 %
Electrical Interconnections	3.8 %
Transportation	2.5 %
Other Non-recurring Costs	1.3 %
Total	100.0 %

(a) Land costs not included

Annual Energy Output

Both the long-term energy content of the local winds and the overall efficiency of the turbines determine the annual energy output of the wind power station in the absence of downtime. However, as illustrated by the coefficients of energy in Equations (14), modern wind turbines are designed to extract about 30 percent of the incident wind energy, regardless of their configuration. Since the energy content of the wind is proportional to the cube of the wind speed, it has been found that the annual average wind speed at the mean elevation of the turbine rotors is a dominant parameter in determining the cost of energy and the economic viability of a wind power station.

Figure 2-11 illustrates the sensitivity of the cost of energy to the annual average wind speed, using data from Table 2-1. For this example, the mean elevation of the rotors is assumed to be 30 m, at which the reference annual average wind speed U_A is 7.80 m/s. Assuming the Weibull factors C and k are related to average wind speed as given in this table, cost of energy is inversely proportional to the annual energy density e_W. As shown in Figure 2-11, a reduction of 1.0 m/s in the annual average wind speed can increase the cost of energy by about 40 percent. Similarly, an increase of 1.0 m/s can decrease COE by almost 30 percent.

The annual average wind speed at an individual wind turbine site may decrease as the result of the operation of turbines upwind of it. This reduction in wind speed within the wind power station itself is often referred to as a *wake effect* or *array effect* on performance and is discussed in more detail in Chapters 4 and 6.

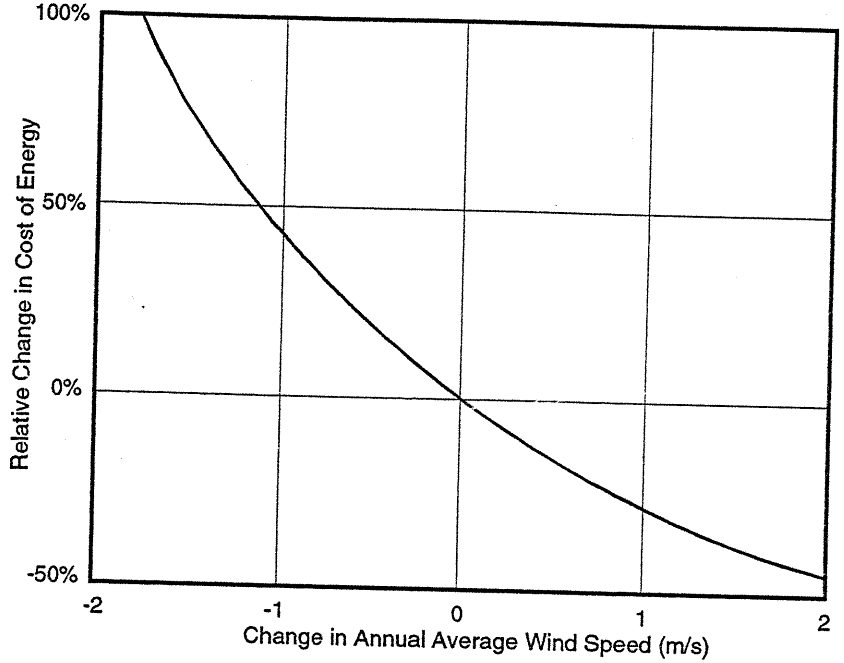


Figure 2-11. Sensitivity of the cost of energy to annual average wind speed. The reference annual average wind speed is assumed to be 7.8 m/s at the mid-rotor elevation.

References

ASME, 1989, *Performance Test Codes - Wind Turbines*, ASME/ANSI PTC 42-1988, New York: American Society of Mechanical Engineers.

Bergey, K. H., 1980, "The Lanchester-Betz Limit," *Journal of Energy*, Vol. 3, No. 6, pp. 382-384.

Boeing Aerospace Company, 1988, *Mod-5B Wind Turbine System Development Final Report - Vol. II, Detailed Report*, NASA CR-180896, DOE/NASA/0200-3, Cleveland, Ohio: NASA Lewis Research Center.

Dodd, H. M., 1990, "Performance Predictions for an Intermediate-Sized VAWT Based on Performance of the 34-m VAWT Test Bed," *Proceedings, Ninth ASME Wind Energy Symposium*, D. E. Berg, ed., SED-Vol. 9, New York: American Society of Mechanical Engineers, pp. 131-136.

Justus, C. G., and A. S. Mikhail, 1976, "Height Variation of Wind Speed and Wind Distribution Statistics," *Geophysical Research Letters*, 3: pp. 261-264.

Spera, D. A., and T. R. Richards, 1979, *Modified Power Law Equations for Vertical Wind Profiles*, NASA/TM-79275, DOE/NASA/1059-79/4, Cleveland, Ohio: NASA Lewis Research Center.

3

Evolution of Modern Wind Turbines

Louis V. Divone
Director, Solar Energy Technologies
U.S. Department of Energy
Washington, DC

Introduction

The modern electricity-generating horizontal-axis wind turbine (now often labelled with the acronym HAWT) is an obvious descendant of the historic European windmill and the small, DC-generating wind turbines of the 1930s. The resemblance is somewhat deceptive, however, since the HAWT and its less-familiar vertical-axis cousin, the VAWT, have evolved as sophisticated products of current technology. Their high performance and reliability are the result of steady improvement in methods of aerodynamic and structural design, in new materials, and in mechanical and electrical engineering. The evolution of wind turbine technology in the United States and elsewhere since World War II is described in this chapter, along with some of the problems that have arisen and how these problems have been faced.

The world's largest wind power plant prior to the 1970s was the *Smith-Putnam* wind turbine (Fig. 1-22) erected in 1939 on Grandpa's Knob near Rutland, Vermont [Putnam 1948]. With a rotor diameter of 53.3 m and a power rating of 1.25 MW, this pioneering HAWT was a major work of mechanical engineering. The Smith-Putnam project was a milestone between the decline of fully-developed, stand-alone wind turbines generating DC power only for local use and the new growth of wind power plants connected to utility lines and producing AC power for distribution throughout the system.

Wind Turbine Development from 1945 to 1970

During the twenty-five years from 1945 to 1970, new growth in wind turbine technology took place principally in western Europe and at a very modest pace. Some of the research and development activities during this period are described in the following sections, according to the country in which they took place.

Denmark

Pre-World War II wind turbine development in Europe took place principally in Denmark under the direction of Poul LaCour (called by many "the Danish Edison") and his protege, Johannes Juul [Juul 1964]. Denmark, a country lacking in indigenous energy sources, utilized wind power to a significant degree during both World Wars when oil supplies were curtailed. With the onset of the World War II occupation the *F. L. Smidth Company* (F.L.S.) developed a series of wind turbines in the 45-Kw range. Wind power eventually produced 4 million kilowatt-hours annually during this period.

The principal product line of F.L.S. was concrete manufacturing equipment; hence the use of concrete towers on the F.L.S. machines and the continued propensity to this day for the towers of larger Danish wind turbines to be built of concrete. Initially, rotors were of the two-bladed configuration, but F.L.S. (like the Jacobs brothers in the U.S. in the '20s) soon switched to three blades to alleviate tower vibration problems. Generally, DC generators were installed, since portions of outlying areas in Denmark were still supplied by small DC grids at that time.

The relative success of the small-scale F.L.S. wind power plants led to further experiments with larger machines in the years immediately following the end of World War II. With the help of Marshall Plan funding and the design experience of Juul, a 200-Kw, 24-meter diameter wind turbine was installed during 1956-57 on the island of Gedser in the far southeast of Denmark (Fig. 3-1). Like its smaller predecessors, the *Gedser wind turbine* had a three-bladed rotor located upwind of a concrete tower. It supplied AC power to the local utility, Sydøstsjaellands Elektricitets Aktieselskab (SEAS), from 1958 until 1967. *Capacity factors* (*i.e.*, ratios of annual energy output to rated power times 8760 hr) of 20% were achieved in some years.

Research on medium- and large-scale wind energy development was discontinued in Denmark in the mid-'60s, but in the mid-1970s the simplicity, ruggedness, and reliability of the Gedser wind turbine provided valuable lessons to Danish engineers who responded to new demands for alternative energy generation. In 1977 the machine was refurbished, equipped with modern instrumentation, and operated intermittently for research purposes [Merriam 1977, Lundsager *et al.* 1980]. Tests of aerodynamic performance and structural loads were successfully conducted. Modern, commercially-successful Danish wind turbines owe much to the pioneering work of F.L.S.

France

During the period from 1958 to 1964, three large-scale HAWTs were built and tested in France by *Electricité de France* (EDF), in collaboration with two companies: *BEST* and *Neyrpic* [Bonnefille 1974]. The first turbine was called the *Type Best-Romani* and was erected at Nogent-le-Roi near Paris. Its three-bladed rotor had a diameter of 30 m, and the system rating was 800 kW at a wind speed of 16 m/s. It operated for five years, from 1958 to 1963, connected to the EDF network. There were some difficulties with gear lubrication,

Figure 3-1. The rugged and reliable 200-kW 34-m diameter Gedser HAWT in Denmark, after its refurbishment in 1977. *(Courtesy of Risø National Laboratory Station for Wind Turbines)*

drive-train clutching, and mechanical braking, but electrical braking was satisfactory. Most importantly, the connection of the wind turbine's generator to the AC grid functioned well.

The second French machine, of a design called *Type Neyrpic*, had a smaller diameter of 21 m. Its rated power was 132 kW at a wind speed of 13.5 m/s. Erected near the English Channel at Saint-Remy-des-Landes, it operated successfully for three years and accumulated only 60 days of outage for various technical reasons.

A larger Type Neyrpic turbine (Fig. 3-2) was built at the same site and operated for seven months in 1963 and 1964. Its three-bladed rotor had a diameter of 35 m and its maximum power was 1,085 kW. During November 1963 it produced 200,000 kWh of electricity. Its total energy output during a period of seven months was about 28 percent of the wind energy available, which is a performance level seldom achieved even by modern turbines. The tests ended in June 1964, when the turbine shaft broke. Although these three prototype turbines clearly demonstrated the feasibility of grid-coupled operation, the French decided in 1964 to discontinue further wind energy research.

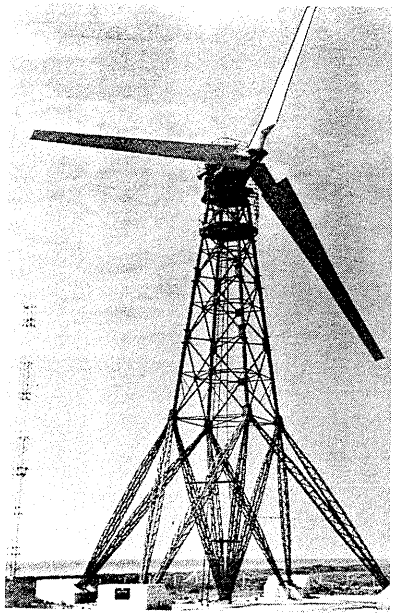


Figure 3-2. France's 1.1-MW 35-m Type Neyrpic turbine. It was the largest of three French prototypes tested during the 1958-64 period. [Bonnefille 1974]

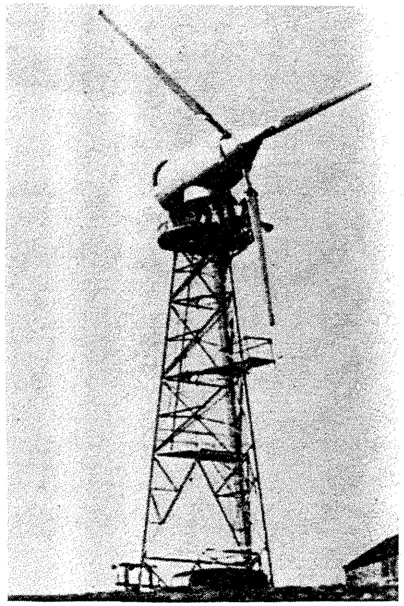


Figure 3-3. The 100-kW John Brown HAWT in the Orkney Islands. Its 18-m rotor was later reduced to 15 m. [Stodhart 1974]

United Kingdom

A variety of electricity-generating wind turbines was developed and tested in the U.K. from 1948 to the early 1960's [Stodhart 1974]. The three largest of these were 100-kW HAWTs of entirely different designs, each developed as a prototype for a wind power plant connected to a utility grid. The first of the prototypes (Fig. 3-3), designed and built by *John Brown & Co.*, was installed in the Orkney Islands in the early 1950's. It had a downwind rotor with three wood blades that were similar in design to helicopter blades. The

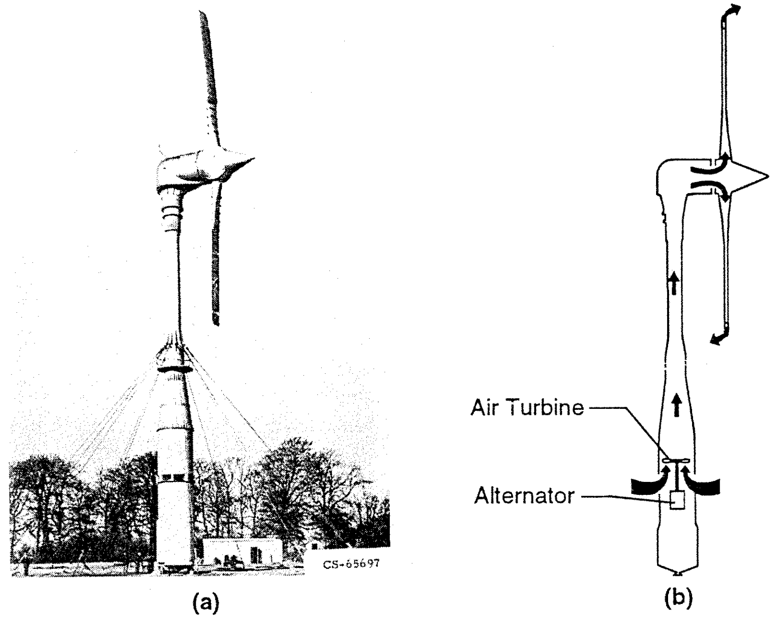


Figure 3-4. The 100-kW 25-m Enfield-Andreau turbine in the early '50s. Hollow rotor blades with tip vents drew air through a turbogenerator in the tower. (a) General view *(©1955, E.W. Golding; 1976, E.&F.N. Spon Ltd.; reprinted by Halsted Press, John Wiley & Sons, Inc.)* (b) Diagram of the flow path.

rotor diameter was initially 18 m, but this was reduced to 15 m after an accident in which one of the blades struck the tower in a high wind. A series of modifications was required to solve structural problems in the hub and resonant vibrations in the tower. Operation of the *John Brown* wind turbine ceased in 1956.

Also in the early 1950's, a 100-kW HAWT 25-m in diameter was built by *Enfield Cables* and installed initially at St. Albans in the U.K. (Fig. 3-4). It was of the *Andreau* design, a unique concept in which mechanical coupling between the turbine and the generator is eliminated by driving the generator pneumatically. The turbine rotor has hollow blades with open tips and acts as a centrifugal air pump. As illustrated in Figure 3-4(b), air is drawn in through side vents in the tower shell, passing upward to drive an enclosed high-speed air turbine coupled directly to the generator. After flowing through the rotor hub into the hollow turbine blades, it is finally expelled from the blade tips. While the *Enfield-Andreau turbine* operated successfully, it had a low overall efficiency. High drag losses in the internal flow paths were suspected to be the cause. The turbine was later moved to Algeria, where it is said to have operated intermittently for about 180 hours. It was shut down permanently after suffering bearing failures at the blade roots.

A third 100-kW wind turbine, built by *Smith (Horley) Ltd.*, was installed on the Isle of Man in the late 1950's and operated until 1963. The *Isle of Man* wind turbine was relatively low in cost ($20,000 installed), and it pioneered two rotor design features that have been used successfully in more recent times: control of peak power through aerodynamic stall of fixed-pitch blades, and blades made inexpensively from extruded aluminum. Operation ended in 1963 after damage to the blades in a severe storm.

Considerable research on wind flow patterns and wind characteristics was also accomplished during this time by E. W. Golding and Arthur Stodhart. Golding describes this work in one of the first modern texts on wind power [Golding 1955, 1976], a book which continues to be a valuable reference for wind turbine engineers. Many aspects of wind power generation are discussed by Golding, including wind characteristics, design configurations, field testing, and economics. An example of the economic projections of the time is shown in Figure 3-5.

United States

One person who had been impressed by the work of Putnam and the Grandpa's Knob machine was Percy Thomas of the then U.S. Federal Power Commission. Thomas firmly believed in the future of windpower and the need for it in this country. He wrote a series of monographs on the subject from 1945 through 1954 [*e.g.* Thomas 1946, 1949], stressing the economics and requirements of size from a utility perspective. He also advocated *multiple rotors* on a single tower (Fig. 3-6) as a method for obtaining multi-megawatt capability within the constraints of current rotor blade technology. In the United States Thomas was a lone voice "in the wind", for he received no funds, even though there was a Congressional hearing on the subject in 1951. No actual design work (much less experimental work) was undertaken.

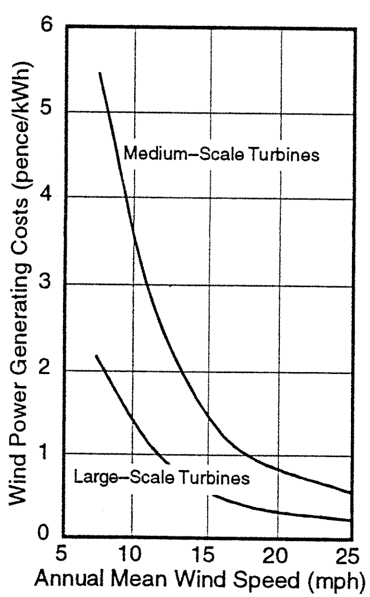


Figure 3-5. Early estimate of the relative costs of electricity from large- and medium-scale wind turbines, as a function of the site's annual mean wind speed. [Golding 1955, 1976]

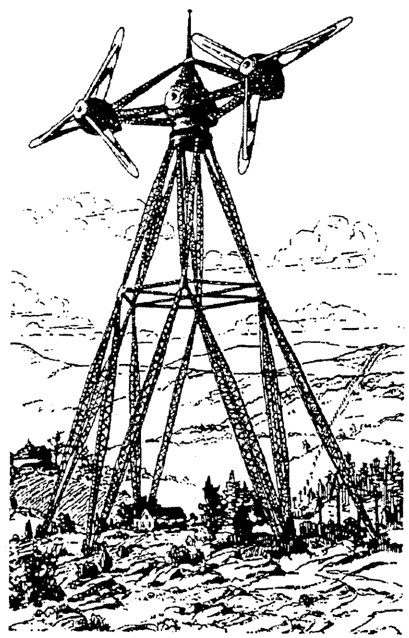
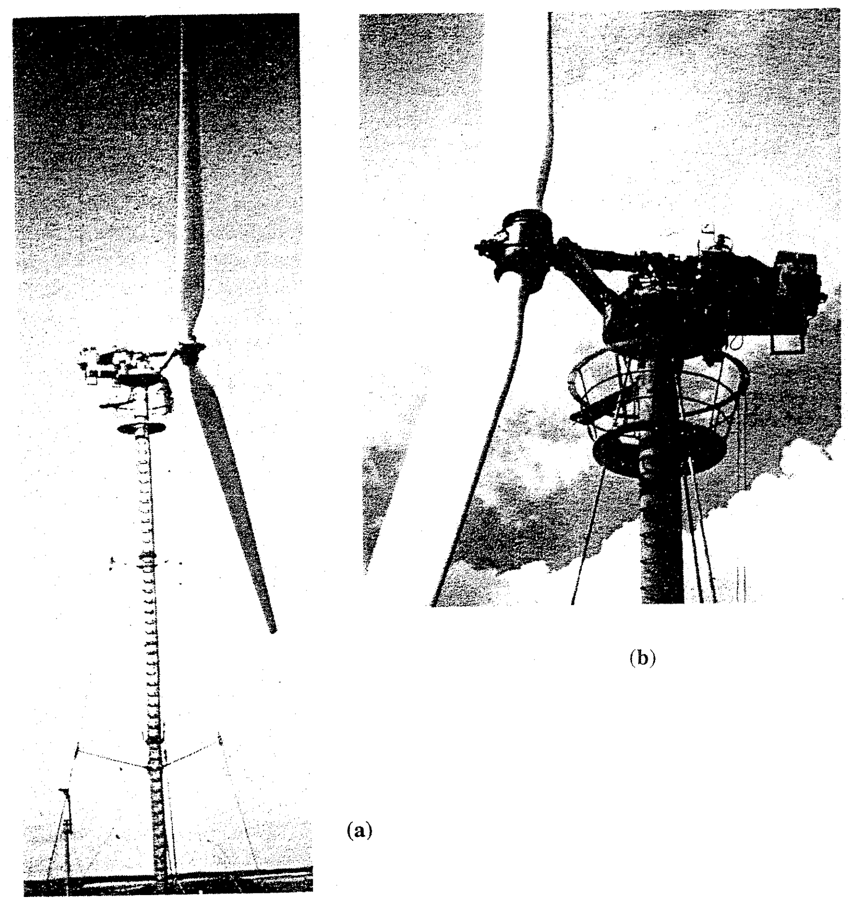


Figure 3-6. Percy Thomas' dual-rotor concept for a multi-megawatt wind turbine. [Thomas 1949]

Germany

Wind turbine activities in Germany resumed after World War II, based on earlier tests at Weimar of *Ventimotor GMBH* wind turbines (8 m and 18 m in diameter), and continued through the '50s and '60s under the guidance of Professor Ulrich Hütter [Hütter 1973a]. During the 1950s Hütter developed and tested a 10-kW, *10-m Hütter-Allgaier* HAWT. In the early '60s this work culminated in the 100-kW *34-m Hütter-Allgaier* wind turbine, shown in Figure 3-7 [Hütter 1973b, 1974], the most technologically advanced system of its time and for decades to follow. Hütter concentrated on pushing the state of rotor technology toward lower solidity, higher tip speed, and flexibility. The 34-m rotor had two blades with full-span pitch control and very low solidity. These slender, flexible blades were constructed of fiberglass and mounted on a *teetered hub*. The rotor was downwind of the tower and incorporated 7 deg of coning. Because of very limited funding, experiments on this turbine proceeded slowly into the 1960s, hampered by flutter problems in the long, thin rotor blades.



(a) (b)

Figure 3-7. The technologically-advanced 100-kW 34-m Hütter-Allgaier wind turbine. (a) General view of the turbine mounted on its 22.3-m guyed shell tower. (b) View of the fiberglass blade roots, teetered hub, and in-line power train. [Hütter 1973b, 1974]

The Beginnings of Modern Developments 1970 to 1974

Professor Hütter's wind turbine program in Germany ended for the same reasons as those that halted experiments in other countries: Energy from fossil-fuel and nuclear power plants was inexpensive, and little emphasis was placed on research on alternative sources of energy. At the end of the 1960's there was, unfortunately, little useful documentation and almost no experimental data from these several decades of activities around the world. For all the large advances in the field of wind energy since the end of the nineteenth century, prospective wind turbine designers in the '70s had little firm information upon which to build.

Revival of Interest in Wind Power

By 1970, there was little or no activity world-wide for producing electricity by wind power. Some water-pumping windmills were still being produced, principally for use in the developing world. In the U. S., a few enthusiasts were rebuilding *Jacobs Wind Electric* (Fig. 1-19) and other small DC wind generators from the 1930s for use in remote rural applications. *Dunlite* (Australia), *Elektro* (Switzerland), and *Aerowatt* (France) were essentially the only active manufacturers. Their systems were imported in very small quantities by the *Solar Wind Company* in Maine. A number of companies in the U.S., staffed by young enthusiasts, were beginning to attempt the design of machines in the 1-kW to 10-kW range. In the academic community, Hughes at Oklahoma State University and Heronomous at the University of Massachusetts and their students were studying small-scale and large-scale wind energy concepts, respectively.

At the *National Research Council* of Canada (NRC), the curve-bladed vertical-axis rotor patented by G. J. M. Darrieus in France in 1925 and in the U.S. in 1931 was re-invented by Peter South and Raj Rangi in the late 1960s. The *4.3-m NRC Darrieus* VAWT which they constructed was tested both in a wind tunnel (Fig. 3-8) and outdoors, producing some of the first wind turbine performance data obtained under controlled testing conditions.

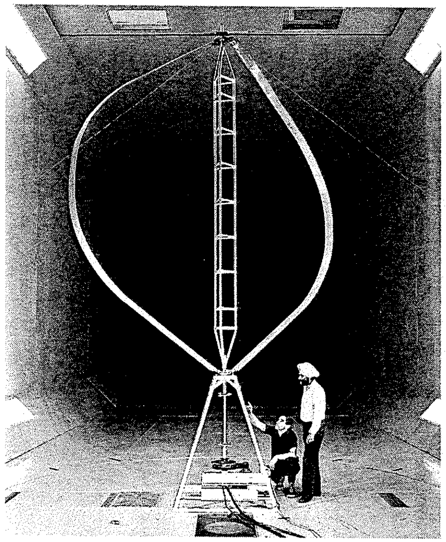


Figure 3-8. Testing the 4.3-m NRC Darrieus VAWT in 1972. (*Courtesy of the National Research Council of Canada*)

In the U.S. in 1972, engineers from the *Lewis Research Center* of the *National Aeronautics and Space Administration* (NASA) were involved in measuring winds in Puerto Rico (for other purposes) and encountered some local interest in wind power. This was the start of wind energy research that continued at that laboratory for over 15 years. Aerodynamicists at NASA's *Langley Research Center* also began theoretical and experimental research on the Darrieus rotor.

In the U.S. federal sector, the *National Science Foundation* (NSF), under their new "Research Applied to National Needs" (RANN) program, had been examining the overall long-term issues of energy supply, and had concluded (along with others) that renewable energy sources could have a major role in the future. However, individual views of that future varied enormously. The NSF was initially given the responsibility and a small budget for a federal research program on renewable energy. That program included solar energy, of which wind energy was considered to be a constituent part. The NSF, without any laboratories of its own, turned to the NASA Lewis Research Center in Cleveland, Ohio, for technical and management assistance [Thomas 1982].

The first step undertaken was the sponsorship of a Wind Energy Workshop by NSF and NASA-Lewis in 1973 [Savino 1973], to which were invited all those who had any prior or current interest in wind power. Pioneers from the 1930s -- such as Marcellus Jacobs, Palmer Putnam, and Beauchamp Smith from this country; and Ulrich Hütter and Arthur Stodhart from Europe -- and a younger generation of wind power developers presented papers and recommended research needs. In 1974 the Swedish government hosted a second international wind energy workshop [Ljungström 1974]. Similar conferences and workshops, held in different countries, became annual events. By the 1980s, workshop sponsors included the American Wind Energy Association, the European Wind Energy Association, the American Society of Mechanical Engineers, and other trade associations from individual countries. The *Wind Workshop Proceedings* from these annual conferences, supplemented by those from more specialized meetings, form a detailed record of the technical development of wind power from the mid-1970s until today. A partial bibliography of these proceedings is given in Appendix B.

Just prior to the 1974 Stockholm workshop, it was discovered that not all of the experimental wind turbines of the 1940-1960 era had been dismantled or destroyed. To everyone's surprise, the Danish *Gedser wind turbine* was found to still exist. With a modest expenditure under a U.S./Danish bi-lateral agreement, the Gedser machine was later refurbished and retested. Data were used to validate new computer codes in the U.S. for predicting aerodynamic and structural dynamic performance. At the same time, the Gedser tests stimulated renewed interest in wind power in Denmark.

The U.S. Federal Wind Energy Program

In 1974, following recommendations from that first workshop, NSF and NASA drew up an initial wind energy research plan, although with little optimism that significant funding would be forthcoming. The shock of the Arab oil embargo a few months later, however, ensured rapid growth in research funds not only in the U. S. but worldwide. In 1975 the NSF program was absorbed into the newly-formed *Energy Research and Development Administration* (ERDA). The core of ERDA was the Atomic Energy Commission, which had numerous government-owned/contractor-operated national laboratories and plants under its aegis. In view of the rapidly growing and broadening program, several of these laboratories were selected to operate various elements of the wind program. In 1977, ERDA was combined with several other Federal organizations to form the U.S. *Department of Energy* (DOE).

The U. S. *Department of Agriculture* (USDA) was also asked to add its expertise in farm machinery applications which led to the continuing involvement of the USDA Agricultural Research Service at Bushland, Texas. Thus, while research was undertaken, supported, and reported in the literature by several agencies and laboratories, that work was all part of a single integrated program.

The initial federal plan envisioned research and technology projects closely coupled with the design and testing of experimental wind turbines that would incorporate increasingly advanced developments as they became available. The plan also assumed that three cycles or "generations" of experimental turbines would be required. First-generation turbines would be necessary merely to develop an understanding of design issues and to obtain basic data. The second generation was needed to put new developments into practice. Finally, a third generation of wind turbines would be required to reach a level of performance and reliability that could be cost effective on a broad scale. This series of wind turbines was designed to prove the technology and to reduce technical risk to the point where significant private capital could be attracted for continued development and commercial production.

Since the role of turbine size in the economics of the wind machine market was not understood at the time (and, to some extent, is still not clearly defined) a second major feature of the federal plan was that it supported the parallel development of prototypes in three sizes: Small-scale turbines (1 kW to 99 kW) for rural and remote use; medium-scale turbines (100 kW to 999 kW) for a remote community or industrial market; and large-scale systems (1 MW to 5 MW), primarily for the electric utility market.

NASA/DOE Mod-0 100-kW Experimental HAWT: 1975 to 1987

One of the first activities under the Federal Wind Energy Program was the design and construction of an experimental, medium-scale HAWT to serve as a test bed. This size was clearly needed in order to reach reasonable risk levels before proceeding to large-scale turbines. Conversely, many of the test results from a medium-scale turbine could well be applied to small-scale systems. This new research wind turbine was designated the *Mod-0* to emphasize its role as a test bed. It was designed and built for NSF by an engineering and fabrication team at the NASA Lewis Research Center [Puthoff and Sirocky 1974]. Installed in 1975 at NASA's Plum Brook Test Station near Sandusky, Ohio, it became a mainstay of experimental work on HAWTs in the U.S. for the next dozen years.

Original Mod-0 Configuration

The diameter of the Mod-0 rotor was selected to be 38.1 m, and a very low rated power of 100 kW (at a rated wind speed of 8.0 m/s at hub elevation) was chosen. This low rating was determined to be suitable for such a large rotor because of the modest wind speeds in the Sandusky area. Available running time for experimental work was a much higher priority than cost optimization at that time.

As shown in Figure 3-9, a two-bladed rotor located downwind of the tower was selected, following the examples of the Smith-Putnam and Hütter turbines and in accordance with economic studies that indicated a third blade was not cost-effective in large-scale systems. The Mod-0 rotor and power train were located in a streamlined *nacelle* atop a stiff, four-legged truss tower, with the rotor axis at an elevation of 30.5 m. Its original set of blades were of aluminum rib/spar/skin construction, following airplane wing design. While quite expensive, they were very light in weight (9,000 N each), which was considered a necessity because of the many unknowns in the structural dynamic behavior of the system.

Details of the Mod-0 power train and yaw drive subsystems are illustrated in Figure 3-10. The rotor drove the *turbine shaft* at 40 rpm which, through a *parallel-shaft step-up gearbox* was increased to the 1,800-rpm speed of the 100-kW *synchronous generator*. At winds above rated, power was held constant at 100 kW by *full-blade pitch* under computer control, with the blades positioned by hydraulic actuators mounted on the *rigid hub*. Wind direction was sensed by a *wind vane* on top of the nacelle and monitored by the automatic yaw control system. When a change in the *nacelle azimuth* was needed, a pair of electric motors operated through a *worm-gear reduction drive* and a *pinion gear* to drive a *bull gear* attached to the *bedplate*. Yawing speed was 1/6 rpm.

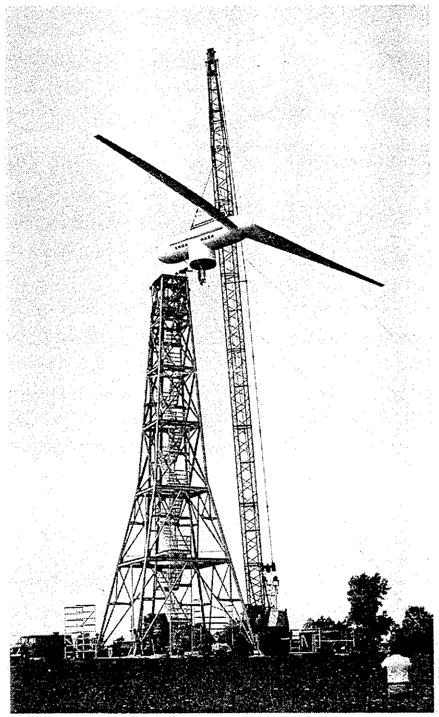


Figure 3-9. Final assembly of the 100-kW Mod-0 HAWT test bed in 1975. It was located at the NASA-Lewis Plum Brook Test Station near Sandusky, Ohio. (*Courtesy of NASA Lewis Research Center*)

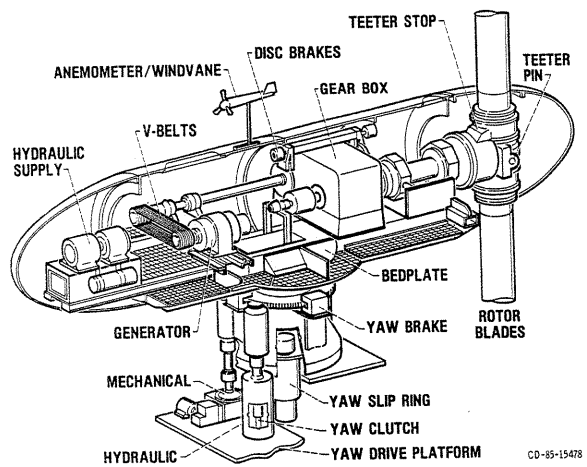


Figure 3-10. Power train and yaw drive equipment in the Mod-0 nacelle. The pulleys and belts at the generator permitted changes in rotor speed, to study tip-speed effects and avoid structural resonances. (*Courtesy of NASA Lewis Research Center*)

Mod-0 Research Tests and Configuration Changes

Over the next decade, more testing to investigate new ideas and new configurations (Fig. 3-11) was accomplished with the Mod-0 HAWT than with probably any other wind turbine before or since. Initially designed as a downwind, two-bladed configuration with full-blade pitch, it was later tested with one (counterbalanced) blade and with two blades in both upwind and downwind configurations. New materials were developed for wind turbine blades and first tested on the Mod-0. These included *laminated wood-epoxy* (Spera *et al.* 1990], a material now used on many small and intermediate wind turbines, and *fiberglass composite blades* fabricated with *transverse-filament-tape* [Weingart 1981].

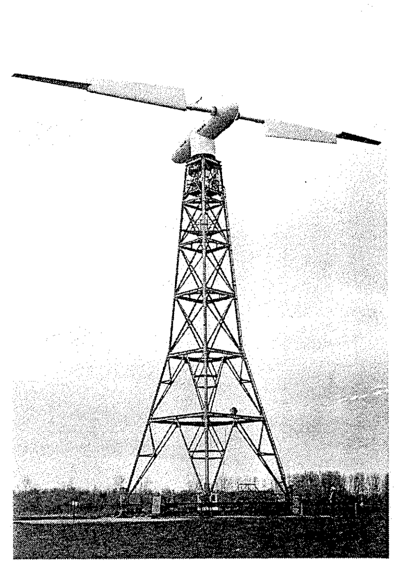
One detrimental result from the original truss tower with its central stairway was high impulsive pressure loading on the blades, from the excessive wind speed reduction in the wake behind this high-drag tower. The staircase was soon removed, which reduced cyclic loads to a tolerable level. However, *tower wake-induced fatigue loads* had been identified as a major design driver for downwind rotors. First-generation machines used rigid hubs in an attempt to overcome the effects of dynamic loads by a simple brute force technique. This approach was never wholly satisfactory, so the Mod-0 test configuration expanded to include a *teetered hub* (Fig. 3-12).

As structural dynamic knowledge increased, the Mod-0 truss tower was placed on a new base composed of flexural steel beams (Fig. 3-11(a)). This allowed the natural vibration frequency of the turbine to be lowered and "tuned" in order to simulate "soft" tower structural concepts. Such concepts would have the potential for lower tower weight and cost, but structural dynamic loads could be lower or much higher, depending on resonances and instabilities that were not well-understood with the available analysis tools. Later, the Mod-0's truss tower was replaced by a slender shell tower (Fig. 3-11(b)) to prove out those tools and the effectiveness of soft structural systems.

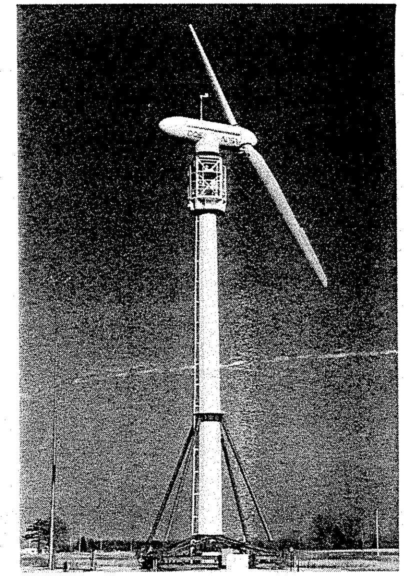
Another area which received considerable emphasis was *variable-speed constant-frequency (VSCF)* operation. Prior to the need for interconnection with the utility grid, many small machines operated at variable rotor speed depending on electric load and wind speed, but this had rarely been attempted on any turbine much over 15 m in diameter. The desire to operate at variable rpm is engendered by the potential for higher energy capture (always operating near peak rotor efficiency) and the potential for gust load alleviation.

Solutions to the electrical problems associated with a variable generator speed could now be envisioned that were not available in a practical way two decades earlier. The structural dynamics issues associated with the need to preclude harmonic vibrations over a range of rotor speeds were not viewed sanguinely. It was enough of a problem in the 1970s to accomplish this at one speed. In spite of this, the Mod-0 was operated as a variable-speed machine, testing several generator and power-conditioning components. More importantly, the Mod-0 tests probed the structural dynamics "envelope" on a relatively large, flexible system and thereby provided the data to develop and validate complex computer models needed to predict natural frequencies and loads under such conditions.

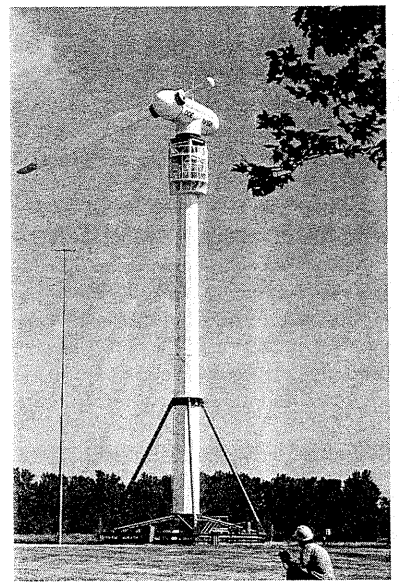
Also tested were rotors with *partial-span pitch control*, *flaps* (often less-correctly termed *ailerons*), *fixed-pitch stall regulation*, and *free-yaw* response to changing wind directions. Tests at Plum Brook determined the effects of precipitation, various airfoils, blade root and tip design innovations, and auxiliary aerodynamic devices such as *vortex generators*. The validation of computer models and control algorithms, though less visible than hardware changes, was probably one of the most valuable contributions of the test bed program. After a useful life of over a dozen years, the Mod-0 experimental HAWT was dismantled in February 1987, leaving as its legacy an extensive set of documentation that forms a principal basis of modern wind turbine technology.



(a)



(b)



(c)

Figure 3-11. Different Mod-0 configurations during a decade of research. (a) **1979:** Upwind rotor, steel spar blades, partial-span pitch, teetered hub, and a spring base; simulated the "soft" second-generation Mod-2 HAWT. (b) **1982:** Shell tower, flap control, inboard blade sections of laminated wood. (c) **1985:** One-bladed, teetered rotor with tip control. *(Courtesy of NASA Lewis Research Center)*

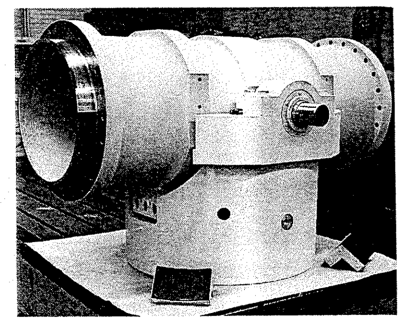


Figure 3-12. Mod-0 teetered hub. *(Courtesy of NASA Lewis Research Center)*

Development of Modern Small-Scale Wind Turbines: 1976 to 1981

During the early 1970s a number of small companies, recognizing the potential of wind power and the limitations and costs of the few Dunlite, Aerowatt, and Elecktro wind turbines being imported, began to develop small wind turbines in the 1 kW to 10 kW range. Several supporting activities were initiated by the U.S. government, as an outgrowth of early studies on the use of wind power for small rural or remote applications.

Major Testing Facilities

For all the long history of wind power, there was actually very little detailed, measured performance or other engineering data available. Few of the limited design tools and analytical models had been validated to any significant degree, and most information was anecdotal in nature. Hence, testing of available machines became an early priority, both in the U.S. and abroad.

The Rocky Flats Test Station

The Rocky Flats Plant near Golden, Colorado, operated by *Rockwell International Inc.* for ERDA (later DOE), was given the responsibility for the development and testing of small wind turbines. The Test Station consisted of an array of 32 test pads, each capable of supporting, servicing, and collecting data from a small-scale turbine (Fig. 3-13). During the years 1976 through 1981, when the bulk of the testing was performed, 54 different wind turbines in the 1-kW to 50-kW range were tested at Rocky Flats. A permanent building housed both personnel and extensive test equipment. Shops with dynamometers allowed rapid check-out testing of components prior to outdoor systems tests as well as rapid turnaround during modifications. The site's low mean wind speed (6 m/s) yielded only modest annual energy, which was of some concern to the manufacturers in the early days, but the relatively frequent high winds and turbulence were excellent for determining design loads, system ruggedness, and reliability within reasonably short test periods.

Machines developed by private industry could be tested at Rocky Flats under two different procedures: First, a wind turbine could be tested at government expense, the results then being public information. However, the degree of testing, instrumentation, and analysis could in many cases be larger than the manufacturer could otherwise perform. Secondly, the manufacturer could pay for testing, in which case the results would remain proprietary.

An important outgrowth of the testing at Rocky Flats (as well as at Sandia National Laboratories and NASA Lewis Research Center), was the development of standardized testing methods for determining *power curves* (power output *vs* wind speed). This most basic performance characteristic is one of the most difficult to measure because of the variability of the wind. Prior to 1979, most power performance curves for commercial wind turbines were generally not reproducible nor comparable within acceptable bounds of uncertainty. Standardization of terms and methodology eventually brought major improvements to the comparability of advertised power curves and *annual energy output.* Data analysis techniques developed at Rocky Flats and Sandia (such as the *method of bins*) were later included in voluntary standards adopted by the International Energy Agency, the American Wind Energy Association, and the American Society of Mechanical Engineers [*e.g.* Frandsen 1982, AWEA 1985, ASME 1989].

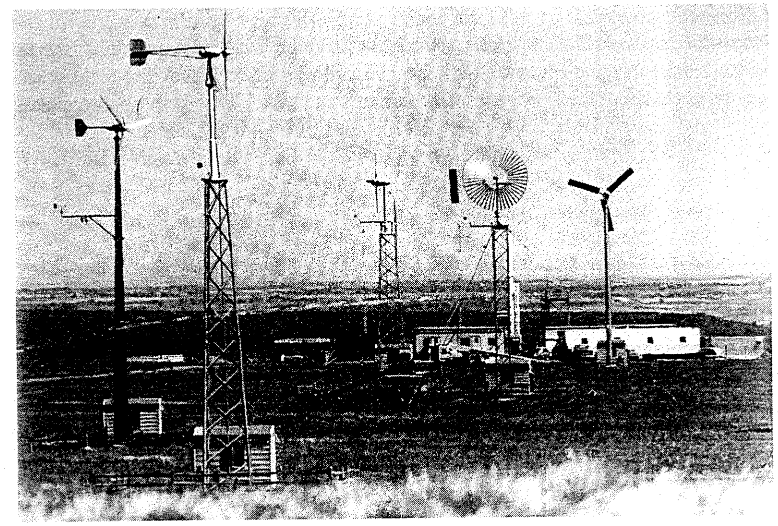


Figure 3-13. The Rocky Flats Test Station, near Boulder, Colorado. The performance and reliability of a wide variety of small-scale commercial and experimental turbines were tested here. *(Courtesy of the U.S. Department of Energy)*

Difficulties in determining a power curve in the rapidly-varying natural wind and the need to validate analytical models led to supplementary performance testing at the nearby *High-Speed Rail Test Facility* operated by the Department of Transportation. Full-scale small turbines were placed on a tower mounted on a flatcar and pushed by a diesel locomotive at speeds covering the turbines's operating wind speed range. Control of the relative velocity between the turbine and the air allowed rapid validation of power curves and the analytical techniques being developed for normal on-site testing.

USDA Bushland Test Station

The *U.S. Department of Agriculture* (USDA) has also tested a variety of small-scale wind turbines in actual agricultural and rural applications, including irrigation, crop drying (both electrically and by churning a viscous fluid), diesel interconnection, and general rural electrical use [USDA 1979, Clark 1983]. Testing is conducted principally at the USDA Agricultural Research Service facility near Bushland, Texas, with some on private farms. Prototypes of turbines developed privately as well as with federal funds are evaluated against particular agricultural requirements. Darrieus VAWTs are also tested at the USDA test station by engineers from the *Sandia National Laboratories* in Albuquerque, New Mexico, because of the superior wind regime at Bushland.

Risø Test Station

Several small wind turbine test stations were set up in Europe during the late 1970s. Most notable was the *Risø National Laboratory Station for Wind Turbines* in northern

Denmark. In addition to research and development testing, the Risø station supports the evaluation and certification of commercial wind turbines. With certification manufacturers are eligible for various Danish tax credits and incentives, as well as for those from certain other European countries. While the merits of government certification can be argued relative to the merits of industry self-certification coupled with the workings of the market place, the Danish program was effective in precluding undeveloped or poorly-developed turbines from reaching the European market in any quantity. This led to the reputation for reliability and performance enjoyed by Danish turbines during the highly-competitive upsurge in the development of wind power stations in the U.S. in the mid-1980s.

U.S. National Wind Technology Center

In the early 1980s reductions in the U.S. government funding of wind research brought an end to major testing activities at Rocky Flats. Other responsibilities of the test station were turned over to the nearby *Solar Energy Research Institute* (SERI), which has recently become the *National Renewable Energy Laboratory* (NREL) of the U.S. Department of Energy. However, with the resurgence of interest in wind energy in the 1990s, the facility at Rocky Flats is to be reconditioned as the *National Wind Technology Center* and operated by NREL. This upgraded facility will provide both government and private industry with the laboratory and field test capabilities required to support the development of advanced small- and medium-scale wind turbines.

Small-Scale Wind Turbine Development Program

Shortly after the start of tests at Rocky Flats on existing wind turbines, a series of competitive solicitations were issued for the development of new small-scale systems with government support [Healy and Dodge 1981]. A number of these solicitations provided "set-asides" for small business, to simulate that segment of the industry. Table 3-1 lists the small-scale turbines developed under this program, with summary design data.

The first series of development projects was initiated in 1978 and included three levels of rated power: 1 kW to 2 kW, for extremely reliable systems for remote use; 8 kW, for rural residential and other uses; and 40 kW, for irrigation and other agricultural applications.

High-Reliability Turbines

Three high-reliability prototype machines in the 1-2 kW range were completed in 1980 by *Enertech Corporation, North Wind Power Company*, and *Aerospace Systems, Inc./Pinson Engineering*. The first two were HAWTs with upwind rotors and two and three blades, respectively. The last was a 3-bladed giromill VAWT configuration. Several copies of the Enertech turbine were built for development purposes. The North Wind turbine evolved into commercial products, the 2-kW *HR-2* and 3-kW *HR-3* HAWTs, of which a significant number have been built that operate successfully in very remote locations. Their reliability stems from having only a few moving parts. Power and speed are controlled by *vertical furling* (*i.e.* tipping up the rotor) in high winds.

8-kW Turbines

Three manufacturers who developed 8-kW prototypes were *Windworks, Inc., Grumman Energy Systems*, and *United Technologies Research Center* (UTRC). The first two designed 3-bladed rotors, while the 2-bladed rotor of the UTRC machine incorporated a unique "self-twisting" concept for speed and power control. Of fiberglass construction, the blade spars

Table 3-1. Small-Scale Wind Turbines Developed with U.S. Government Support [Healy and Dodge 1981]

Manufacturer	Rating (kW)	Rotor Configuration	Annual Energy [1] (kWh/y)	Power Train	Weight on Tower (Tower Weight) (kg)
ASI/Pinson	2.0	4.6-m giromill VAWT 3 aluminum blades 2.4-m high Cyclical pitch	1,830	Gearbox Alternator	272 (680)
North Wind	2.0	5.0-m upwind HAWT 3 wood blades Vertical furling	6,870	Direct-drive Alternator	361 (499)
Enertech	2.0	5.0-m downwind HAWT 2 wood blades Centrifugal control	8,400	Gearbox Alternator	345 (556)
Structural Composites Industries	4.0	9.5-m downwind HAWT 3 fiberglass/foam blades Pitch control	22,000	2-Stage Spur GB Induction generator	726 (576)
North Wind	6.0	9.5-m downwind HAWT 2 wood blades Passive pitch control	22,100	Direct-drive Lundel synch. alternator	477 (1,776)
Tumac	4.0	11.9-m Darrieus VAWT 3 fiberglass blades Mech. & aero. brakes Cantilevered tower	22,300	Planetary GB MSCF induction generator	2,365 (946)
UTRC	8.0	9.45-m downwind HAWT 2 GRP blades Flex-beam pitch control	25,000	Gearbox Induction generator	839 (1,120)
Windworks	8.0	10-m downwind HAWT 3 aluminum blades Hydraulic pitch control	30,000	Direct-drive Alternator	735 (844)
Grumman	11.0	10.1-m downwind HAWT 3 aluminum blades Electric pitch control	32,000	Gearbox Induction generator	1,174 (1,189)
UTRC	15.0	14.6-m downwind HAWT 2 fiberglass/foam blades Self-twist pitch control	50,000	Gearbox Induction generator	703 (544)
Enertech	15.0	13.4-m downwind HAWT 3 wood blades Stall control Tip brakes	51,500	Gearbox Induction generator	431
McDonnell	40	17.7-m giromill VAWT 3 steel/aluminum blades 12.8 m high Cam pitch control	128,400	Gearbox Induction	7,128 (4,730)
Kaman	40	19.5-m downwind HAWT 2 fiberglass blades Pitch control	134,000	Gearbox Induction generator	2,766 (1,814)

[1] Predicted for a site with a 5.3-m/s annual-average wind speed

were laid-up with fiber orientations that gave them specific torsional properties. Changes in aerodynamic and centrifugal forces caused the spars to twist and untwist, enabling a totally passive blade pitch control with varying wind and rotational speed.

40-kW Turbines

The larger 40-kW prototype wind turbines were developed by the *Kaman Aerospace Corporation* and the *McDonnell Aircraft Company*. The Kaman design was a HAWT with a 2-bladed, downwind rotor (Fig. 3-14), while the McDonnell design was a 3-bladed giromill VAWT (Fig. 3-15). Both prototypes were delivered to Rocky Flats in 1980 and tested in 1981.

17-m Alcoa VAWT

Alcoa Corporation, under contract to Sandia National Laboratories, developed a pre-commercial prototype of the *Sandia/DOE 17-m VAWT* (Fig. 3-20) and built four units. One of these was installed at Rocky Flats for comparative testing, and to verify predictions of performance and loads. Using the data obtained, two manufacturers developed the design further for commercial use (Fig. 3-24).

Additional Small-Scale Wind Turbine Development Projects

A second series of competitions followed in 1980 with contract awards to *Tumac Industries, Structural Composites Industries* (SCI), and *North Wind Power Company* for 4-kW prototypes. The application for this size wind turbine were seen as a power source for remote residences, either standing alone or inter-connected with a utility line. SCI designed a HAWT with a 3-bladed, downwind rotor, while Tumac developed a small Darrieus VAWT with a cantilevered tower and no supporting cables. The last of the competitions for government support of small-scale wind turbine development was for a light agricultural application, on farms and ranches. It resulted in awards to the Enertech and UTRC companies, both of which selected HAWTs with downwind rotors.

The wide spectrum of design concepts listed in Table 3-1 is indicative of the early uncertainty amongst wind turbine designers as to what constitutes an optimum configuration for a specific application. While some blind alleys were followed for a time, a number of these configurations were eventually selected for commercial machines. The inclusion of wind energy in the solar energy tax-credit legislation in the early 1980s encouraged numerous other companies to enter the wind turbine development and manufacturing field. Future development of wind turbine systems in the U.S. was undertaken without direct government support, while the federal program concentrated on supporting research to expand the technology base for all sizes and applications of wind turbines.

Supporting Technology for Small-Scale Wind Systems

A series of analytical and experimental projects conducted under the Federal Wind Energy Program provided data for both a technology base and decision-making related to the further development of small-scale turbines. Pacific Northwest Laboratories tailored the techniques of wind resource assessment for the use of manufacturers, planners, distributors, and agricultural extension agents. This work led to the development of "stand-alone" courses on the siting of turbines, using slides, audio tapes, and workbooks. Economic and market analyses were made by organizations such as A. D. Little, JBF Scientific, and General Motors on subjects crucial to the developing wind turbine industry, such as

Figure 3-14. The prototype Kaman 40-kW HAWT. *(Courtesy of the U.S. Department of Energy)*

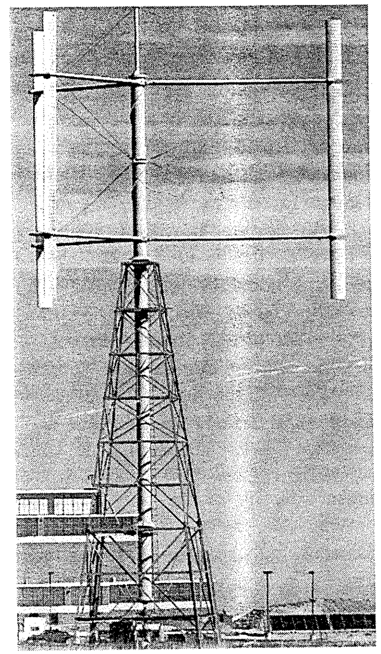


Figure 3-15. The prototype McDonnell 40-kW giromill VAWT. *(Courtesy of the U.S. Department of Energy)*

-- market penetration barriers;
-- market characterization and demographics;
-- markets with near-term high potential;
-- decision analysis for the small-system user;
-- economics of small systems owned by the end user;
-- product liability insurance;
-- industry consensus standards;
-- producibility of small-scale turbines;
-- effects of production rates on the economics of small systems.

The electrical stability and safety implications of many wind turbines distributed over a utility distribution grid were studied, as well as the potential electrical and aerodynamic interactions between multiple units at a given location.

Similar studies relating specifically to the farm and rural use of small-scale wind turbines were performed or sponsored by the USDA. Topics included economic analyses of wind-powered

-- irrigation pumping;
-- space heating systems for farm houses and other buildings;
-- grain drying;
-- refrigeration;
-- water heating.

Experimental research at the Rocky Flats plant included dynamometer, vibration, and electrical testing of small-scale turbines, and the validation of computer models for the prediction of power performance and loads. At the USDA, research on both shallow- and deep-well pumping and the matching of wind turbines and pumps was conducted to optimize the performance of the total system.

Small Turbine Deployment and Applications

In the 1970s many institutional problems had to be faced by owners of wind turbines interconnected with utility power lines, and by developers of small wind turbines. These included safety, power quality, standby and reserve power criteria, buying and selling rates for electricity, zoning requirements, and even the determination of the authority and office to which the turbine owner should apply. Since most of these problems were at the state and local levels and outside federal responsibility, another type of testing was undertaken to solve them. In 1979 the "Field Evaluation Program" (FEP) was initiated, in which federal funds were provided for the installation of 100 or more commercial, small-scale wind turbines throughout each of the United States and its territories, and to provide advice and assistance. In return, utilities and state and local authorities would facilitate the interconnection of private turbines and develop local permitting and approval processes.

Many of the early turbines available commercially at the time had not, unfortunately, been adequately tested, and the difficulty of achieving adequate reliability had been underestimated by many of the new entries into the field. Failure rates were excessively high, giving a negative image to wind energy in some quarters. On the other hand, there were significant successes. Much was learned about correcting operation and installation problems that may have been missed in the design phase. Utility companies and state and local governments became familiar with both the potential benefits and issues associated with wind power systems. About 40 of the planned 100 turbines were installed before the FEP was discontinued in 1983.

The New England Wind Project, a program similar to the FEP, was implemented in 1980 to evaluate some of the DOE-sponsored small-scale turbines under field conditions. Fourteen sites were selected, and a number of prototypes were installed. These included an 8-kW UTRC HAWT on Moon Island in Boston harbor.

There is no doubt that efforts under the Field Evaluation Program and the New England Wind Project helped mature the small-scale wind turbine industry and added impetus to the development of new designs. Many institutional issues were resolved in key states, aiding the introduction of reliable commercial machines in large numbers in the mid-1980s.

Innovative and Unconventional Wind Turbine Concepts

Before describing *unconventional* wind turbines, a definition of a *conventional* turbine is in order. For the purpose of this discussion, a conventional configuration is that which was established as practical by the DC wind power plants of the 1930s and by the Smith-Putnam project. Thus, a conventional wind turbine system is a HAWT with a low-solidity rotor powered by aerodynamic lift driving an electrical generator, with all rotating components mounted on a tower. There have been, throughout history, a myriad of attempts to use other techniques for harnessing wind power. In principle any movable device subject to wind forces can be made to rotate (on some axis), oscillate, or translate. It can then be coupled to some sort of converter and be made to produce mechanical and/or electrical power. Whether an innovative device can generate energy at a lower cost than a conventional wind turbine is quite a different question, however.

Early Unconventional Systems

Panemones

The earliest practical windmills (see Chapter 1) were of the vertical-axis type driven by drag forces and known generically as *panemones*. Panemones are multi-bladed machines often designed with some type of articulating mechanism to fold or *feather* the blades that are moving upwind, while deploying the working blades moving downwind. Panemone devices are re-invented at frequent intervals. Their relatively poor efficiency, low blade speed (a tip-speed ratio necessarily much less than unity), and large surface area have led panemones into a continual dead end. While simple to manufacture in small sizes, they have not proven to be cost-effective in other than primitive installations, owing to the need for large amounts of material and the problem of withstanding high wind loads.

The *Savonius* rotor (Fig. 3-16) is another innovative vertical-axis device and one which has somewhat better performance. With its "S-shaped" cross section, the Savonius rotor, (named for its Finnish inventor) is really more of a semi-lift or low lift-to-drag device. Since the blades are simple to form from sheet metal, the Savonius finds an occasional niche in developing countries for tasks such as water pumping. For the same reasons as the panemone, the Savonius turbine has not been successful for general use.

By the 1950s a number of unconventional wind turbine configurations had been explored in some detail. One of the more unusual of these was the *Enfield-Andreau* HAWT described earlier (Fig. 3-4).

HAWTs with Multiple Rotors

Honnef, in Germany, was an advocate of multiple rotors in the same plane on a single tower as a means of achieving high power levels with rotors of intermediate size [Honnef 1932, Hütter 1974]. In the early 1940s he tested systems with two counter-rotating rotors in the 8-m and 10-m diameter range, but his large-scale designs never got further than artist's drawings. Nevertheless, the idea of multiple rotors continues to attract followers. Studies in the early 1970s concluded that it was more cost-effective to use multiple turbines or larger turbines than to pay for the complex structure needed to support and yaw a multiple-rotor system. One company briefly went into limited production of a six-rotor, single-tower HAWT in 1987.

Multiple rotors in the same plane increase net swept area and should not be confused with multiple rotors on the same axis. In some cases the latter are counter-rotating. Advocates of such systems usually misunderstand the physics behind wind energy conversion. The effects of induced velocity limit the theoretical maximum power coefficient of two rotors on the same axis to little more than that of a single rotor. Counter-rotation does decrease the rotational energy lost in the wake, but this benefit is trivial compared to the costs of the second rotor and associated gearing. These systems have rarely been successful, much less cost-effective. The *Noah* HAWT, privately developed in northern Germany in the mid-1970s, is the most recent example known.

Translating Units

Translating wind power systems have been conceived as a means of achieving power levels far beyond that of an individual wind turbine. These concepts generally involve a large circular or oval track upon which a "train" of vehicles moves, each vehicle supporting a sail or vertical wing of some type. The wheels of the vehicles turn generators, and power is conducted away through a third rail, in the reverse of a conventional electric railway

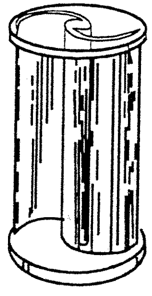


Figure 3-16. Savonius rotor.

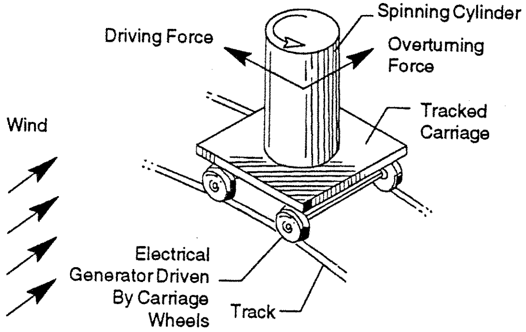


Figure 3-17. The Madaras concept for generating electricity using the Magnus effect.

system. By increasing the lengths of the track and the train, more power could be obtained, presumably without limit.

The only known large-scale test conducted to develop the technology needed for a translating wind power plant was the 1933 *Madaras* experiment. Madaras conceived a plan for a 40-MW plant in which the railway cars were propelled around a track by "sails" in the form of large, vertical *rotating cylinders*, as illustrated in Figure 3-17. Wind flowing across a spinning cylinder or sphere can create a high lift force at right angles to the flow. This is the *Magnus effect*, known since the 1850s. In a preliminary test of the Madaras design, one full-scale cylinder -- 27.4 m high and 8.5 m in diameter -- was built and mounted on a stationary platform in order to measure the Magnus-effect forces. The test was performed in conjunction with the Public Service Company of New Jersey, in Burlington. Test results were mixed, and high cost estimates combined with the economic climate of the Great Depression led to abandonment of the project.

The basic ideà of the translating system re-emerged in the early 1970s with some enthusiastic sponsors. Several small test articles were constructed privately with various types of sails or wings. Translation was usually horizontal, but at least one translated vertically like a conveyor belt. None of these was successful because of mechanical complexity, low "tip speed" with an associated low aerodynamic efficiency, high track loads and overturning moments, the need to reverse the blade angle (or direction of cylinder rotation) at each end of the oval track, and lower wind speeds near the ground.

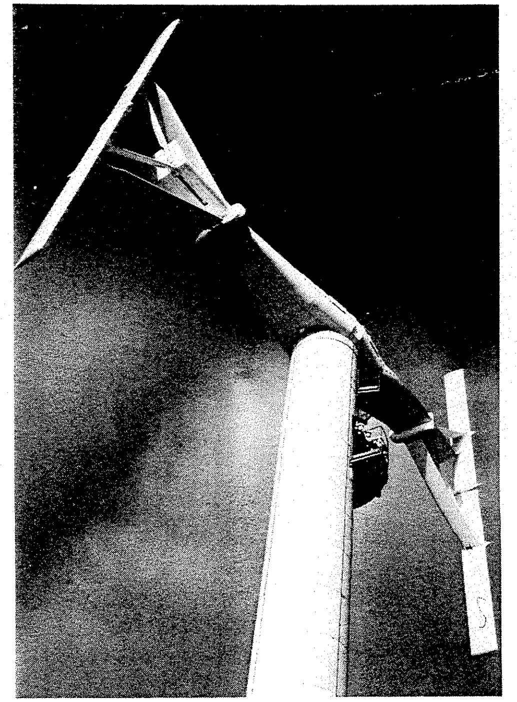
Searching for Modern Unconventional Concepts

To ensure that promising ideas were examined, the Federal Wind Energy Program funded an "Innovative Concepts Research" activity [Vas and Mitchell 1979], inviting proposals on any concept that could extract energy from the atmosphere. Many proposals were received, and a number were supported through the exploratory research phase. In addition, privately-funded unconventional concepts for wind energy conversion appeared regularly. Some examples from both the public and private sectors are described here.

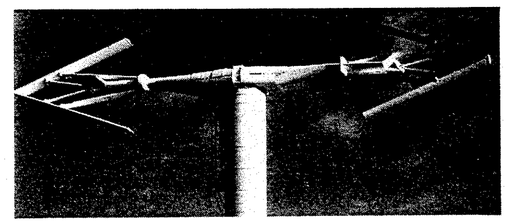
Vertical Axis Systems

Several vertical-axis concepts have been proposed for wind turbines that are driven by lift forces, rather than the drag forces that turn a panemone. These include the *Darrieus rotor* which has been the most successful, and this VAWT configuration is discussed in the following section. The *giromill*, another lift-driven vertical-axis machine, has been developed by several manufacturers. Giromills use straight vertical blades whose pitch angles vary cyclically during rotation and are independently controlled. The 40-kW prototype built and tested by the *McDonnell Aircraft Company* was discussed previously (Fig. 3-15). The mechanical complexity of the blade support and pitch-change systems has usually prevented giromill designs from being cost-effective.

An innovative VAWT rotor, invented by Peter Musgrove at Reading University in England, is the *Arrow* configuration shown in Figure 3-18. This prototype at Carmarthen Bay, South Wales, is 25 m in diameter and rated at 130 kW [Musgrove and Clare 1987]. Its vertical turbine shaft and a horizontal crossarm form a rotating "T". Two blades are attached to the ends of the crossarm by struts, and each is hinged at its mid-length. Below the rated wind speed the blades are vertical, but at wind speeds above rated they are furled or "reefed" to an arrow-head shape by hydraulic actuators in the crossarm. This reduces their swept area and limits both the output power and blade loads.



(a)



(b)

Figure 3-18. The 125-kW, 25-m diameter Musgrove Arrow VAWT at Carmarthen Bay, South Wales. (a) Blades vertical for maximum swept area (b) Blades furled. (Courtesy of *Vertical Axis Wind Turbines Ltd.*)

Wind Flow Augmentation

Another category of innovative concepts encompasses methods of augmenting (accelerating) the wind stream. For example, a *diverging exit cone* or *diffuser* extending downwind from the rotor plane can augment the mass flow into and through the turbine. To prevent separated flow the angle of divergence in a conventional diffuser must usually be rather shallow, which would make the exit cone very heavy and expensive. Research at *Grumman Aerospace Corporation* [Foreman and Gilbert 1979, Loeffler 1981] showed that placing annular slots in the cone allowed external air to energize the boundary layer and delay separation. This could lead to a shorter exit cone with an *augmentation factor* (*i.e.*, maximum augmented power divided by the maximum power of an unducted rotor of the same size) of two to three. Even with these favorable aerodynamic results, the cost of the exit cone and its supporting structure has been estimated to exceed that of using a larger conventional rotor to obtain the additional power.

An attractive alternative, conceived at the University of Delft (Netherlands), is the use of *tip vane dynamic inducers* to provide the same flow effect as a diffuser. Considerable research on dynamic inducers was also undertaken in the U.S. by *AeroVironment, Inc.* [Lissaman *et al.* 1980]. Performance was found to be extremely sensitive to tip-vane operating parameters, and this has prevented significant augmentation over a practical operating range, at least to-date.

Atmospheric Energy Conversion

Several laboratory-scale research efforts examined methods of extracting the *latent heat of vaporization* existing in the humidity in the atmosphere (the same energy source that causes thunderstorms) and the possibility of tapping the energy of *tornado-like vortices*. It turned out that these would require structures several thousands of meters high to achieve reasonable efficiency. Cost and institutional issues precluded further consideration.

Another "tower-type" energy concept which is re-discovered at intervals utilizes atmospheric convection currents, either natural or augmented. The most-notable attempt in recent times was the construction of a large tower in Spain by a German-Spanish team. Several acres of black Mylar plastic sheet were suspended a meter above the ground around the tower, forming a solar "oven" to heat the air below. Convection forces then drew the heated air to the base of the tower and through an internal turbine, exhausting upward through the tower. The predictable result of such experiments is a finding that the system has a low efficiency and a high capital cost.

A more esoteric scheme utilized *electrostatic generators* incorporating charged screens which could extract kinetic energy from the wind by electric fields operating on minute charged particles in the air. In theory, that could lead to a "no-moving-parts" wind power device. In experiments at the University of Dayton and at *Marks Polarized, Inc.* power was actually extracted, but not enough to justify further research and development.

Unconventional HAWT Subsystems

An interesting innovative concept developed with private funds was the 50.3-m diameter *Schachle-Bendix* HAWT shown in Figure 3-19, sponsored by the *Southern California Edison Company* and tested at its Devers site near Palm Springs [Rybak 1981]. One of its innovative features was a tripod truss tower rotating on a track, there being no yaw drive at the nacelle. This approach was similar to that of some early French HAWTs and the pioneering Russian *Balaclava* turbine of the 1930s (Fig. 1-21). A second unusual feature was the use of a *variable-speed hydraulic drive* in the power train. Fourteen fixed-

displacement hydraulic pumps in the nacelle, driven by the turbine shaft, supplied high-pressure fluid to 18 variable-displacement hydraulic motors on the ground, and these in turn drove a synchronous generator. This allowed flexibility in the rotor speed and in the control system. A third unconventional feature was the use of new, non-aircraft airfoils designed by the manufacturer for very high lift. The system was found to have large power losses in the hydraulic drive and an aerodynamic performance which did not meet expectations. Although it did attain a power output of 1.1 MW, a very high wind speed would have been required to achieve its 3-MW rating.

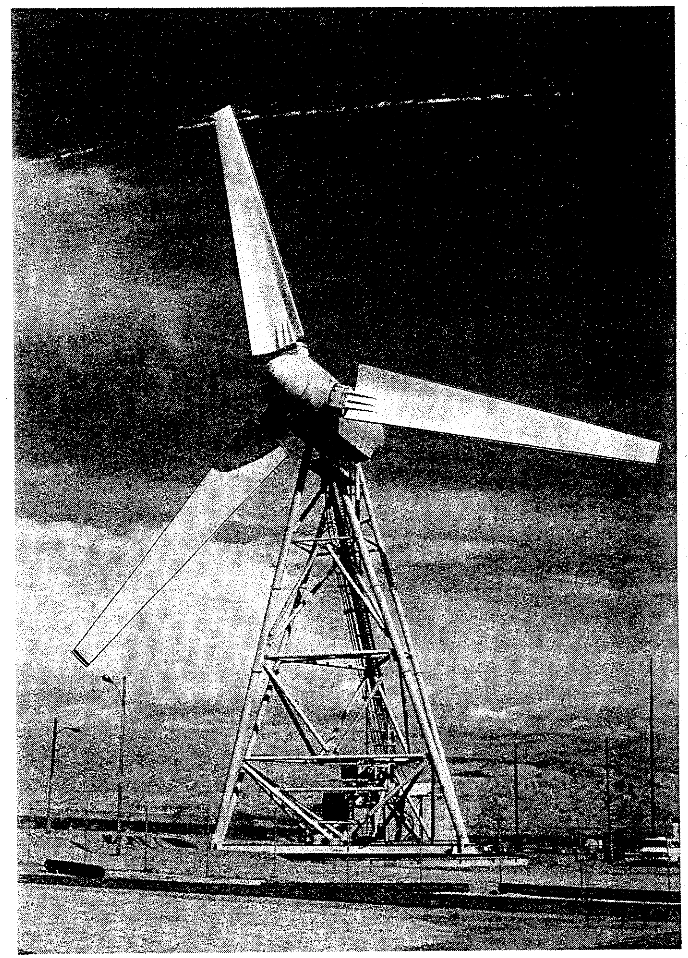


Figure 3-19. The Schachle-Bendix 3-MW HAWT. *(Courtesy of Southern California Edison Co.)*

Sandia/DOE Experimental VAWTs

The Darrieus Wind Turbine Rotor

An elegant rotor design had been invented in France in the 1920s by G. J. M. Darrieus [Darrieus 1931]. It utilized a vertical axis around which rotated curved airfoil blades in the shape of a hoop, somewhat resembling an egg-beater. This curved-blade rotor was re-invented in the late 1960s by engineers at the National Research Council in Canada (Fig. 3-8), where it was the subject of extensive study and development for two decades [*e.g.* South and Rangi 1972].

The *Darrieus rotor* has long been recognized as containing the seeds of a highly efficient and intrinsically simple VAWT. It has its gearbox and generator located at the base of the rotor for ease of maintenance. It will accept the wind from any direction without a yaw mechanism. Although Darrieus blades are about three times as long as the blades of a HAWT with the same swept area, they are generally so slender that the actual rotor solidities (*i.e.*, planform area per unit of swept area) are similar. However, a cost-effective Darrieus VAWT required considerable development to overcome several disadvantages. Guy cables required to support the top rotor bearing make it difficult to mount the rotor very far above ground level to take advantage of higher wind speeds. Also, a Darrieus rotor produces higher gearbox torques, both steady and cyclic, than a HAWT of the same power and requires more material.

Sandia/DOE 17-m Experimental VAWT

Darrieus research was undertaken briefly at the NASA Langley Research Center in the early '70s [Muraca, *et al.* 1975, Muraca and Guillote 1976]. However, the Sandia National Laboratories in Albuquerque became the center of VAWT research and development in the U.S., building on technology from the NRC in Canada. After initial analysis, laboratory research, and small-scale field tests, a *17-m VAWT* was designed and built at Sandia (Fig. 3-20). The main purpose of this turbine was to determine what design and manufacturing improvements would be required to make Darrieus VAWTs competitive with HAWTs.

Economic studies supporting the early research tests on the 17-m VAWT suggested several improvements: First, two blades would be more cost-effective than the original three on this turbine. Second, the long struts used to strengthen the rotor should be eliminated. These struts were adding drag that consumed significant power, and their cost was of the same order of magnitude as that of the working blades. Third, the blade airfoil shape should be changed to one specifically tailored for the VAWT application. It is worth noting that all three of these findings also applied to HAWTs. Strut drag losses, for example, were found to be significant on the Gedser HAWT (Fig. 3-1) during tests in the late 1970s, and few (if any) modern HAWT rotors have struts.

VAWT Blade Airfoils

Each time the blade of a VAWT makes a 360-deg rotation around its central column, its angle of attack changes rapidly and over a wide range. This presents VAWT designers with a complicated aerodynamic problem not present in aircraft and only to a small degree in HAWT rotors. Airfoils tailored for VAWT use must have not only enhanced lift at low angles of attack, both plus and minus, but must also be shaped to control stall behavior during normal operation. In high winds, stall moderates lift so that constant power is

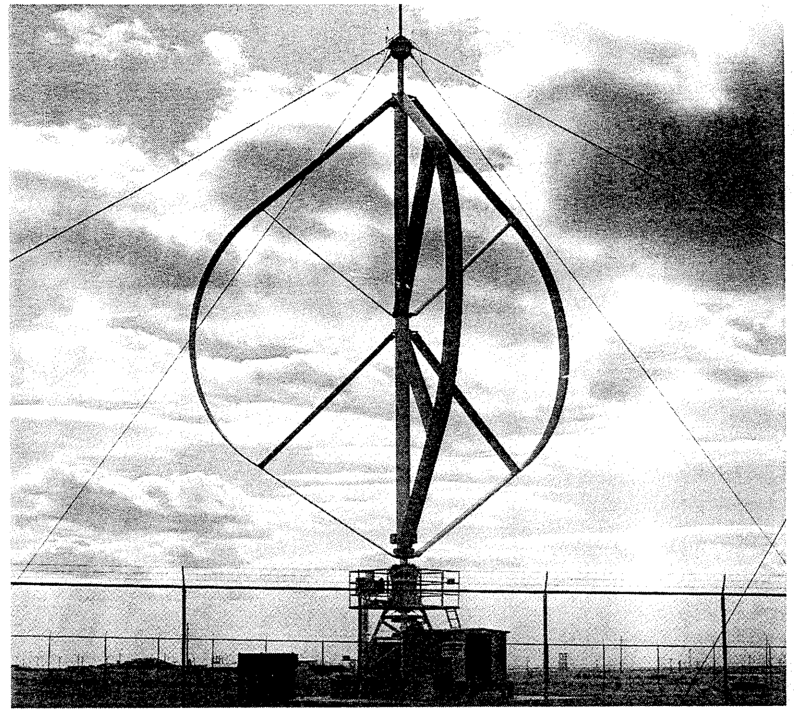


Figure 3-20. The Sandia/DOE 17-m experimental Darrieus VAWT under test near Albuquerque, New Mexico. (Courtesy of Sandia National Laboratories)

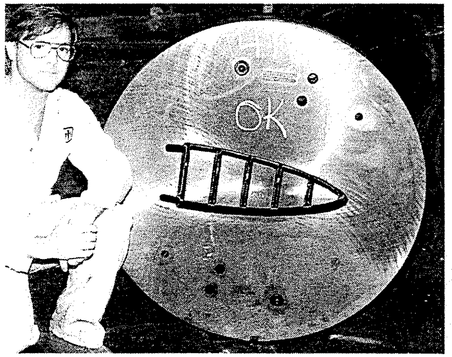
achieved, and regulating power in high winds without movable aerodynamic surfaces helps to control system costs. Sandia researchers patented an early attempt to tailor stall behavior by *pumped spoiling*, which involves drilling lines of holes along the blade and forcing small quantities of air into the boundary layer. While technically feasible, initial cost and maintenance expenses were found to be a major disadvantage of pumped spoiling. Redesigning the blade shape proved to be much more practical.

Engineers at Sandia and at various universities have developed airfoils that can regulate power through stall. In 1980 researchers at Ohio State University originated the concept of *natural laminar flow airfoils*, which met the two requirements of enhanced lift at low angles of attack and regulated stall at high angles. These specially-tailored components were first tested on a 5-m research VAWT at Sandia, and then their improved performance was verified on the 17-m VAWT [Klimas and Worstell 1986]. As a result of the NRC and Sandia airfoil development programs, peak power coefficients of today's Darrieus turbines have reached the same level as those of modern HAWTs.

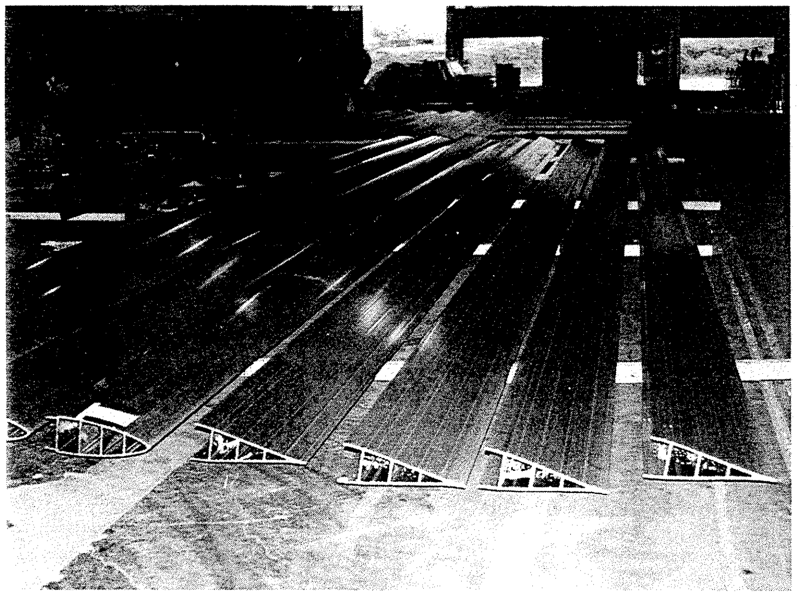
Blade Manufacturing Improvements

The first VAWT blades were expensive because they were made of aluminum, fiberglass, and honeycomb materials, all of which had to be carefully fitted together by hand to form precise compound curves. In the mid-1970s *Alcoa Industries* became interested in aluminum VAWT blades and systems as potential product lines and investigated methods for reducing blade manufacturing costs. Working with Sandia engineers, the company developed an extrusion process for Darrieus blades in which partially molten bars of aluminum are forced through an airfoil-shaped die, after which the shaped structure cools and solidifies. This process dramatically reduced the cost to manufacture VAWT blades, produced long sections of uniformly high quality material, and controlled the airfoil shape to very close tolerances.

Extruded aluminum blades were first flown on the 17-m VAWT, and extrusion continues to be used today to manufacture VAWT blades. Figure 3-21 shows a steel extrusion die and extruded aluminum sections for a large VAWT airfoil. The leading and trailing-edge sections in Figure 3-21(b) are joined together before the complete airfoil is given its curved shape.



(a)



(b)

Figure 3-21. Extrusion of aluminum VAWT blades.
(a) Steel die used to form the leading-edge section of an airfoil integrally with its interior spars. (b) Leading- and trailing-edge extrusions prior to being joined and bent to their final, curved shape. *(Courtesy of Sandia National Laboratories)*

Structural Dynamics

Because of its relatively long and slender blades, a detailed knowledge of the structural-dynamic behavior of a Darrieus VAWT is critical to achieving an acceptable fatigue lifetime. Engineers must be able to accurately predict a VAWT's many modes and frequencies of vibration, as well as static and dynamic stresses caused by gravity, centrifugal forces, and the wind. Predicting natural frequencies requires a computer model of the complete VAWT system, including the supporting cables, that must be validated by *modal testing* of the actual turbine [Lauffer *et al.* 1987]. To conduct a modal test, accelerometers are mounted at strategic points on the structure; a cable is attached to the VAWT, tensioned, and then quickly released. The resulting dynamic signals from the accelerometers are analyzed by computer for their frequency content, which identifies the vibration modes. The modal testing procedures developed at Sandia using the 17-m VAWT as a test bed are now applied throughout the world on both VAWTs and HAWTs.

Sandia/DOE 34 m VAWT

Between 1984 and 1987 a *34-m Darrieus VAWT* test bed for developing advanced concepts was designed and fabricated in modules at Sandia and then installed at the U.S. Department of Agriculture Test Station at Bushland, Texas [Ashwill *et al.* 1987]. This highly-instrumented 625-kW turbine (Fig. 2-2) has *variable-chord blades* for aerodynamic and structural optimization, *tailored airfoils* designed specifically for VAWTs, and a *variable-speed constant-frequency (VSCF)* generating system. The test program began in 1988, in cooperation with the USDA personnel, and by early 1989 full rated power was achieved.

Figure 3-22 shows the *operating map* of the control system. The test bed uses a variable-speed system in which the generator's variable-frequency AC output is converted to DC and then converted back to AC at the utility line frequency. *Elastomeric couplings* are incorporated in the drive train to attenuate the *torque ripples* associated with VAWTs (caused by the blades traveling in alternating upwind and downwind paths).

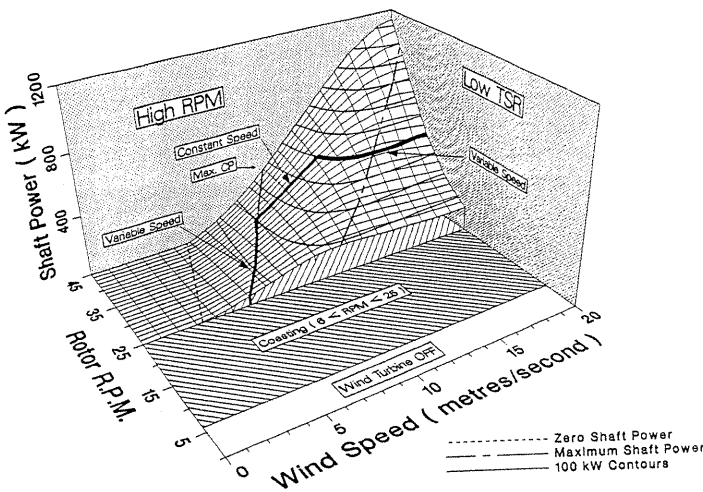


Figure 3-22. Operating map of the 34-m VAWT test bed. [Ashwill *et al.* 1987]

The 34-m diameter rotor has two *step-tapered* blades, each with five sections of extruded 6063-T6 aluminum. Airfoil cross-sections along the curved blade are illustrated in Figure 3-23. The use of step-tapered blades, with a longer chord near the hubs, a smaller chord at the equator, and a transition section in between, maintains a more uniform *Reynolds Number* over most of the blade length. The high-lift, *natural laminar flow* airfoils used in the equatorial sections are part of a series developed specifically for use on VAWTS. Root sections use conventional *NACA airfoils*, which offer superior aerodynamic properties at lower Reynolds numbers and higher structural strength. The chord widths of the various blade sections are too large for extrusion in one piece, so each section is made up of either two or three extrusions with bolted lap joints in the spanwise direction, as shown in Figure 3-23.

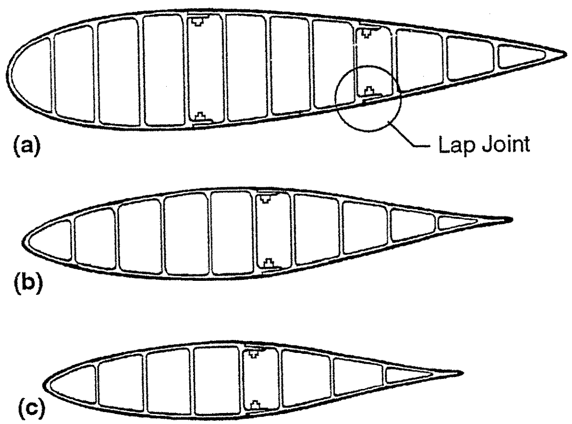


Figure 3-23. Airfoil cross-sections in the 34-m VAWT blades. (a) Root sections, near the hubs (b) Transition sections (c) Center (equatorial) section [Berg *et al.* 1990]

Continued research work, centered on the 34-m VAWT test bed, includes validating aerodynamic and structural-dynamic computer models, testing airfoil designs and new blade materials, and developing various control strategies. The purpose of this work is to assist industry to improve the VAWTs in commercial operation, as well as to develop technology that can be used in the next generation of VAWTs.

Developing a Commercial VAWT System

Testing and modification of the 17-m VAWT at SNL in the late 1970s rapidly improved its performance and reliability. A low-cost, pre-commercial design was then derived from it in 1979 under a Sandia development contract won by *Alcoa Industries*. Specifications required a rotor diameter of 17 m and a power output of 100 kW, and that the system be designed for manufacturing at low cost. By 1981 three units were installed on sites representing specific applications: Bushland, Texas, at the U.S. Department of Agriculture Test Station, to demonstrate an agricultural application; Rocky Flats, Colorado,

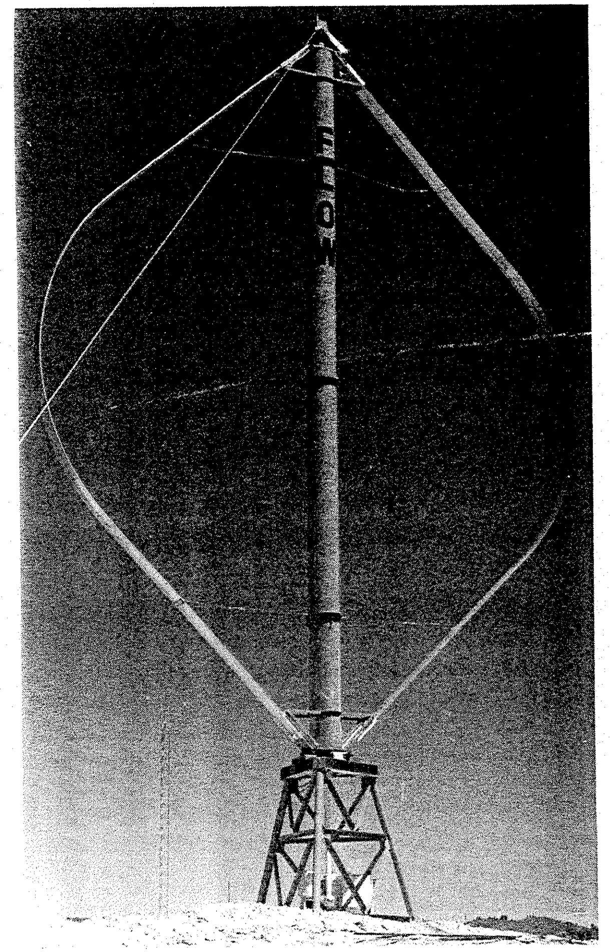


Figure 3-24. A typical commercial VAWT in a California wind power station whose design was derived from the Sandia/DOE 17-m experimental VAWT.

at the Wind Turbine Test Station, to confirm structural and performance predictions; and Martha's Vineyard, Massachusetts, to demonstrate the VAWTs applicability to a small utility system.

The successful operation of the pre-commercial prototypes, including more than 10,000 hours for the Bushland machine, convinced two other manufacturers to further develop the Sandia/DOE 17-m VAWT into commercial products. The *VAWTPOWER* and *Flowind* companies each manufactured VAWTs for use in California wind power stations, with two-bladed configurations like that of the turbine shown in Figure 3-24. By the late 1980s, over 600 Darrieus VAWTs were installed in California, with a total rated capacity of over 90 MW (see Chapter 4 for additional information).

Supporting Research and Technology

While the construction and testing of particular wind turbines engendered the most interest and publicity, these systems evolved due to the advances in the basic technologies that underlie the design and siting of the turbines themselves. Research and technology development were financed principally by government grants and contracts because of the limited financial resources of the wind industry and the uncertain markets during the 1970s and 1980s. The three technical needs underlying the future success of wind power were (1) the need to *improve performance*, particularly annual energy output, (2) the need to *extend structural lifetime and integrity*, while decreasing material costs and design complexity, and (3) the need to be able to rapidly *locate and evaluate productive wind turbine sites*, with reasonable accuracy. The disciplines of aerodynamics, structural dynamics, and the atmospheric sciences are interrelated in all three of these areas.

Wind Characteristics

In wind energy conversion systems, the wind "fuel" is the source of both the energy and the principal structural loads. Hence, the wind's characteristics directly affect both energy production and system cost. Moreover, the wind speed varies with time on scales from seconds to years, affecting mean and transient loads, control of peak power, and utility dispatch and planning. The wind also varies with location, affecting siting, turbine spacing, and profitability. Furthermore, the wind's power can range from zero to an order of magnitude above the mean. This inconstant behavior of the wind leads to unique design problems that require an understanding of wind fundamentals for solution. Lastly, wind measurement and research in the past have been aimed at weather prediction, with the bulk of the existing data being collected for aviation purposes and, more recently, environmental studies. This data base, therefore, contains major biases toward airports and urban sites and away from potential wind turbine locations.

In 1974, the Battelle Pacific Northwest Laboratory (PNL) undertook the task to develop both the data base and the analytical modeling tools for site evaluation and description of wind characteristics. On the siting front, an initial *U.S. Wind Atlas* was developed [Barchet *et al.* 1980-81] from National Atmospheric and Oceanographic Administration data (principally from airports), utilizing early interpolation tools. This Atlas presented estimates of the annual and quarterly mean wind speeds for every 25 square kilometers of the U.S., and the level of uncertainty in those wind speeds. It formed the basis for the first estimates of the national wind resource and served as a guide for the early "wind prospecting" by entrepreneurs endeavoring to develop and commercialize wind power. The California Energy Commission, recognizing the state's potential for wind power, extended the California atlas to a finer scale [Miller and Simon 1980].

PNL developed the first *world wind resource map* (on a coarser scale) for the World Meteorological Organization [WMO 1981]. At the United Nations Conference on New and Renewable Sources of Energy in Nairobi in 1981, this work was a stimulus to the investigation of the worldwide potential of wind power. Later, more advanced interpolation tools and analytical techniques, utilizing climatological and upper air data as well as additional wind data from numerous sources, led to the creation of an advanced *Wind Energy Resource Atlas of the United States* in 1987 [Elliott *et al.* 1987].

While wind atlases are useful for estimating large-scale resources and identifying potentially high wind areas, terrain and climate cause variations too localized to be identified on any reasonable map scale. Thus, models were developed to estimate flow patterns and wind velocities across relatively small geographical areas. Such models and other techniques allow estimation of wind speeds over a site less than 10 square kilometers in area, given

a few local measuring locations. These computer models are used today to lay out wind power stations, although their accuracy varies depending on the complexity of the terrain (PNL 1980, 1981].

On an even finer scale, the character of both the wind *inflow* into a turbine rotor and the *wake* behind it are critical. Knowledge about the wake is needed to determine effects on downwind turbines in wind power stations, such as energy losses and increases in structural loads, as a function of wind turbine spacing. The turbine wake structure is also important in assisting analysis of the flow pattern through the rotor. Improved mathematical models of turbine wakes have resulted from wind tunnel test results and field measurements. The latter can be extremely demanding.

Knowledge of the characteristics of the wind inflow is also critical to understanding the performance, dynamics, and structural loads imposed on the wind turbine. Early analyses assumed a steady wind across the turbine rotor disk, allowing for *wind shear* (variation with elevation) and *tower shadow* (a sector downwind of the tower with reduced speed). Such inputs to structural analyses predicted mean loads fairly well, but badly underestimated cyclic loads caused by *wind turbulence*. This in turn led to underestimation of fatigue damage. Extensive research was undertaken in the 1980s to understand the expected *turbulence spectra* under various climatic, terrain, and wind velocity conditions.

Vertical and horizontal *planar arrays of anemometers* (Fig. 3-25), in which rings of anemometers are located upwind or downwind of the rotor swept area, have provided experimental data from which the turbulence experienced by a blade element can be synthesized. *Whirling arm* tests, utilizing instrumented booms rotating as if they were a turbine blade, directly measured local wind velocities as an airfoil section would actually see them. Kites, smoke tests, and sonic techniques have also been used. By 1986, *empirical turbulence models* became available which significantly improved the ability to analyze rotor fatigue loads through knowledge of wind inflow details smaller than the rotor itself.

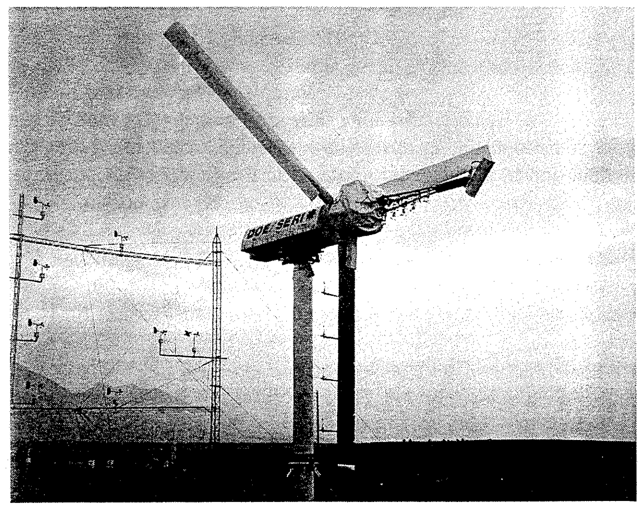


Figure 3-25. A vertical plane array of anemometers near the 25-kW research HAWT at the NREL test station. By sequentially sampling the data around this ring of anemometers (a process called "rotational sampling"), inflow turbulence experienced by a moving rotor blade can be measured. (*Courtesy of the National Renewable Energy Laboratory*)

Validation of these models continues, using turbulence data from sites where turbines have experienced wind damage. Data from U.S. sites are being collected at the Pacific Northwest Laboratory. Turbine wake turbulence data are currently shared under an International Energy Agency (IEA) agreement amongst eight countries [Milborrow and Ainslie 1992]. A better understanding of small-scale turbulence is considered a major key to improved fatigue life and performance in future wind turbines.

Aerodynamics

While the fundamental aerodynamics of wind turbines was well understood over half a century ago, adequate analytical tools were not readily available to assist designers to rapidly and accurately predict power performance. In addition, the characteristics of hundreds of different airfoils for airplane wings, propeller blades, and helicopter rotors, well-documented in wind-tunnel test reports, were less useful to wind turbine blade designers than had been expected. Trends in aviation led to relatively thin airfoils, while wind turbines (with less concern for weight and more for extremely long fatigue life) require moderate-to-thick airfoils that are proportionately stronger while retaining good performance. In addition, the *lift and drag* characteristics of most available airfoils had been measured thoroughly for a relatively narrow range of *angles of attack*, only slightly beyond the angles of *stall* (+/-18 to 20 degrees or so). Yet, portions of wind turbine blades often operate at angles of attack well beyond stall.

The fundamentals of wind turbine aerodynamics, started by Prandtl and Betz, were re-derived and extended by the initial work of Wilson and Lissaman at Oregon State University and AeroVironment, Inc. [Wilson and Lissaman 1974, 1976]. A compendium of aerodynamics design methods (as well as methods for other aspects of wind turbine design) was developed at the Massachusetts Institute of Technology [Miller et al 1978]. From this base, persistent in-house and contract research at the NASA Lewis Research Center, the Solar Energy Research Institute, and Sandia Laboratories led to continual improvements in aerodynamic modeling tools and understanding of rotor aerodynamic issues. Early models based on *single stream tube* analysis and simple *blade element* theory were replaced by computer codes using *multiple stream tubes* and *lifting line* models. These, in turn, have been giving way to improved multiple stream tube models, *lifting surface* models, and models incorporating three-dimensional flow and turbulence effects.

At first, both aerodynamic analyses and wind tunnel tests consistently under-predicted the power output and blade loads encountered in the field, for all but the smallest wind turbines. Causes of these discrepancies included *three-dimensional flow*, *inflow turbulence*, and *dynamic stall* during rapid changes in angles of attack.

Airfoils specifically tailored to the needs of wind turbine designers were developed in the 1980s, including *natural laminar flow* airfoils, new moderate-to-thick airfoils for increased strength and stiffness, and airfoils with *lower sensitivity to roughness*. Accumulated dirt and insects have caused significant energy losses in many wind power stations. Development of advanced airfoils continues today, aimed particularly at increased energy capture in low-to-moderate winds and limited output power and loads in higher winds.

Structural Dynamics and Fatigue Life Design

The limitations of analytical models for wind characteristics and aerodynamic behavior were aggravated in the mid-1970s by serious limitations in the state-of-the-art for predicting structural dynamic loads and fatigue life. Widely-used structural analysis codes such as *NASTRAN* were useful for predicting *natural frequencies* and static loads, but were totally inadequate for calculating *aeroelastic* dynamic loads, in which wind forces are coupled to

structural motions. These limitations became more evident as designs of advanced turbines incorporated flexible towers, teetered hubs, and variable-speed power trains.

The effects of unattended, all-weather operations on loads, fatigue life, and damage mechanisms became better understood as first-generation turbines (heavily instrumented with anemometers, *strain gages*, and *accelerometers*) provided the first valid field data (Fig. 3-26). Various computer models (with a plethora of acronyms) were soon developed which, in turn, led to more accurate load predictions and better insight into design and operating issues [Spera 1977, Thresher 1981]. Codes such as *REXOR*, *MOSTAB*, *FLAP* [Wright *et al.* 1988], and *DYLOSAT* [Finger 1985] incorporated more and more capabilities, although limitations were still significant.

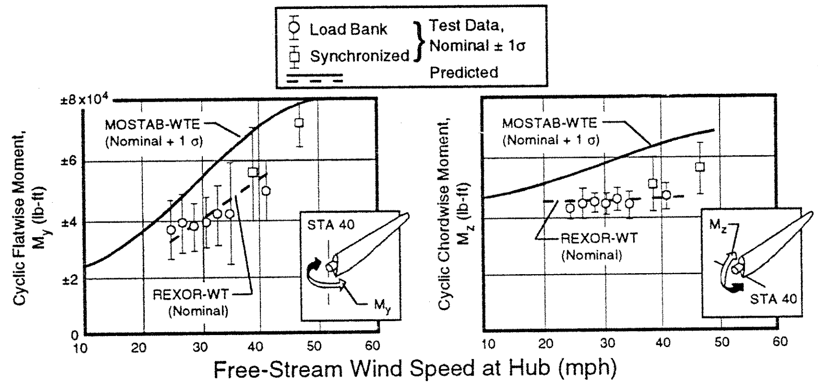


Figure 3-26. Typical comparison between measured and calculated dynamic loads on the blades of first-generation HAWTs. Early Mod-0 loads are shown here. [Spera 1977]

Today, codes named *HAWTDYN*, *VAWTDYN* (for the Darrieus), *NASTRAN/FFEVD*, and *DUWECS* [Bongers *et al.* 1993], and models using the general-purpose *ADAMS* software[1] [Wright *et al.* 1993] enable the structural analyst to include *statistical techniques*, non-linear *damage accumulation* models, integrated *rotor/tower/controls coupling*, and complex wind inflow conditions. A wealth of field test data has led to significant validation of structural modeling techniques and the identification of remaining limitations.

Public Acceptance

Research on the public's acceptance of the *aesthetics* of wind turbines has not produced any definitive conclusions, a not wholly unexpected result. Early research in the vicinity of isolated prototype turbines and subsequent experience with multiple installations have shown that the presence of a few turbines normally does not create more than isolated complaints. The same is true for wind turbines in larger numbers if they are located in relatively remote areas, are not exposed to much public visibility, and do not occupy particularly scenic ground. With only a few exceptions, most medium- and large-scale turbines in small numbers were usually greeted as beneficial, as potential tourist or advertising attractions, or as representative of the pioneering spirit of the community. The apparently leisurely turning of the larger rotors with their slender blades has generally led to a positive aesthetic reaction, in most surveys undertaken. Conversely, some *wind power*

[1] *ADAMS* is a registered trademark of Mechanical Dynamics, Inc.

stations with hundreds of smaller turbines in highly-visible locations have stimulated considerable public opposition.

Two additional factors clearly improve the degree of public acceptance. The first factor is the perceived energy benefit to the community, including lower cost and higher availability. The second factor is the degree of careful planning and open communication with the community and its leaders well before construction starts. However, one can recall that European and American windmills, which society now views with nostalgic fondness as romantic artifacts from our past, were work-a-day machines in their time, no different from our tractors and factory smokestacks. Only history will determine whether the same will be said in the future about today's modern wind turbines.

System Configuration Tradeoffs

A wind turbine, like an aircraft, is a complex system which is the result of many tradeoff decisions made in the search for optimum overall performance and economy. In the evolution of modern wind turbines, there are a number of major configuration variables whose trends over time (and the reasons for those trends) are fairly evident. In other cases, there is still doubt as to the "best" or optimum approach. For example, the pros and cons of HAWTs versus VAWTs are still debated. In some cases the "optimum" approach changes with time as technological developments in one subsystem affect the overall design.

Turbine Size

The question of optimum size of wind turbines for large-scale electrical generation is probably the most controversial one in the field of wind power, and there is yet no clear answer. From a first-order standpoint, there are two countervailing forces: Rotor *swept area* and power increase as the square of the rotor diameter, but weight and cost would be expected to increase roughly as the cube, for geometrically similar structures. This *square-cube relationship* should favor small systems and limit the maximum turbine size.

However, a converse effect occurs for several reasons. Most sites have a *positive wind shear*, so wind speed increases with elevation. Input wind energy increases as the cube of the wind speed, so a larger wind turbine, being taller, should capture more energy per unit of swept area. This additional energy capture also implies reduced *land requirements* for a wind power station of a given rating composed of larger turbines, when the turbine separation is a fixed number of diameters. In addition, the size and cost of many components (*e.g.* the control system) do not increase at a cubic rate with increasing rotor diameter, and sometimes increase very little. Clearly then, there are some *economies of scale* to offset the square-cube relationship. Thus, there is some optimum size at which these two countervailing forces are economically balanced.

Several studies in the 1970s attempted to determine optimum size by examining families of hypothetical wind turbines, estimating scaling laws for individual subsystems, and calculating *cost-of-energy* (COE, in cents per kilowatt-hour) *vs* turbine size. Many in the field concluded that there were, in fact, two minimum energy cost points. Very small, simple turbines would be expected to be relatively expensive because of the threshold cost of many components and services. A site maintenance call, for example, could cost the equivalent of a month's electrical output. As this small turbine is made larger, then, energy costs would be expected to decrease. However, this downward trend would rapidly reverse and energy costs would increase again, because simple "brute force" components become very heavy as dynamic loads increase with size (*e.g.*, a tail fin for yaw control of a HAWT). This reversal establishes the *first minimum of energy cost.*

Changing the system configuration to one utilizing advanced structural concepts and active aerodynamic, electronic, and electrical controls reduces loads and increases energy capture, causing the cost of energy to decrease again. This assumes that the system is large enough to afford such controls. Finally, as rotor size continues to increase, the square-cube law eventually dominates, and further increases in rotor size lead to increases in the cost of each unit of energy produced. This establishes the *second minimum of energy cost.*

In practice, of course, many other factors come into play. *Technical risk*, at today's stage of technology, is higher in larger machines. The higher *capital investment* required for manufacturing large-scale turbines represents a major commitment that is unlikely to be made unless a very firm market and market advantage are discerned. For a given capital investment, more small units can be fabricated, and the advantages of *production tooling* and improvements based on *production experience* can be realized. Small- and medium-scale turbines may also be able to use standard *off-the-shelf components*, such as gearboxes or low-cost automotive brakes. While a number of large-scale prototype turbines have been successful in both European and U.S. government programs, only a few private ventures have occurred in this size range. None of these has yet gone into production, nor is that expected until there is a major change in the energy market and in energy prices. The size of new commercial wind turbines has, however, been steadily increasing over time.

Tip Speed Ratio and Solidity

Tip-speed ratio (tip speed divided by wind speed) is a key configuration variable that has increased over several centuries and continues to do so today, albeit at a slower rate. The reasons are numerous. A higher tip-speed ratio reduces *rotational wake losses*, and hence increases the theoretical peak power coefficient. More importantly, a higher tip-speed ratio means a higher *turbine shaft speed* (for a given rotor diameter) and thus a lower *torque* for a particular power output. This in turn means smaller gearbox shafts, cases, bearings, and gears. Higher turbine shaft speed may permit fewer *step-up stages* in the gearbox to reach an efficient generator speed or a smaller generator, if a direct-drive concept is used. This can be significant in anything other than the smaller wind turbines.

For highest aerodynamic efficiency, tip-speed ratio and *rotor solidity* (total blade *planform area* divided by swept area) are inversely related, so higher tip-speed ratios lead to lower blade area and hence less blade material. This is particularly important at the larger sizes in which the blades form a larger percentage of total system cost.

Factors that make higher tip speed ratios difficult to achieve include the added *starting* difficulties associated with a low-torque rotor, particularly in moderate or low wind conditions and the potential for *acoustic noise* from the tips. The starting problem can be solved by using a generator which can motor the rotor up to operating speed. This involves a small amount of energy consumption and added equipment cost, but *motor-starting* is an attractive solution. The Darrieus VAWT, for example, does not produce torque (of any significance) when stopped, and it is essentially always motored up to a rotational speed where aerodynamic forces can take over.

Number of Blades

At very low solidities, blade dimensions become sufficiently small that it becomes difficult to design them with adequate structural strength and stiffness. For a given solidity, dividing the total planform area amongst fewer blades maximizes the cross-sectional size and strength of each blade. Thus, modern wind turbine rotors have almost universally either two or three blades. Some experiments have been undertaken on one-bladed (counterbalanced) machines as the logical limit of this trend. One-bladed rotors appear to have peak power coefficients only 5% to 10% below those with two or three blades. The structural dynamic behavior of a HAWT becomes increasingly more difficult to analyze and to accommodate as the number of blades is reduced from three to two to one.

Research on one-bladed rotors has been conducted in Germany (since the 1930s), Italy, and in the U.S. on the Mod-0 experimental HAWT. Structural dynamics questions associated with asymmetric loading are a worrisome issue for the one-bladed concept. A one-bladed, 24-m diameter 370-kW *Monopteros* wind turbine erected near Bremerhaven, Germany, was tested with sufficient success that three 50-m, 640-kW commercial units were erected at nearby Wihelmshaven. An Italian-German team now produces several sizes of one-bladed *Riva Calzoni* wind turbines, including a 350-kW unit 33 m in diameter.

Large-scale wind turbines around the world, both government and privately funded, have tended more to use two blades, rather than one or three. The benefits of higher tip-speed ratios are more important to larger turbines with their intrinsically lower shaft speeds, higher step-up ratio requirements, very large torques, and higher ratios of rotor cost to total installed cost. Moreover, large-scale system manufacturers generally have proportionately more engineering and analytical facilities and budgets available to solve structural dynamics problems. Exceptions to this trend, retaining the three-bladed configuration, include the two *630-kW Nibe turbines* in Denmark and larger commercial units (up to 500 kW) built with Danish utility and European Economic Community (EEC) funds. For the converse set of reasons, smaller commercial turbines have generally used three blades.

Rotor Blade Materials

Early electricity-producing wind turbines used wood blades, as did many of their water-pumping predecessors. Early experiments into larger systems (such as the Mod-0 HAWT) used *aluminum rib/spar/skin construction* typical of airplane wings. This design, however, is labor intensive and expensive, and the many rivets and bolts are subject to fatigue failure. Other early machines used everything from *riveted and bolted steel* (the Smith-Putnam turbine) to *laid-up fiberglass*, cured in molds (the Hütter turbines). Fiberglass, manufactured in this manner, remains one of the dominant materials for blades under 10 m long, especially in Europe.

The *Hamilton Standard-KKRV WTS-3 and -4 wind turbines* successfully utilized filament-wound fiberglass blades each 24 m long. Other large turbines, such as the *Mod-2* and the *3.2-MW Mod-5B* have utilized *welded steel rotors*, and one would expect that to remain the case for rotor diameters larger than about 60 m, particularly if the blades contain outboard mechanisms for tip pitch control. However, an increasing market may allow further investment in automated filament-winding machinery, which could cause the trend to shift toward fiberglass and away from welded steel. Composite materials more exotic than conventional fiberglass have been used, but rarely. The German *Growian* and *Aeolus II* HAWTs, for example, had some *carbon fiber composite* in their blades, but in most cases the economics of wind turbines preclude the use of such expensive materials.

In a blade technology program at the NASA Lewis Research Center, numerous blade designs and materials were examined and tested [Linscott *et al.* 1984]. The chronology of this extensive program, with field installations of the various materials developed, is illustrated in Figure 3-27. Some techniques failed, but several fiberglass variants were among those that were successful. Both *filament- and tape-wound fiberglass* were shown to be amenable to fabrication over mandrels on automated machinery [*e.g.* Weingart 1981]. Reducing hand labor should lead to lower costs and improved quality control, always an issue in highly-stressed composites.

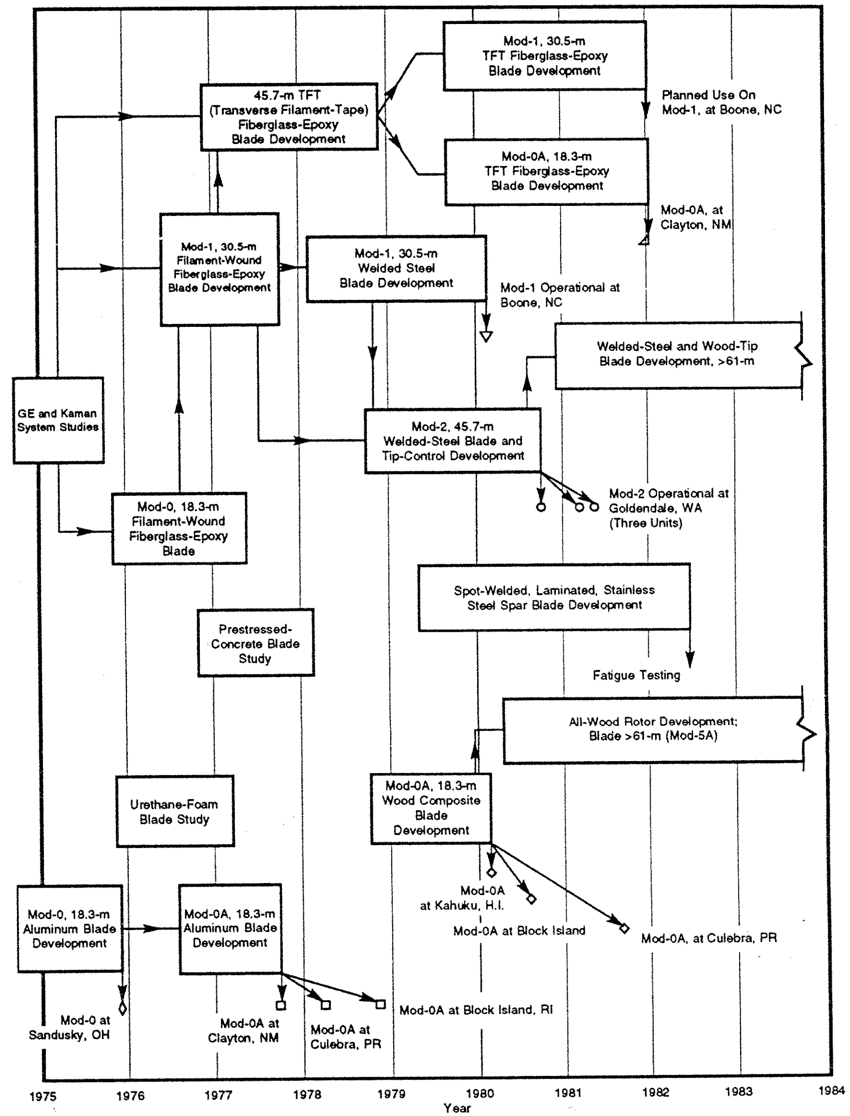


Figure 3-27. Chronology of the development and application of rotor blade materials for medium- and large-scale HAWTs, at the NASA-Lewis Research Center. [Linscott *et al.* 1984]

One of the most successful families of blades were (surprisingly) made of wood. They evolved from the *WEST* laminated wood-epoxy technique developed by *Gougeon Brothers, Inc.* (GBI) for racing yachts. Under contract to NASA, GBI adapted the process to the building of wind turbine blades of their own design. Carried further by private development, laminated wood blades have been utilized on a significant number of turbines up to 43 m in diameter. GBI became a major supplier of wood-epoxy blades which have competed successfully with fiberglass blades in the U.S.

A comprehensive review and assessment of the status of materials for wind turbine rotor blades is contained in a recent report from a special committee of the National Research Council [Dieter *et al.* 1991]. This committee reviewed the three related subjects of structural loading characteristics, materials properties and life prediction, and wind turbine rotor design, drawing conclusions regarding the following issues:

-- adequacy of existing models to predict dynamic stress patterns;
-- properties of wind turbine materials in dynamic and fatigue failure;
-- understanding of the performance of joints, fasteners, and critical sections in relation to failure modes and fracture;
-- adequacy of analytical tools such as computer design models and material databases;
-- need for special laboratory facilities and turbine prototypes to improve the design and operation of wind energy systems;
-- opportunities for new materials, better manufacturing processes, and advanced control techniques to improve wind turbine performance and durability.

Aerodynamic Control

Some form of aerodynamic control is generally required for speed and power regulation, normal startup and shutdown, overspeed protection, and emergency shut-down situations. In particular cases, some of these functions can be performed mechanically, electrically, or even with passive aerodynamic techniques. Mechanical brakes (other than for parking) may be prohibitive in size and cost in the largest turbines because of the amount of rotational energy contained in the rotor and power-train equipment. Part of the tradeoff in selecting the method of aerodynamic control depends on whether a fixed- or variable-speed system is contemplated. In any event, the synchronous speed of the electrical generator provides the basic speed regulation, but separate overspeed protection is also normally required in the event of electrical system failure.

Traditionally, many of the smaller systems have been able to use the *fixed-pitch stall-regulated* approach, albeit with some penalty in energy capture. Medium- and large-scale systems have utilized *full-span variable-pitch* rotors, much like conventional constant-speed aircraft propellers. This does, however, involve relatively complex and heavy *pitch change mechanisms* at the blade root where structural loads are high. A number of rotors have been built with *tip controls*, wherein the majority of the blade is at a fixed pitch while the pitch of the remaining tip section may be varied. Examples of this approach include the *2.5-MW Mod-2* and the *3.2-MW Mod-5B HAWTs* in the U.S. and several commercial Danish, Dutch, and British turbines.

Research has been performed using outboard *flap control surfaces* which show a number of mechanical and structural advantages, but which have only been used experimentally in the U.S. and Japan. The *multiple hinge points* of a flap control surface have intrinsically better structural and safety features (because of *redundancy*) than the single spindle shaft which typically anchors a tip control surface.

Several approaches have been undertaken to develop *passive pitch control* techniques that automatically adjust the blade pitch angle without a need for hydraulic or electro-mechanical actuators and their power supplies and controls. The design of the *Jacobs Wind Electric* turbines of the 1940s allowed the rotor blades to slide in and out of the hub for a short distance, balancing centrifugal force against springs. During the sliding action, cams changed the blade pitch angle, and a simple passive pitch control was obtained that responded to rotor speed. A number of modern technology equivalents have been developed in the 1980s. One concept is the *self-twisting blade*, in which the *blade spar* in the vicinity of the hub is fabricated from a composite material carefully tailored so that increasing thrust and centrifugal loads cause the blade to twist toward the feathered position. Utilized in several small wind turbines, this concept may find broader application as experience is gained.

A unique method of power regulation for a modern large-scale wind turbine is embodied in the Italian *Gamma 60* 1.5-MW machine (Fig. 10-1) which employs an active yaw control system for the purpose. The blades of this turbine are fixed in pitch, and peak power is controlled by yawing the rotor out of the wind.

Considerable research and testing have been undertaken to develop *aerodynamic yaw control* systems for HAWTs that would face the rotor into the wind without active control, but these have not yet been wholly successful. This has been partly due to erratic, unstable performance and also to low cost savings. Often, *high-wind safety* and "parking" under storm conditions can be more easily satisfied by an active yaw control system. The old techniques of *tail vanes*, or auxiliary *side rotors* and *fantails* have given way to *active yaw control* using wind-direction sensors and electric or hydraulic drive motors.

Power Train Configuration

As illustrated in Figure 3-10, a typical first-generation wind turbine utilized a heavy *steel bedplate* on which to mount mechanical and electrical equipment, with the *turbine shaft* supported by separate bearings and attached to a conventional *parallel-shaft gearbox*. Medium- and large-scale systems rapidly moved to lighter-weight *planetary gearboxes*. Some also introduced a *duplex turbine shaft*, composed of two concentric shafts: An inner flexible *quill shaft* transmits only rotor torque, while a stiff outer shaft supports the weight and thrust of the rotor. Various forms of gearbox *shock mountings* have been used to reduce and dampen dynamic torsional loads entering the power train, for both structural and electrical reasons. Increased understanding of power-train dynamics and variable-speed generators have reduced the dependence on such devices in recent years.

Two other design features have appeared on wind turbines and have the possibility of future development. One is the use of the *gearbox case as primary structure*, thus reducing the need for a bedplate, or even the *nacelle* itself. The difficulty with this approach is the need for extra strength and stiffness in the gearbox, which would now have to be a custom-designed structure.

A second innovation is to omit the gearbox entirely and use a direct-drive to a very low speed, multiple-pole generator. This could result in a weight increase (such generators are relatively large), but this may not be critical for a VAWT generator on the ground. Recently, the large-scale Canadian *Eolé 64-m VAWT* was constructed with a direct drive between its rotor and a hydroelectric-type generator, with power electronics that permit operation at sub-synchronous speed. Several very small HAWTs use direct-drive generators or alternators, and a German manufacturer, *Enercon*, is testing a 500-kW HAWT with a direct drive to its ring-type generator.

Type of Electrical Generation

Early wind power plants produced DC electricity, as do many small systems today which are designed for remote stand-alone applications. Batteries are used for energy storage, and generator speed is allowed to vary or is controlled only within modest limits. Interfacing with conventional utility grids or diesel-electric systems, however, requires an AC output and more stringent controls on *power quality* and *synchronization*. Until recently, most medium- and large-scale wind turbines utilized *synchronous generators*. Larger turbines can afford the controls necessary for the more-difficult synchronization requirements. Utilities generally favor synchronous generators, because they provide their own *reactive power* or *VARS* and can usually deliver excess VARS to the line when needed.

Most designers of wind turbines in the 1- kW to 100-kW range have selected *induction generators*, because they are relatively inexpensive and easy to synchronize with the grid. They also provide some valuable *power-train damping*. Their principal disadvantage is that they consume considerable reactive power. When induction generators were used in limited numbers, this was not significant and was usually ignored by the utility. The problem can be solved through the use of *capacitors* in the system at a small additional cost. However, capacitors may introduce a potential safety hazard, which is the possibility that *self-excitation* after a *fault* opens the utility line could cause the turbine to keep generating. Appropriate additional controls can eliminate this type of hazard.

The efficiency of an electrical generator usually falls off rapidly below its rated output. Since the power in the wind fluctuates widely, this becomes a major consideration in the selection of rated wind speed and rated power. Some small- and medium-scale systems have utilized two generators of different sizes. The smaller generator operates near its rated power at low wind speed, switching over to the larger generator during higher winds. The costs of the additional smaller generator and controls must be balanced against the losses associated with operating the larger generator at a low percentage of its rated power.

Of necessity, both induction and synchronous generators must be operated at constant speed in order to maintain the *grid frequency*. It has long been recognized, however, that variable speed operation has two major advantages over synchronous operation. First, the aerodynamic efficiency of the rotor is improved at low wind speeds if the rotor speed is also reduced. Second, system dynamic loads are attenuated by the "flywheel" action of the rotor, as it speeds up and slows down in response to wind gusts. There are several methods to produce constant frequency power from a variable speed generator, at some cost. However, the primary deterrent to the incorporation of variable speed in all but the smallest wind turbines has been the difficulty in predicting and preventing harmonic resonances.

By the mid-1980s, advances in structural dynamic analysis, *variable-speed constant-frequency (VSCF)* generators, and *power electronics* combined to make variable speed operation practical in larger sizes. The Mod-5B HAWT, the Sandia 34-meter and the Eolé VAWTs, and most new systems under development in Europe have VSCF generators.

HAWT Tower Stiffness

The towers for most early HAWTs were made of heavy *steel trusses* designed more for stiffness than strength. High stiffness was needed to keep the *fundamental (lowest) natural frequency* of the system higher than the blade passage frequency, in order to minimize the possibilities of resonant vibrations and associated structural dynamic problems. Some smaller wind turbines also used *guy cables* for stiffening. The development of better analytical design tools allowed a change to *steel shells* for towers, which is now the predominant configuration. These are so-called *soft tower* designs, in which the fundamental system frequency is less than the blade passage frequency. Care must be taken

that the rotor speed passes rapidly through resonance with tower bending modes (and others) during starting and stopping. As shown in Figure 3-28, low-frequency cylindrical steel designs require much less material than stiff towers of the same height, and therefore cost considerably less. Safe, soft-tower design technology also permits taller towers, to take advantage of positive wind shears and increase the average wind speed at the rotor.

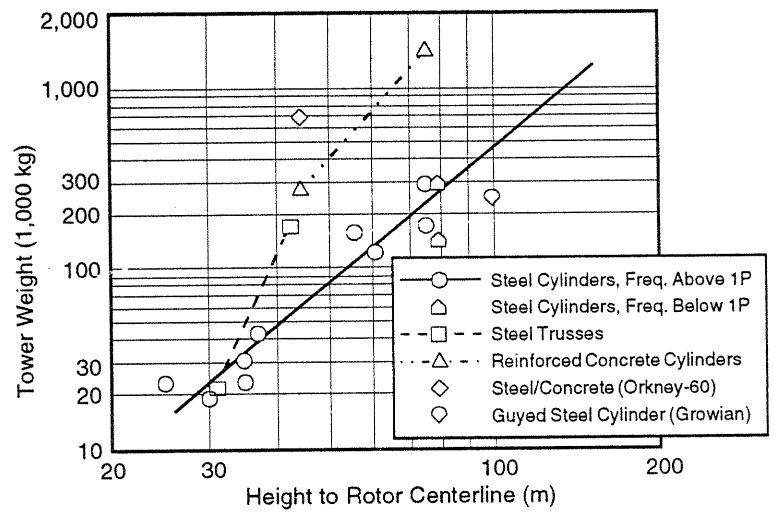


Figure 3-28. Trend of HAWT tower weight with height, stiffness, and type of construction. [Frederick and Savino 1986]

NASA/DOE Mod-0A Experimental HAWTs

During the 1970's, progress continued on several developmental cycles of medium- and large-scale machines. Soon after the initial testing of the 38.1-m diameter Mod-0 HAWT test bed, the U.S. Department of Energy decided to install a pair of upgraded replicas (later increased to four through Congressional actions) into actual utility operation. These machines were designated the *Mod-0A* wind turbines (Fig. 3-29), and each had a rated power of 200 kW, twice that of the Mod-0. While their power was still quite small as viewed by a utility, these would be the largest wind turbines integrated into a utility since the Smith-Putnam turbine of 1939. In fact, at the time there was almost no experience in the U.S. in operating a wind turbine of any size in an electric utility environment.

The purpose of the Mod-0A program was to identify and resolve technical and operational *utility interconnection issues*. These included questions of power quality, transient effects, safety, re-closure, and startup/synchronization/shutdown procedures. In addition, the Mod-0A HAWTs would form a visible validation of such operations. Through a competition aimed at the utility industry, 17 sites (later expanded to 35) were selected and instrumented with anemometer towers for detailed site wind assessments. This became the base from which the locations of the Mod-0As (and later NASA/DOE machines) were selected in follow-on competitions. The four Mod-0A HAWTs were installed from 1977 to 1979 at Clayton, New Mexico; Block Island, Rhode Island; Culebra Island, Puerto Rico; and near Kahuku on the northern tip of the island of Oahu, Hawaii. Mod-0A sites were selected at relatively small utilities or isolated locations, so that some understanding of the problems of *significant penetration* of wind power into a grid could be investigated. Some

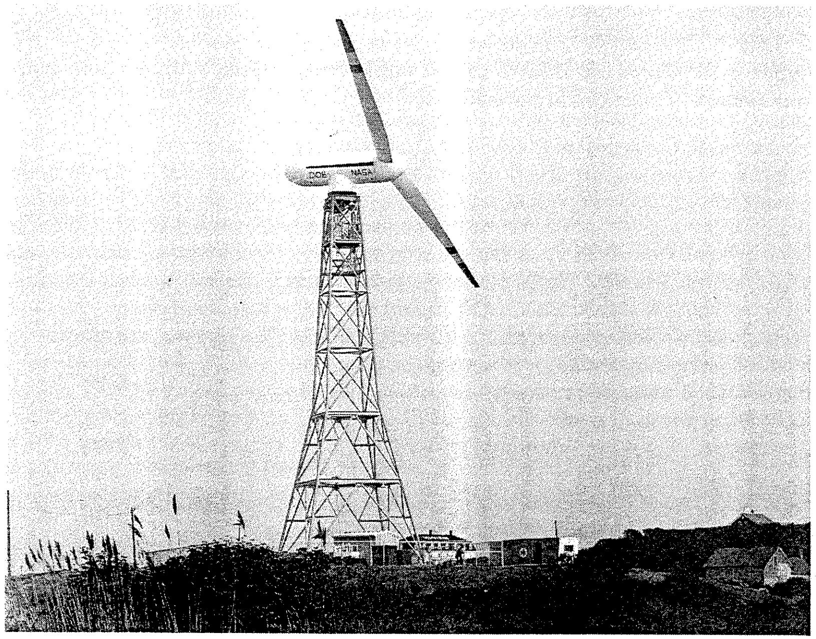


Figure 3-29. The 200-kW 38.1-m diameter Mod-0A wind turbine on Block Island, Rhode Island. It was one of four turbines of the same design installed on small grids in the U.S. to identify and resolve utility interconnection and operation issues.
(Courtesy of NASA Lewis Research Center)

issues could have remained unidentified if the wind turbine rating was an extremely small percentage of the local generating capacity.

The first unit was fabricated at NASA Lewis, while a parallel contract was awarded to *Westinghouse Electric Corporation* to construct the remainder. While ostensibly identical, each machine received detailed improvements based on the experiences of the prior installation. The *Lockheed Corporation*, which had built the original fabricated-aluminum blades for the Mod-0, provided the initial sets of Mod-0A blades to the same general design but with thicker skin panels. However, the downwind configuration and rigid hub introduced high and (at that time) uncertain dynamic loads that caused fatigue cracks in the aluminum skins and ribs near the blade roots. Eventually all four rotors were fitted with laminated wood-epoxy or fiberglass blades and operated successfully for extended periods.

Probably the most severe operational test of the Mod-0A came in the installation at Block Island, which was one of the reasons for the selection of that site. The Block Island grid is powered by several diesel-electric generators and is not interconnected with any other utility. Block Island has many summer vacationers and only a very small year-round population. Thus, summer peak loads reach over 1,800 kW, while during night hours in winter (which is also the high-wind season) the total load can go down to only a few hundred kilowatts. Occasionally the Mod-0A at 200 kW was producing over 50 percent of the power for the island. This large penetration introduced several problems in terms of both *voltage and frequency stability* and diesel operating problems caused by excessive throttling. The Block Island Mod-0A was therefore derated to 150 kW during winter operations, unless under special test.

When the Mod-0A project was completed in June 1982, the four machines had accumulated over 38,000 hours of operating time and had fed some 3.6 million kWh into their host utility grids [Shaltens and Birchenough 1983]. At a *Hawaiian Electric Company* site near Kahuku, the fourth and most reliable Mod-0A (Fig. 3-30) achieved a *capacity factor* of 0.48 during its last months of operation and was a principal cause of the developing interest in wind power in the Hawaiian Islands. The highly successful operation of the Kahuku turbine also led its builder, the Westinghouse Corporation, to privately develop a 600-kW HAWT and Hawaiian Electric Industries (the parent corporation of the utility) to participate in the later Mod-5B program and encourage private wind power developers. The most important contribution of the four Mod-0A HAWTs was that they produced the first visible evidence that wind turbines, while not yet cost-effective, could be successfully integrated into a utility's normal operations and could produce high-quality AC power of value to that utility. They also provided a technology base that paved the way for the growth in size of privately-developed wind turbines, from the 10- to 15-m diameter and 10- to 25-kW sizes of the early 1970s to the 100- to 300-kW and 20- to 30-m diameter turbines that were developed and installed in the late 1980s.

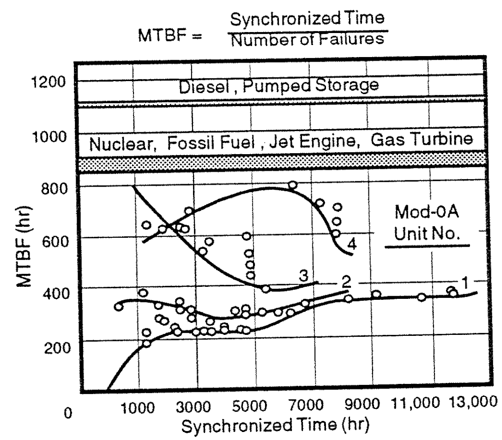


Figure 3-30. Mod-0A mean times between failure. Unit No. 4, on Oahu in the Hawaiian Islands, was the most durable.
[Shaltens and Birchenough 1983]

NASA/DOE Mod-1 HAWT and Environmental Issues

The Wind Turbine System

Development of the *Mod-1 Experimental HAWT* (Fig. 3-31), the first megawatt-scale wind turbine on a utility grid since the 1939 Smith-Putnam turbine, began in parallel with the installation of the Mod-0As. Rated at 2.0 MW and with a rotor 61 m in diameter, the Mod-1 HAWT used the same general design configuration as the Mod-0: a two-bladed, rigid hub rotor with full-blade pitch control, mounted downwind of a stiff, truss tower. The experimental system was designed and built by the *General Electric Company*, with welded-steel blades fabricated by the *Boeing Aerospace Company* (Fig. 3-32). It was installed on a small mountain called Howard's Knob near Boone, North Carolina, and was dedicated on July 11, 1979. The local utility, the Blue Ridge Electric Membership Cooperative, operated the Mod-1 for two years, proving that megawatt-scale wind turbines could be successfully interfaced with a large, conventional utility power system [Collins *et al.* 1982].

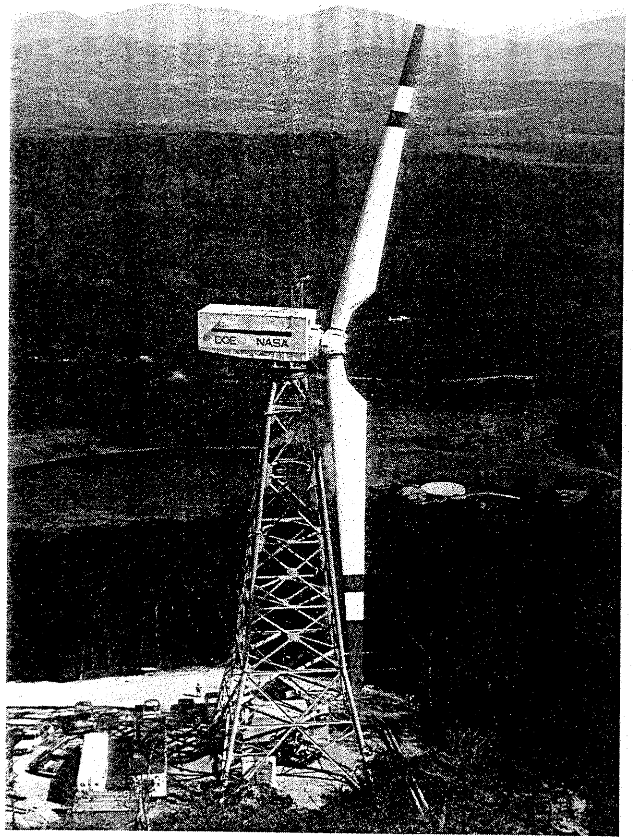


Figure 3-31. The 2.0-MW 61-m diameter Mod-1 experimental HAWT in 1979 on Howard's Knob overlooking Boone, North Carolina. It was the first megawatt-scale wind turbine since the Smith-Putnam HAWT. (*Courtesy of NASA Lewis Research Center*)

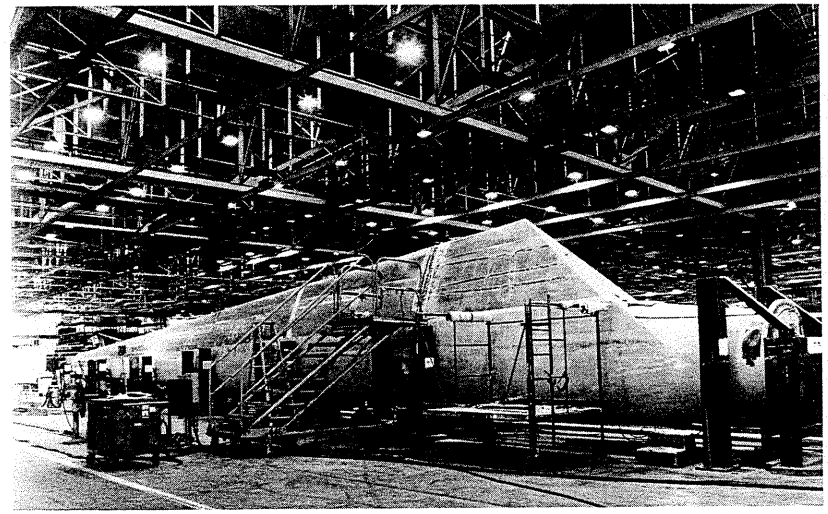


Figure 3-32. A 30-m long Mod-1 blade during final assembly at the Boeing Aerospace plant in Seattle, Washington. The structural spar was fabricated from welded steel plates, to which trailing edge sections of foam-filled fiberglass were bonded. [Linscott *et al.* 1984]

The Mod-1 design, however, was not completely successful. While it achieved its rated power and operated safely in an unattended, automatic mode, the wind velocity decrements behind the stubby truss tower applied high, impulsive loads to the rigidly-mounted blades. While no major blade problems actually occurred, it was clear that this design configuration would not have the 20- to 30-year life necessary in a commercial turbine. Improperly-torqued bolts attaching the turbine shaft to the hub did fail near the completion of the test program, but no major damage ensued because the rotor was supported by a large bearing mounted directly to the nacelle structure. However, it was deemed wisest to dismantle the turbine. The 60-m welded steel rotor, at that time the largest that had ever been built, was placed on display at the Science Museum in Raleigh.

Environmental Problems

The Mod-1 encountered two environmental problems: interference with television signals and acoustic noise. In parallel with the technology portion of the wind energy development program at the NSF, a major study was initiated with Battelle Memorial Institute in Columbus, Ohio, to identify any conceivable environmental effects that could be caused by either an individual wind turbine or by the large-scale use of wind power [Rogers *et al.* 1977]. These ranged from the possibility of affecting the micro-climate to striking birds. The latter was, in fact, a major initial worry regarding the large scale use of wind power, regardless of the size of the individual turbines. Extensive tests on and around the Mod-0 HAWT showed that there were no significant ecological effects. However, while the locale is rich in herbivorous and migratory birds, it has few local raptors. Some later wind power stations in California did encounter bird strikes with raptors, for which potential ameliorating approaches are under study.

Three potential problem areas were identified: the possibilities of *acoustic noise*, *electromagnetic interference* with local microwave radio or TV reception, and uncertain public acceptance of the *aesthetics* of wind turbines on the landscape. Following the initial Battelle study, specialized research projects concentrating on these potential issues were undertaken [Balombin 1980, Senior *et al.* 1977, Ferber 1977].

Electromagnetic Interference

The first environmental issue to be actually encountered at the Mod-1 site was the electromagnetic interference (EMI) problem. Results of the research showed that, while there would not be a significant effect across most frequencies (unless the turbine was close to, and literally in the path of, a microwave or other antenna), the *upper VHF* and *lower UHF television bands* were the most vulnerable and could be affected. Analytical tools began to be developed to predict the possibility of EMI in any given installation. Early analysis showed that, of the 17 sites under consideration by DOE, the Block Island site would likely experience TV interference, given the already marginal television reception in that area. Because it was ideal in all other respects, Block Island was selected for the third Mod-0A site partially to allow measurement of actual TV interference under complex real-world situations. A television cable system was first installed in cooperation with the nearby town in order to mitigate any effects on the public.

Like Block Island, the area around Boone had TV signals of marginal strength, and some EMI was encountered there also. EMI measurements around the large-scale Mod-1 turbine with its steel blades, coupled with the Block Island measurements and laboratory tests at the University of Michigan, led to the development of accurate tools for the evaluation of future sites. The EMI potential was found to be a predictable function of blade size and material, rotor speed, and the local transmitter/receiver/turbine geometry (see Chapter 9).

Acoustic Noise

A second environmental issue at the Mod-1 site was, for a time, an intractable noise problem. Prior wind turbines were generally relatively quiet, and the Mod-1 itself was not noticeably noisy close-up. Under certain conditions, however, it emitted low frequency pressure pulsations. At seemingly random intervals, this would produce unacceptable noise at various locations a considerable distance from the site, even though at other locations or times, no noise was detectable. The source was determined to be coupling between the blade passage and wakes from the heavy tubular legs of the truss tower. Atmospheric conditions, particularly inversions, combined with the complex mountain terrain could then focus the noise at some locations distant from the site. Research conducted in the area eventually led to the development of refined and verified methods for analyzing and predicting wind turbine noise (see Chapter 7). The Mod-1 noise problem was eventually solved by reducing the rotor speed, an operation that required replacing the generator.

Noise generated from blade tips or protrusions (for tip control mechanisms or aerodynamic brakes) and some gearboxes and hydraulic motors have occasionally led to some "noisy machines," regardless of turbine power or rotor size. Careful tip design, fairings, upwind rotor location, and component selection have led to generally quiet machines.

Foreign Medium- and Large-Scale Wind Turbines

In the late 1970s a resurgence of interest in wind power also reached a high level of momentum in Europe. Denmark, Germany, and the Netherlands developed broad programs which included basic technology efforts, the direct and indirect support of the private development of smaller wind turbines, and government-funded development of medium-scale or larger systems. Several countries commissioned testing centers: Denmark at Risø, Germany at Pellworm Island, and the Netherlands at Petten. These centers allowed for the testing of both experimental and commercial machines as well as setting in place *certification programs* as a requirement for tax or subsidy benefits, which effectively precluded turbines in Europe from entering the market prematurely.

Since the mid-1970s, some degree of international information exchange has been accomplished through the *International Energy Agency* (IEA). The IEA, headquartered in Paris, was modelled after the International Atomic Energy Agency, and was conceived as a way for western nations to coordinate and cooperate in energy policy, research, and development after the shock of the 1973 oil embargo. Two IEA agreements were implemented covering wind energy. One, a general research and development agreement, initially involved 12 countries (later increased to 16). A second agreement involved the exchange of information between those countries developing megawatt-class turbines. The *IEA Wind Energy Annual Reports* are an excellent source of information on national wind energy development programs. Table 3-2 is an example of the detailed data in these reports, listing wind turbines in Europe and the U.S. with ratings larger than 500 kW, together with specification and performance data [IEA 1993].

IEA cooperative projects have included research activities on comparison of siting models, wake flow, wind flow over terrain features, and analysis of system test results. Development of comparative testing methodology and resource assessment studies are also undertaken. Of particular interest to the European countries are studies of the potential for off-shore wind power. With their higher population densities and fewer open areas, this possibility is of importance even in view of the expected higher cost associated with shallow water foundations and marinization requirements.

Denmark

For their first entries into the field of larger wind turbines, Denmark constructed a pair of 40-m diameter, 630 kW turbines, placed side by side, at *Nibe*, near Alborg in northern Jutland. Conservative in concept, they were a direct outgrowth of the old Gedser machine. Both had concrete towers, as has been traditional with the larger Danish wind turbines. Each had an induction generator, a three-bladed rotor upwind of the tower, and steel blade spars. One of the rotors was tip-controlled with cables for external bracing, while the other had full-span pitch-controlled cantilevered blades. These were the first of the new generation of wind turbines in Europe to reach the testing stage. Operating now for over 13 years with various types of blades, they provided some of the first information on operation and maintenance costs, reliability, and flow interactions between machines, supporting the expansion of the Danish wind energy industry [Godtfredsen *et al.* 1993].

Netherlands

The Netherlands government installed a 300 kW, variable-speed experimental machine at Petten in 1980. It was designed for maximum test flexibility. It still represents one of the most versatile of test machines and can be rapidly re-configured and operated in various modes, with fast turn-around on data reduction.

Table 3-2. Wind Energy Systems Larger Than 500 kW [IEA 1993]

Country	Machine		Rotor Specifications						
Member	Manufacturer	Model	Axis	B	L	M	D (m)	H (m)	A (m^2)
Belgium	Windmaster-VUB		H	2	U	GRP	46.0	63.0	1,662
Canada	Shawinigan	Eolé	V	2		S	64.0	56.0	4,000
Canada	Indal Technol	6400	V	2		A	24.4	21.3	595
Denmark	Several	Nibe-A	H	3	U	Wood	40.0	45.0	1,256
Denmark	Several	Nibe-B	H	3	U	Wood	40.0	45.0	1,256
Denmark	Several	Tvind	H	3	D	GRP	54.0	53.0	2,290
Denmark	DWT	Windane 40	H	3	U	GRP/W	40.0	45.0	1,257
Denmark		Tjæreborg 2MW	H	3	U	GRP	60.0	60.0	2,827
Germany	M.A.N.	WKA 60	H	3	U	GRP	60.0	50.0	2,827
Germany	MBB	Monopt. 50	H	1	D	CRP	50.0	60.0	1,963
Germany	M.A.N.	WKA 60 Land	H	3	U	GRP	60.0	60.0	2,827
Germany	MBB	Aeolus II	H	2	U	CRP	80.0	77.0	5,077
Germany	Husumer Sch.	HSW 750	H	3	U	GRP/W	40.0	45.0	1,257
Germany	Tacke	TW 500	H	3	U	GRP	36.0	35.0	1,018
Italy	Aeritalia	Gamma 60	H	2	U	GRP	66.0	60.0	2,827
Netherlands	Holec	Holec 500	H	3	U		35.0		962
Netherlands	Stork-FDO	NEWECS-45	H	2	U	GRP	45.0	60.0	1,590
Netherlands	Windmaster NL	500	H	2	U	GRP	33.0		855
Netherlands	Windmaster	Windmast750	H	2	U	WE	40.0	50.0	1,257
Netherlands	Newinco	Newinco 500	H	2	U	S	34.0		908
Spain	Asinel, M.A.N.	AWEC 60	H	3	U	GRP	60.0	46.0	2,827
Spain	MADE								
Sweden	KMW AB	WTS-75	H	2	U	S/GRP	75.0	77.0	4,418
Sweden	KKRV	WTS-3	H	2	D	GRP	78.0	80.0	4,778
Sweden	Kvaerner-MBB	Nasudden I	H	2	U	S	75.0		4,418
Sweden	Kvaerner-MBB	Nasudden II	H	2	U	CRP	80.0	77.0	5,027
U.K.	WEG	LS-1	H	2	U	S/GRP	60.0	45.0	2,827
U.K.	WEG	LS-2							
U.K.	Howden	750 kW	H	3	U	WE	45.0	35.0	1,590
U.K.	Howden	1MW	H	3	U	WE	55.0	45.0	2,376
U.K.		HSW	H	3	U	GRP/W	40.0	45.0	1,257
U.K.	VAWT Ltd	500kW	V	2		GRP			
USA	Boeing	Mod-5B	H	2	U	S	97.5	61.0	7,472
USA	Ham. Std.	WTS-4	H	2	D	GRP	78.0	80.4	4,778
USA	Westinghouse	WWG-0600	H	2	U	WE	43.0	31.0	1,452

Axis:
- H = Horizontal
- V = Vertical

A = Swept Area
B = Number of Blades:
D = Rotor Diameter
H = Elevation of Center of Swept Area
L = Location of Rotor:
- U = Upwind of Tower
- D = Downwind

M = Blade Material:
- A = Aluminum
- CRP = Carbon Fiber Reinforced Plastic
- GRP = Glass Fiber Reinforced Plastic
- W = Wood
- WE = Wood Epoxy
- S = Steel

Table 3-2 (Continued). Wind Energy Systems Larger Than 500 kW [IEA 1993]

Weight		Rating		Generator		Performance				
W_{OT} (1000 kg)	W_T	U_R (m/s)	P_R (kW)	Type	No. of Units	Run Hours	Output (MWh)	From	To	Source
		16.0	1,000	I						
344.0 (Rotor)		23.0	4,000	A	1	10,395	6,730	07/87 -	11/90	EMR
20.2 (Rotor)		18.2	522	I	2	5,873	557	05/87 -	07/90	EMR
80.0	47.0	13.0	630	I	1	6,146	1,313	09/79 -	04/92	DEFU
80.0	47.0	13.0	630	I	1	25,699		08/80 -	12/91	
			2,000	S						
60.5	47.0	15.0	750	I	5	87,500		11/86 -	12/91	DEFU
156.0	500.0	15.0	2,000	I	1	6,779		12/87 -	12/91	DEFU
	470.0	12.2	1,200	S	1	1,800	950	09/89 -	11/92	IEA
		11.0	640	S	3			09/89 -	11/92	IEA
		17.2	1,400	S	1			04/92 -	11/92	IEA
			3,000		1			09/92 -	11/92	IEA
20.0	47.0	14.0	750	A				1993		IEA
25.1	35.0	14.5	500	A				1993		IEA
95.0	145.0	13.5	1,500	A	1			9/91 -		IEA
			500		1					
31.7	59.0	13.9	1,000	A	1			06/86 -	10/89	IEA
			500	I	1			05/89 -	10/89	IEA
41.0		14.0	750	I						MFG
			500	I	1			11/89 -		IEA
186.0	92.0	12.2	1,200	I	1	2,400	559	11/89 -	02/92	IEA
			500							
205.0	1,500.0	12.5	2,000	I	1	11,350	12,600	02/83 -	10/89	IEA
191.0	291.0	14.0	3,000	S	1	23,079	29,847	07/82 -	02/92	NUTEK
			2,000		1	11,400	13,000		1988	IEA
	1,500.0		3,000	S	1			11/91 -		IEA
197.0	654.0	17.0	3,000	S	1	4,758	6,375	10/87 -	03/92	NSHEB
									10/87	IEA
			750	S	1	2,480	1,206	06/88 -	11/91	NSHEB
			1,000		1	2,150	798	02/90 -	04/91	
20.0	47.0	14.0	750	A						
			500	I						
265.3	160.5	13.0	3,200	C	1	20,561	26,776	07/87 -	09/92	HERS
198.2	192.8	15.0	4,000	S	1	4,100	8,000	01/82 -	08/87	MFG
36.2	34.8	13.0	600	S	15		36,384	12/85 -	09/92	HERS

W_{OT} = Weight on Top of the Tower
W_T = Weight of the Tower
U_R = Rated Wind Speed at Mid-Elevation of Rotor
P_R = Rated Power

Generator Type:
- A = AC/DC/AC
- C = Cycloconverter
- I = Induction
- S = Synchronous

Sweden

Sweden proceeded rapidly into a large-scale turbine research program, after first experimenting with the *SAAB-Scania 100-kW HAWT*, which was tested near Uppsala. A Swedish consortium named KaMeWa developed a 2.5-MW, 75-m diameter turbine with two blades on a rigid hub upwind of the tower, and installed it at Nassudden on the island of Gotland. The *KaMeWa HAWT* contained two unusual features: As shown in Figure 3-33, the last stage of the gearbox utilized bevel gears to drive its generator. This component was mounted vertically in the tower just below the nacelle, thus eliminating the need for power sliprings. A second unusual feature was a carriage assembly mounted on vertical rails on the side of the concrete cylindrical tower, for raising or lowering all major components (including the nacelle with rotor blades mounted). This eliminated the need for a large crane during construction or maintenance.

The second Swedish turbine was designed as a joint venture between Karlskronavarvet (KKRV) in Sweden and Hamilton Standard in the U.S. Called the *WTS-3*, it was built at Maglarp, near Malmo in southern Sweden (Fig. 3-34). Although more conventional than the KaMeWA design, the 3-MW WTS-3 was nonetheless technologically advanced. It had a tall, "soft-soft" tower and a two-bladed, teetered, downwind rotor 78-m in diameter. Its gearbox was mounted on springs to absorb dynamic torques. The fiberglass blades of the WTS-3 were designed by engineers at Hamilton-Standard and fabricated on a specially-built and automated filament-winding machine.

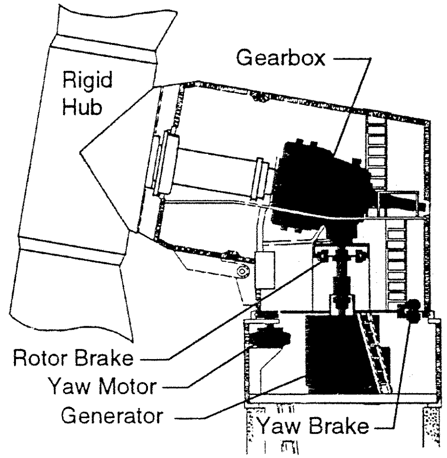


Figure 3-33. The unique drive train in the 2.5-MW KaMeWa HAWT eliminated sliprings to carry power from the generator. *(Courtesy of the National Energy Administration, Sweden)*

Figure 3-34. The 3-MW WTS-3 HAWT near Maglarp, Sweden. *(Courtesy of Hamilton Standard)*

While both turbines encountered various early problems (the KaMeWa turbine was once nearly destroyed due to a sheared yaw drive shaft), they both have operated successfully for an extended period of time.

An up-rated version of the WTS-3, the *Hamilton Standard/KKRV WTS-4* was purchased by the U.S. *Bureau of Reclamation* (USBR) and installed at a site near Medicine Bow, Wyoming (Fig. 4-4), under a project managed by the NASA Lewis Research Center. With its rating of 4 MW, it is the most powerful wind turbine ever built. The Bureau wanted to examine the possible large-scale use of wind power in connection with hydroelectric systems. Percy Thomas' ideas were finally being realistically investigated!

Germany

The development of the German *3-MW Growian HAWT* (Grosse Windenergie Anlage) in 1982 (Fig. 3-35) represented the greatest technological leap of the times, as well as the highest technological risks [Windheim 1983]. It encompassed just about every advanced feature yet considered. At 100 m in diameter with a 100-m tall tower, it was the largest wind turbine ever built. The rotor used two, full-span pitch-controlled, carbon-filament blades with a high degree of *coning*. It utilized the downwind rotor configuration combined

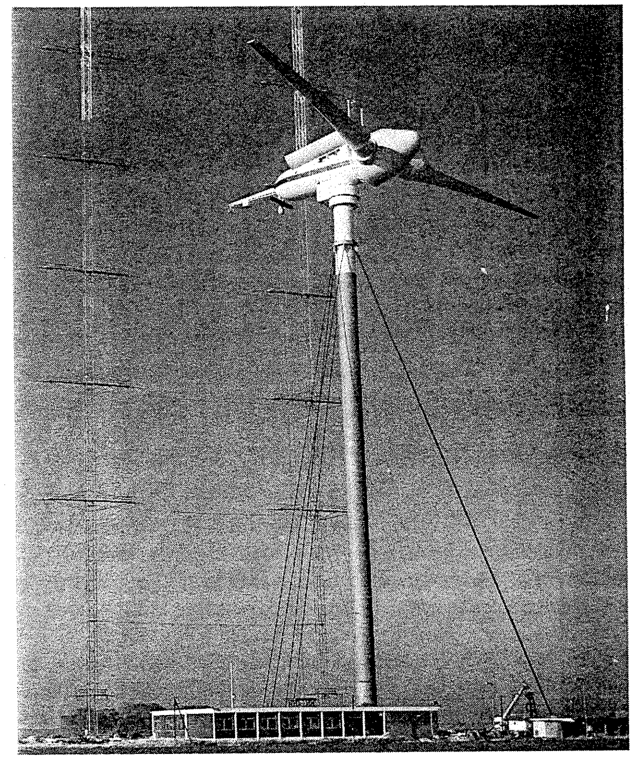


Figure 3-35. The 3-MW Growian HAWT near Bremerhaven, Germany. It was the largest wind turbine ever built, with a 100-m diameter rotor and a 100-m tall tower. *(Courtesy of MAN-Neue Technologie)*

with a very slender, flexible tubular steel tower stabilized by many guy cables. The majority of the turbine was assembled at the site near Bremerhaven, with less factory assembly than most other machines.

The Growian HAWT was the only other large-scale turbine besides the KaMeWa to be erected without a crane. The nacelle, with a central opening through which the tower passed, was winched up the tower with rotor attached. The guy cables were tightened, and the generator was then slid forward into place over the tower hatch, completing the installation. The Growian was also the first large-scale wind turbine to attempt variable-speed operation. Unfortunately, the technology at the time could not support the number and magnitude of the innovations undertaken. The Growian project encountered an inordinate number of problems, including fatigue cracking of major components in the hub. While it made significant contributions to the understanding of large wind turbines, it never operated satisfactorily and was dismantled after only limited testing time.

A more successful turbine was the 370 kW, 48-m diameter *Monopteros* HAWT [Stahl and Windheim 1987]. The Monopteros, constructed in 1981 near Bremerhaven, was the first large experiment in achieving very low solidities by utilizing a one-bladed rotor. This concept is still under investigation in Europe.

United Kingdom

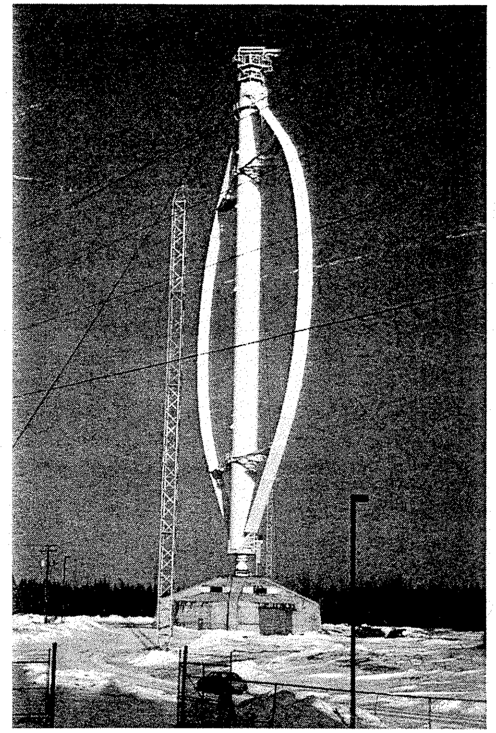
Another European country investigating wind power on a large scale was the United Kingdom. The Orkney Islands, with the interest of the North of Scotland Hydro Board, became the major test site. The UK took a much slower and more deliberate approach than most of the other countries and installed a 250-kW scale model, designated as the *MS-1*, of its proposed large-scale system in 1982. The scale model was of rather rigid design with a two-bladed downwind rotor of 20-m diameter. A privately developed prototype, the *300-kW Howden* wind turbine, 22 m in diameter and of much more flexible tower construction, was installed nearby. Thus two machines -- one of stiff design and one of "soft", flexible construction -- could be compared side-by-side. The megawatt-class prototype, the 3-MW *LS-1*, was developed at a deliberate pace. It evolved through several design configurations, ending as a two-bladed upwind turbine. Built by the *Wind Energy Group* (a consortium of *Taylor-Woodrow Construction, British Aerospace*, and *GEC*), it was installed in the Orkneys, and testing commenced in 1987 [Page and Bedford 1987].

Canada

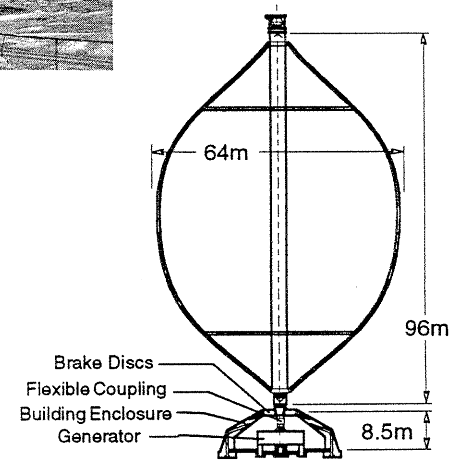
In Canada the technological route was different from other countries. Based on early research there on Darrieus VAWTs, Canadian planners elected to concentrate future projects in that direction. In addition to smaller systems for use in remote areas, a 230-kW experimental Darrieus turbine of 24.4-m diameter was installed in 1977 at a Hydro-Quebec utility facility on the Magdalen Islands in the Gulf of St. Lawrence. Basic testing of the turbine proceeded satisfactorily, until a maintenance error caused the generator to be disconnected without locking the rotor. While a Darrieus rotor has low starting torque, the unsecured rotor started without load, oversped, and destroyed the turbine. This occurred, however, after sufficient positive results had been obtained to justify continuing the program. The *Magdalen Island* VAWT was rebuilt, and the development of two prototypes of the same size, but up-rated to 500 kW, was initiated with *Indal Technologies, Inc.*

Installation of the *Eolé* VAWT (Fig. 3-36) was completed in early 1987 at Cap-Chat, Quebec, near the banks of the St. Lawrence River [Richards 1987]. This giant machine is 64 m in diameter and was originally rated at 4 MW. It thus represents the first *megawatt-class Darrieus* turbine. Like a hydroelectric turbine, it has no gearbox. Instead, the rotor

drives directly a large-diameter 162-pole alternator at ground level, which is then connected through an *AC-DC-AC* link to the Hydro-Quebec grid, to provide variable-speed constant-frequency operation. The system has generally been operated at reduced speed to ensure longevity, and power is now limited to 2.5 MW. Hydraulically-deployed *aerobrakes* at the rotor equator are a back-up to the primary dual-disk mechanical brake above the generator.



(a)



(b)

Figure 3-36. The 4-MW Eolé VAWT. (a) General view of the turbine at Cap-Chat, Quebec (*Courtesy of the Hydro-Quebec Company*) (b) Sketch of major components, including the direct-drive generator [Richards 1987]