Wind Power—An Ancient Answer to Modern Needs?

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One of the tasks assigned to AIAA student members in the 1975 AIAA Bendix Design Competition involved the harnessing of wind energy: "Design a windmill capable of delivering 3000 kW in a 25 knot wind or design a complete wind energy generation and storage system capable of satisfying the electrical power needs for a city of 100,000 inhabitants at a cost of 50 mils per kilowatt hour." A formidable task indeed, but according to many experts, well below the ultimate potential of wind energy extraction schemes. With our apparently insatiable thirst for energy growing every day, many of these "sky blue" schemes may become reality in the not too distant future.

The only thing really new about wind power is the scale of the projects currently being proposed, such as the system designed by W. E. Heronemus. This system is envisioned to extend almost 200 miles off the coast of Cape Cod, to cover approximately 25,000 square miles, and to generate 159 x 10^9 kWh per year by 1990, enough to satisfy the projected demands of New England. Other systems of similar magnitude have been proposed for Long Island, Wisconsin, and Holland.

The use of windmills dates back to ancient times. They were used in Japan and China thousands of years ago. The great irrigation systems of Babylon are thought to have been powered by windmotors. Examples of windmills erected almost two thousand years ago still exist in Egypt.

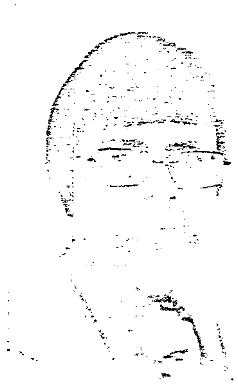
Wind power generation was first introduced to the Western world around the 8th century A.D. By the 16th century windmills were a significant source of energy in Great Britain, Holland, and Germany. As late as 1900, the entire wheat crop of Northern Europe was ground by windmills scattered across Holland, Denmark, and Germany.

The windmill has played a rather unique role in the development of Holland since 1500 AD. Windpower was used not only for grinding grain and sawing wood, but also for pumping water from the lowlands. These drainage mills were a major factor in the successful struggle by the Dutch to carve a country out of the sea.

Even today, many windmills are on standby service for the drainage of many low-lying areas called poulders. One poulder close to Amsterdam still depends entirely on a system of windmills to remain dry.

Windmills have become part of the mystique of Holland. Their beauty is held in high esteem and the remaining 1000 windmills, all that is left from an estimated 10,000 units at the turn of the century, are carefully protected as national monuments. The windmill is such an integral part of the Dutch landscape that it can be termed as an almost ideal blending of man's machine and his environment. Considerable research effort has been expended to improve the aerodynamic efficiency of the classic Dutch design without detracting from the unique lines of the lattice work construction of the blades or "sails." Unfortunately, little improvement can be made on the old design.

In a less dramatic way, windmills have played a significant role in the development of rural areas in many parts of the world including the United States. Many of us have driven through the midwest and seen the familiar small tower mounted windmill on



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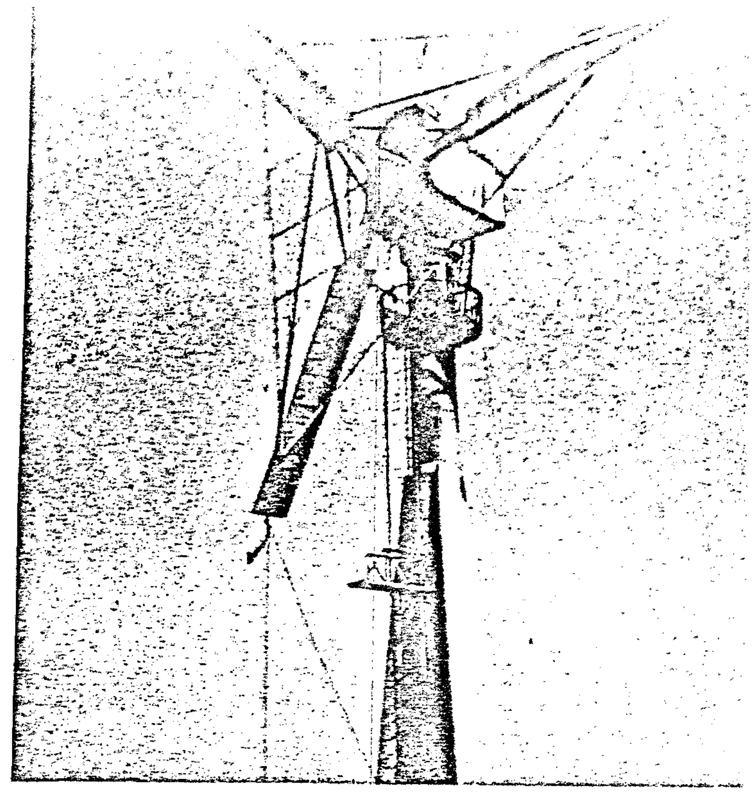
almost every farm and ranch. According to a recent article in the Wall Street Journal, an estimated 6.5 million of these units were built in the United States from 1880 to 1930. Most were used for pumping water and running sawmills, but some were used to meet the relatively light electrical needs for a farm household. It is still possible for a small windmill to supply the electrical needs of an American family.

As late as 1954, it was estimated that 250,000 to 300,000 kWhr were still produced annually in Germany from small windmills. This is, of course, a fairly insignificant quantity of energy in comparison to the total annual energy consumption of an industrialized nation, but such amounts of power could play a significant role in the growth of underdeveloped nations, a fact which has not gone unnoticed by several investigators.

Although most windmills have been used as a direct and localized source of energy, there have been many cases where windmills have been integrated into a public power grid. As early as 1890, a 23-m diameter wind generator was developed in Denmark. This development blossomed into several hundred wind generators in Denmark by 1910, with generator capacities ranging from 5-25 kW. The Dutch have successfully experimented with some classic windmills that were modernized by replacing the original pump or mill stone with an electrical generator and improving the aerodynamic characteristics of the sails.

According to a recent survey of wind power potential, the largest windmill ever built was erected, you guessed it, right here in the United States. Conceived by P. C. Putnam, it was a two blade design having variable pitch with a diameter of 53 m (175 ft) and mounted on a 34 m (110 ft) tower on Grandpa's Knob near Rutland, Vermont. Designed to produce 1.2 megawatts at 14 m/sec (30 mph) its average power delivery to the AC power grid of the Central Vermont Public Service Corporation was 210 kW at an average wind velocity of 8 m/sec , far below the estimated average wind velocity of 11 m/sec. Although its power production was below expectations, it operated successfully from 1941 to 1945 with reasonable reliability in winds as high as 31 m/sec and was able to withstand the loading of 51 m/sec (115 mph) winds. Fatigue-induced failure of the stainless steel blades terminated its operation. Technical feasibility was proved, but, at that time, relatively abundant sources of hydroelectric energy were more economical.

But now the tide is turning. Costs of petroleum are skyrocketing. Environmental considerations are limiting the construction and increasing the costs of thermo and thermonuclear power plants. Hydroelectric power development has almost reached the saturation point. As the demand for



200-kW, 24-m-rotor-diameter, Danish Gedser wind turbine, designed for 15-m/sec wind, built in 1957 at a cost of $41,000 [$205/kW]. The electrical generator was located in a rotatable platform housing atop the 26-m [85-ft]-high tower.

energy continues and the sources dwindle, the increased price per unit of energy makes less conventional sources more attractive, among them, the windmill.

Although there are obvious advantages to wind power—it is pollution free, and apparently limitless in quantity—there is a definite upper limit on its potential. It has been estimated that about 2.5% of the power radiated to earth from the sun is contained in atmospheric motion. This amounts to a total power level of about 2×10^{12} kW. Of this an estimated 2×10^{10} kW is available from selected sites around the world. The results of studies sponsored jointly by NSF and NASA indicate that the potential annual U.S. wind production, by the year 2000, is approximately 1.5×10^{12} kW, just about our *current* annual consumption of electricity.

Assuming our appetite is whetted for some of this energy, the next question is "where are the best sites for our windmills and how reliable will our energy resource be?" This is, of course, a rather difficult question to answer, especially so since most wind velocity data have been collected at airports which are not necessarily the best wind-power sites. However, some estimates can be made. Wind power is calculated on the basis of total kinetic energy per unit time passing through a unit cross-sectional area normal to the flow:

$$P/A = 1/2\ \rho\ V^3$$

where ρ is the air density and V the wind speed. At standard conditions this reduces to:

$$P/A = 0.1625\ V^3 \text{ watts/m}^2,\ V \text{ in m/sec}$$

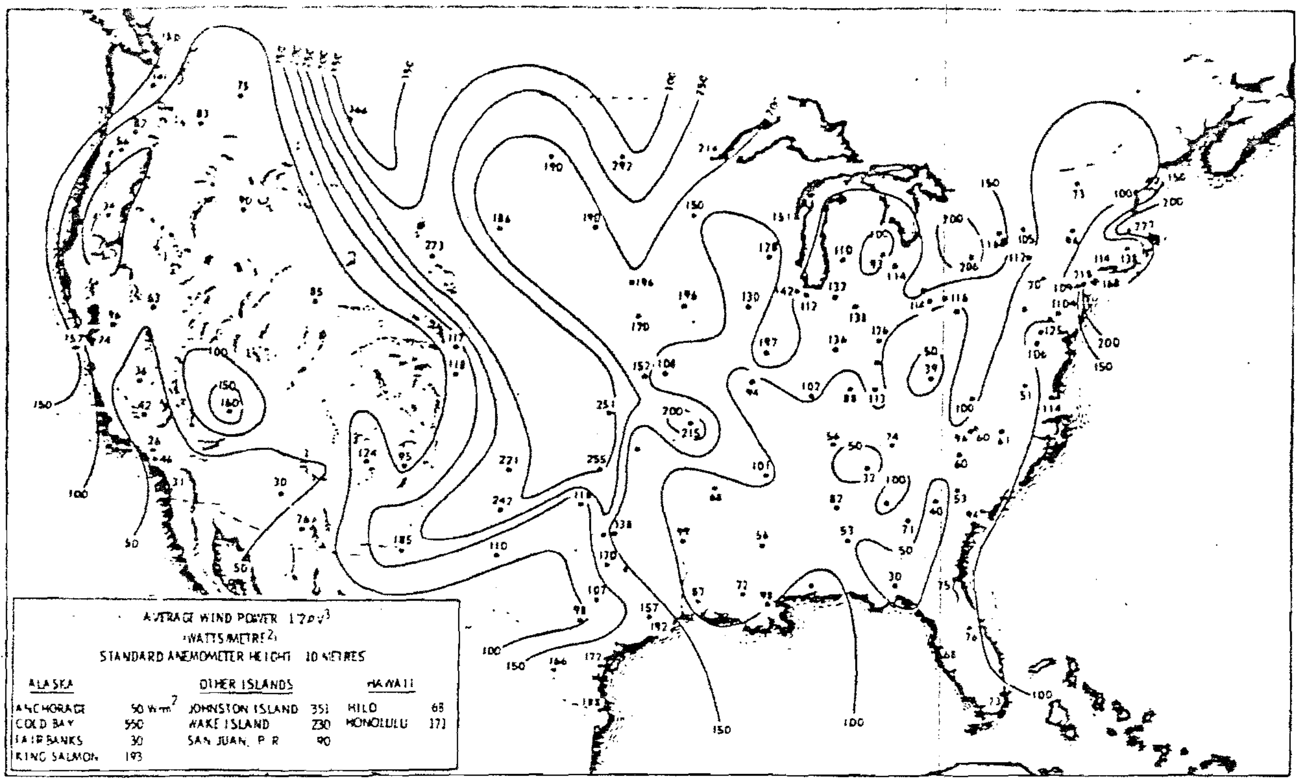


Fig. 1 The distribution of wind power in the United States.

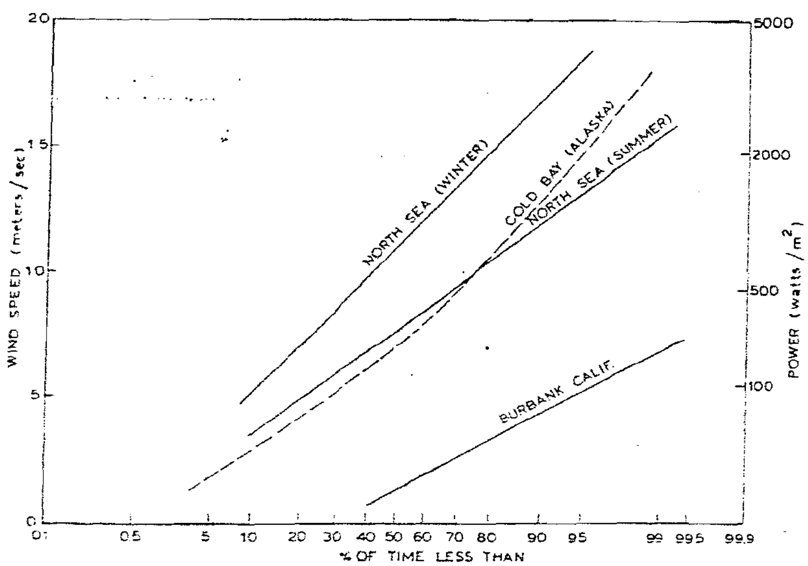


Fig. 2 Cumulative distribution of wind speed at three different sites.

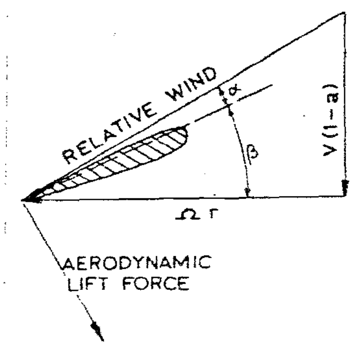


Fig. 3 Basically a windmill is a propeller in reverse.

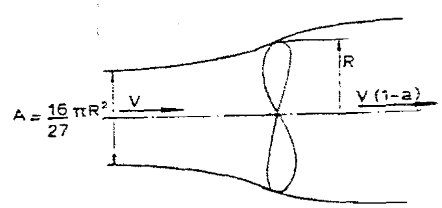


Fig. 4 This schematic provides a visual explanation of the power equations.

Taking the variation of wind speed with time into account, engineers at Sandia Laboratories have prepared a wind power map of the United States, which gives the distribution of average wind power as shown in Fig 1. Immediately evident from inspection of this figure is the nonuniform distribution of this resource. The best potential wind power sites within the continental U.S. appear to be in the north central region.

Not only is the distribution of wind power over the earth's surface quite nonuniform, there are also distinct seasonal and daily variations. Illustrated in Fig. 2, is the cumulative distribution of wind speed at three different sites: a very poor U.S. site, a U.S. site with excellent potential, and the summer and winter variation in the North Sea off the coast of Holland. The large seasonal and daily variations in wind speed are immediately evident. Because of the cubic dependence of power on wind speed, the variations in wind *power* are greatly magnified.

Evidently there is great potential use of wind power, but there are serious problems with its variability. Proper site selection will be crucial and imaginative schemes must be developed to smooth out the variations in power output.

Recognizing the potential in wind power and its limitations, the next step is to look at the windmill itself. How does it work? How much power can it produce? Basically a windmill is a propeller in reverse. As shown in Fig. 3, aerodynamic forces are induced on each blade element whose magnitude and direction are dependent on wind velocity, V, the rotational speed, Ω, and the blade pitch angle, β There is a component of the lift force acting in the direction of rotation which produces a torque and hence power. Ideally, this power is given by

$$P = 2 \pi R^2 \rho V^3 (1 - a)^2 a$$

where a is a factor accounting for the deceleration of wind through the windmill rotor as shown schematically in Fig. 4. Maximum power is attained when a is 1/3. Thus the ideal power of a windmill is

$$P_m = (16/27) \pi R^2 (1/2 \rho V^3)$$

Even under ideal conditions, only a little more than one-half of the wind power per unit area can be extracted by a windmill. More detailed analysis, including the effects of rotation in the slip stream, show that the ideal power developed depends on the relative rotational speed, Ω R/V. This is illustrated in Fig. 5, which shows that a theoretical power factor of 16/27 is only approached when the tip speed of a windmill exceeds about 4 times the wind speed. In addition, maximum aerodynamic performance of a blade section is attained when the angle of attack to the relative wind is a specified value depending on the blade section shape. In order for this criterion to be compatible with the ideal power at a given relative tip speed, the blade area expressed as a percentage of disk area must decrease with an increase in design speed. Theoretical values of the product of solidity,

$$\delta = \text{Blade area} / \pi R^2$$

and design lift coefficients, C_L, are as follows:

Theoretical Solidity as a Function of Tip Speed

Ω R/V =	1	2	3	4	5
δ C_L	0.98	0.48	0.29	0.19	0.14

Thus, if the design lift coefficient where unity, the theoretical blade area would be around 100% of the area swept by the blades for a slow running windmill (Ω R/V=1) and only 14% of the disk area for a relatively high-speed windmill (Ω R=5). Thus, modern, high-speed windmill designs will have blades closely resembling those of a helicopter with all of the accompanying flex and vibration problems.

Although a lot of design information can be gained from a steady flow analysis, there are additional complicating factors of unsteady wind speed and the vertical wind profile to deal with also. Early Dutch research showed that operation in an unsteady wind meant that maximum average power output depended on both the steady and unsteady characteristics of the windmill. Figure 6 shows a reproduction of the measured power output of a typical Dutch mill correlated with wind speed. Two things are immediately evident, power output can be quite unsteady and there is a minimum value of wind speed below which operation ceases altogether. The Dutch found that average power could be optimized when the rate of change of tip speed with wind velocity is optimized. It can be shown that

$$d(\Omega R)/dV = \rho R^4 V / I$$

where I is the moment of inertia of the rotor and t is a time constant related to the wind fluctuations. Classic Dutch windmills apparently have optimum output when the moment of inertia is such that $I / R^4 V$ is about 1 sec. Several poorly operating mills in Holland have been improved by simply adding lead weights to the tips of the sails to increase the moment of inertia.

Much more sophisticated methods of handling fluctuating loads are planned for modern wind generators. Constant speed units which have hydraulically actuated blades for variable pitch can be designed in a manner similar to the familiar constant speed propeller on an airplane. Nonuniformities in loading with blade position due to the vertical wind profile can be handled in the same way that nonuniformities in blade loading are handled on a helicopter.

In summary, classical aerodynamics tells us that the most efficient windmills operate with tip speeds greatly exceeding the average wind velocities and with few, relatively slender blades. Also there are

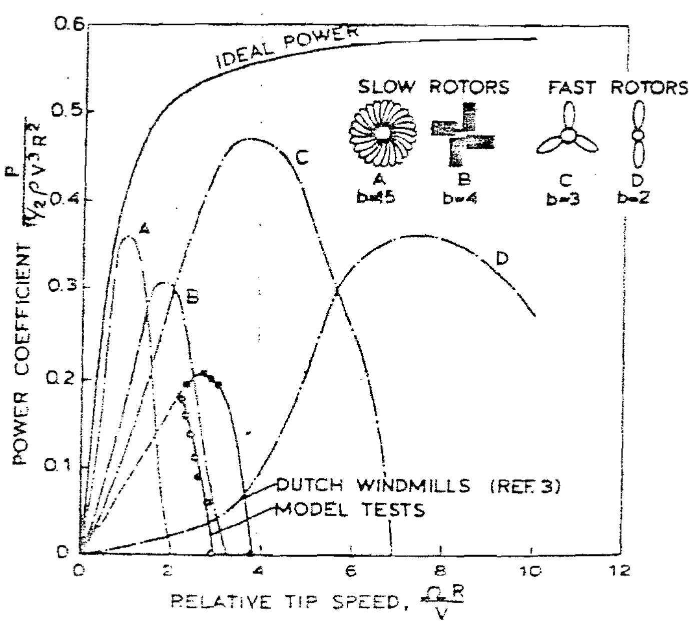
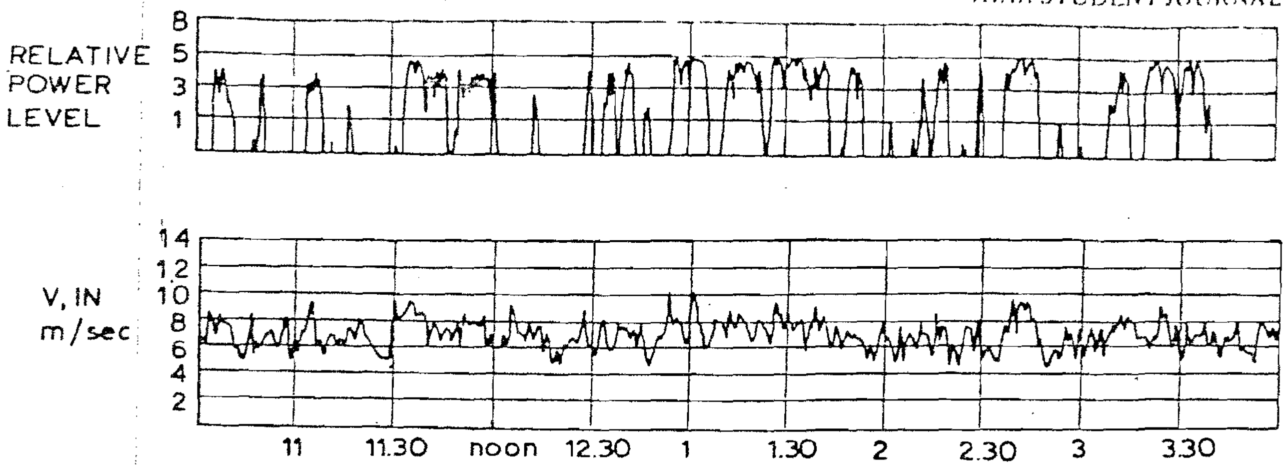


Fig. 5 The ideal power coefficient is only approached when the tip speed of a windmill exceeds approximately 4 times the wind speed.



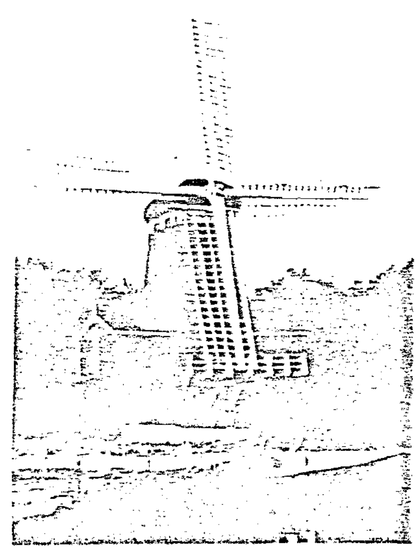
The correlation of power output of a Dutch Windmill with wind speed shows not only that power output can be quite unsteady but also below a certain minimum wind speed, the whole operation will grind to a halt.

major structural and aerodynamic problems associated with both the nonsteadiness of the wind and its nonuniform distribution with elevation.

Several alternate forms of energy are now being seriously investigated. Wind energy is one potential energy resource being considered by both the government and private industry. There is a joint NASA/NSF 5 year program in progress which hopes to develop several practical and economical wind energy systems. A first-stage experimental 100 kW wind generator is scheduled for operation by NASA this year. In addition, there are plans for two additional experimental units, one in the 50-250 kW range and the other in the 0.5 to 3 megawatt size. Many new types of windmills have been proposed recently. Among them is a semi-rigid airfoil design being developed by Grumman Aerospace Company and a vertical axis wind generator proposed by Sandia Laboratories.

Several energy storage schemes are being studied to offset the undesirable fluctuating power output of a wind generator. In the offshore wind generation system mentioned at the beginning of this article, electrolysis of water into hydrogen and oxygen which is stored and then subsequently used to generate electricity in fuel cells has been suggested as a method for smoothing out the energy flow. Economic analysis of the system, using state-of-the-art components, indicates that electricity could be provided to New England at a cost of about 2.2 cents per k/hr. Projected hardware improvements reduce this figure by about 40%.

Although it does not appear that the wind will ever be our major source of power, there is ample evidence it can be an alternate source, complementing other resources. The challenge is there and the rewards are great. Perhaps those students competing for the Bendix award will come up with something?



Without the windmill much of the Netherlands would still be part of the North Sea.

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