INTRODUCTION

Look at the ships also:, though they are so great and are driven by strong winds, they are guided by a very small rudder wherever the will of the pilot directs. James 3:4

The wind is a free, clean, and inexhaustible energy source. It has served mankind well for many centuries by propelling ships and driving wind turbines to grind grain and pump water. Interest in wind power lagged, however, when cheap and plentiful petroleum products became available after World War II. The high capital costs and the uncertainty of the wind placed wind power at an economic disadvantage. Then in 1973, the Arab nations placed an embargo on petroleum. The days of cheap and plentiful petroleum were drawing to an end. People began to realize that the world's oil supplies would not last forever and that remaining supplies should be conserved for the petrochemical industry. The use of oil as a boiler fuel, for example, would have to be eliminated. Other energy sources besides oil and natural gas must be developed.

The two energy sources besides petroleum which have been assumed able to supply the long term energy needs of the United States are coal and nuclear energy. Many people think there is enough coal for several centuries at present rates of consumption, and likewise for nuclear energy after the breeder reactor is fully developed. These are proven resources in the sense that the technology is highly developed, and large coal and nuclear powered electrical generating plants are in operation and are delivering substantial blocks of energy to the consumer. Unfortunately, both coal and nuclear present serious environmental problems. Coal requires large scale mining operations, leaving land that is difficult or impossible to restore to usefulness in many cases. The combustion of coal may upset the planet's heat balance. The production of carbon dioxide and sulfur dioxide may affect the atmosphere and the ability of the planet to produce food for its people. Coal is also a valuable petrochemical feedstock and many consider the burning of it as a boiler fuel to be foolish.

Nuclear energy has several advantages over coal in that no carbon dioxide or sulfur dioxide are produced, mining operations are smaller scale, and it has no other major use besides supplying heat. The major difficulty is the problem of waste disposal, which, because of the fears of many, will probably never have a truly satisfying solution.

Because of these problems, wind power and other forms of solar power are being strongly encouraged. Wind power may become a major source of energy in spite of slightly higher costs than coal or nuclear power because of the basically non-economic or political problems of coal and nuclear power. This is not to say that wind power will always be more expensive than coal or nuclear power, because considerable progress is being made in making wind power less expensive. But even without a clear cost advantage, wind power may become truly important in the world energy picture.

1 HISTORICAL USES OF WIND

The wind has been used to power sailing ships for many centuries. Many countries owed their prosperity to their skill in sailing. The New World was explored by wind powered ships. Indeed, wind was almost the only source of power for ships until Watt invented the steam engine in the 18th Century.

On land, wind turbines date back many centuries. It has been reported that the Babylonian emperor Hammurabi planned to use wind turbines for irrigation in the seventeenth century B.C. [3]. Hero of Alexandria, who lived in the third century B.C., described a simple horizontal axis wind turbine with four sails which was used to blow an organ [3].

The Persians were using wind turbines extensively by the middle of the seventh century A.D. Theirs was a vertical axis machine with a number of radially-mounted sails [3].

These early machines were undoubtedly crude and mechanically inefficient, but they served their purpose well for many centuries. They were made from local materials by cheap labor. Maintenance was probably a problem which served to keep many people at work. Their size was probably determined by the materials available. A need for more power was met by building more wind turbines rather than larger ones. There are many of the lesser developed countries of the world today which could profitably use such low technology machines because of the large amounts of cheap, unskilled labor available. Such countries often have difficulty acquiring the foreign exchange necessary to purchase high technology machines, and then have difficulty maintaining them.

The earliest recorded English wind turbine is dated at 1191. The first corn-grinding wind turbine was built in Holland in 1439. There were a number of technological developments through the centuries, and by 1600 the most common wind turbine was the tower mill. The word mill refers to the operation of grinding or milling grain. This application was so common that all wind turbines were often called windmills even when they actually pumped water or performed some other function. We will usually use the more general terms wind turbine or wind machine rather than windmill, unless the application is actually that of grinding grain.

The tower mill had a fixed supporting tower with a rotatable cap which carried the wind rotor. The tower was usually built of brick in a cylindrical shape, but was sometimes built of wood, and polygonal in cross section. In one style, the cap had a support or tail extending out and down to ground level. A circle of posts surrounded the tower where the support touched the ground. The miller would check the direction of the prevailing wind and rotate the cap and rotor into the wind with a winch attached between the tail and one of the posts. The tail would then be tied to a post to hold the rotor in the proper direction. This process would be repeated when the wind direction changed. Protection from high winds was accomplished by turning the rotor out of the wind or by removing the canvas covering the rotor latticework.

The optimization of the rotor shape probably took a long time to accomplish. It is interesting to note that the rotors on many of the Dutch mills are twisted and tapered in the same way as modern rotors and appear to have nearly optimized the aerodynamic parameters necessary for maximum efficiency. The rotors presently on the tower mills probably do not date back to the original construction of the tower, but still indicate high quality aerodynamic engineering of a period much earlier than the present.

Dutch settlers brought this type of wind turbine to America in the mid-1700's. A number were built but not in the quantity seen in Europe.

Then in the mid-1800's a need developed for a smaller wind turbine for pumping water. The American West was being settled and there were wide areas of good grazing lands with no surface water but with ample ground water only a few meters under the surface. With this in mind, a distinctive wind turbine was developed, called the American Multibladed wind turbine. It had high starting torque and adequate efficiency, and suited the desired water pumping objective very well. If the wind did not blow for several days, the pump would be operated by hand. Since this is a reasonably good wind regime, hand pumping was a relatively rare occurrence.

An estimated 6.5 million units were built in the United States between 1880 and 1930 by a variety of companies. Many of these are still operating satisfactorily. By providing water for livestock, these machines played an important role in settling the American West.

2 HISTORY OF WIND ELECTRIC GENERATION

Denmark was the first country to use the wind for generation of electricity. The Danes were using a 23 m diameter wind turbine in 1890 to generate electricity. By 1910, several hundred units with capacities of 5 to 25 kW were in operation in Denmark.

About 1925, commercial wind-electric plants using two- and three-bladed propellers appeared on the American market. The most common brands were Wincharger (200 to 1200 W) and Jacobs (1.5 to 3 kW). These were used on farms to charge storage batteries which were then used to operate radios, lights, and small appliances with voltage ratings of 12, 32, or 110 volts. A good selection of 32 Vdc appliances was developed by industry to meet this demand. Then the Rural Electric Administration (REA) was established by Congress in 1936. Low interest loans were provided so the necessary transmission and distribution lines could be constructed to supply farmers with electricity. In the early days of the REA, around 1940, electricity could be supplied to the rural customer at a cost of 3 to 6 cents per kWh. The corresponding cost of wind generated electricity was 12 to 30 cents per kWh when interest, depreciation, and maintenance were included [6]. The lower cost of electricity produced by a central utility plus the greater reliability led to the rapid demise of the home wind electric generator.

After 1940, the cost of utility generated electricity continued a slow decline, dipping under 3 cents per kWh in the early 1970's. This was accomplished by their using larger and more efficient generating plants. A trend of decreasing cost for electricity while other costs are increasing could not be continued forever, and utility generated electricity started increasing in cost in the early 1970's reaching the 1940 cost level around 1976. This was accompanied by many consumer complaints, of course, which were largely unjustified when the long term performance of the utilities in providing low cost, reliable electricity is considered.

In addition to home wind electric generation, a number of utilities around the world have built larger wind turbines to supply power to their customers. The largest wind turbine built before the late 1970's was a 1250 kW machine built on Grandpa's Knob, near Rutland, Vermont, in 1941. The concept for this started in 1934 when an engineer, Palmer C. Putnam, began to look at wind electric generators to reduce the cost of electricity to his Cape Cod home [8]. In 1939, Putnam presented his ideas and the results of his preliminary work to the S. Morgan Smith Company of York, Pennsylvania. They agreed to fund a wind-energy project and the Smith-Putnam wind turbine experiment was born. The wind machine was to be connected into the Central Vermont Public Service Corporation's network. This utility had some hydro-electric capacity, which makes a good combination with wind generation in that water can be saved when the wind is blowing and used later when the wind is not blowing.

The Smith-Putnam machine had a tower which was 34 m high and a rotor 53 m in diameter. The rotor had a chord (the distance from the leading to the trailing edge) of 3.45 m. Each of the two blades was made with stainless steel ribs covered by a stainless steel skin and weighed 7300 kg. The blade pitch (the angle at which the blade passes through the air) was adjustable to maintain a constant rotor speed of 28.7 r/min. This rotational speed was maintained in wind speeds as high as 32 m/s. At higher wind speeds, the blades were feathered and the machine stopped. The rotor turned an ac synchronous generator that produced 1250 kW of electrical power at wind speeds above 13 m/s.

Between 1941 and 1945 the Smith-Putnam machine accumulated about 1100 hours of operation. More would have been accumulated except for the problem of getting critical repair parts during the war. In 1945 one of the blades failed, due more to inadequate design than to technological limitations. The project was reviewed and was determined to be a technical success. The economics did not justify building more machines at that time, however. It appeared that additional Smith-Putnam machines could be built for about $190/installed kW. Oil and coal fired generation could be bought in 1945 for $125/installed kW. This was too large a difference to justify to the stock-holders, so the project was stopped and the wind machine was dismantled.

The technical results of the Smith-Putnam wind turbine caused Percy H. Thomas, an engineer with the Federal Power Commission, to spend approximately 10 years in a detailed analysis of Wind Power Electric Generation [14]. Thomas used economic data from the Smith-Putnam machine and concluded that even larger machines were necessary for economic viability. He designed two large machines in the size range he felt to be best. One was 6500 kW and the other was 7500 kW in size. The tower height of the 6500 kW machine was to be 145 m with two rotors each 61 m in diameter. Each rotor was to drive a dc generator. The dc power was used to drive a dc to ac synchronous converter which was connected to the power grid.

Thomas estimated the capital costs for his machine at $75 per installed kW. This was low enough to be of interest so the Federal Power Commission approached Congress for funding a prototype of this machine. It was in 1951 when the Korean War was starting, and Congress chose not to fund the prototype. The project was later canceled. This basically marked the end of American wind power research for over twenty years until fuel supplies became a problem.

Other countries continued wind research for a longer period of time. Denmark built their Gedser wind turbine in 1957. This machine produced 200 kW in a 15 m/s wind. It was connected to the Danish public power system and produced approximately 400,000 kWh per year. The tower was 26 m high and the rotor was 24 m in diameter. The generator was located in the housing on the top of the tower. The installation cost of this system was approximately $250/kW. This wind turbine ran until 1968 when it was stopped [14].

Dr. Ulrich Hutter of Germany built a 100 kW machine in 1957. It reached its rated power output at a wind speed of 8 m/s, which is substantially lower than the machines mentioned earlier. This machine used lightweight, 35 m diameter fiberglass blades with a simple hollow pipe tower supported by guy wires. The blade pitch would change at higher wind speeds to keep the propeller angular velocity constant. Dr. Hutter obtained over 4000 hours of full rated power operation over the next 11 years, a substantial amount for an experimental machine. This allowed important contributions to the design of larger wind turbines to be made.

3 HORIZONTAL AXIS WIND TURBINE RESEARCH IN THE UNITED STATES

The Federal Wind Energy Program had its beginning in 1972 when a joint Solar Energy Panel of the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) recommended that wind energy be developed to broaden the Nation's energy options for new energy sources.[9] In 1973, NSF was given the responsibility for the Federal Solar Energy Program, of which wind energy was a part. The Lewis Research Center, a Federal Laboratory controlled by NASA, was selected to manage the technology development and initial deployment of large wind turbines. Early in 1974, NASA was funded by NSF to (1) design, build, and operate a wind turbine for research purposes, designated the MOD-0, (2) initiate studies of wind turbines for utility application, and (3) undertake a program of supporting research and technology development for wind turbines.

In 1975, the responsibility within the Federal government for wind turbine development was assigned to the newly created Energy Research and Development Administration (ERDA). ERDA was then absorbed by the Department of Energy (DOE) in 1977. The NASA Lewis Research Center continued to direct the technology development of large turbines during this period.

During the period following 1973, other Federal Laboratories became involved with other aspects of Wind Energy Collection Systems (WECS). Sandia Laboratories, a DOE Laboratory located at Albuquerque, New Mexico, became responsible for federally sponsored research on Darrieus wind turbines. Battelle Pacific Northwest Laboratories, Richland, Washington, became responsible for wind resource assessments. Solar Energy Research Institute, (now the National Renewable Energy Laboratory) Golden, Colorado, became responsible for innovative wind turbines. Small wind turbine research was handled by Rockwell, International at their Rocky Flats plant near Golden, Colorado. Agricultural applications were handled by the U. S. Department of Agriculture from facilities at Beltsville, Maryland, and Bushland, Texas. This division of effort allowed existing personnel and facilities to be shifted over to wind power research so that results could be obtained in a relatively short time.

It was decided very early in the program that the MOD-0 would be rated at 100 kW and have a 38-m-diameter rotor with two blades[12]. This machine would incorporate the many advances in aerodynamics, materials, controls, and data handling made since the days of the Smith-Putnam machine. The choice of the two bladed propeller over some more unusual wind turbines was made on the basis of technology development. The two bladed machines had been built in larger sizes and had been operated more hours than any other type, hence had the highest probability of working reasonably well from the start. For political reasons it was important to get something working as soon as possible. This machine became operational in September, 1975, at the NASA Plumbrook facility near Sandusky, Ohio.

A diagram of the turbine and the contents of the nacelle (the structure or housing on top of the tower which contains the gearbox, generator, and controls) is shown in Fig. 1. The rotor and nacelle sit on top of a 4-legged steel truss tower about 30 m high. The rotor is downwind of the tower, so the wind strikes the tower before striking the rotor. Each rotor blade thus sees a change in wind speed once per revolution when it passes through the tower shadow. This introduces vibration to the blades, which has to be carefully considered in blade design. An upwind design tends to introduce vibration in the tower because of blade shadowing so neither design has strong advantages over the other. In fact, the MOD-0 was operated for brief periods as an upwind machine to assess some of the effects of upwind operation on structural loads and machine control requirements.

The MOD-0 was designed so the rotor would turn at a constant 40 r/min except when starting up or shutting down. A gear box increases the rotational speed to 1800 r/min to drive a synchronous generator which is connected to the utility network. Startup is accomplished by activating a control which aligns the wind turbine with the wind. The blades are then pitched by a hydraulic control at a programmed rate and the rotor speed is brought to about 40 r/min. At this time an automatic synchronizer is activated and the wind turbine is synchronized with the utility network. If the wind speed drops below the value necessary to get power from the rotor at 40 r/min, the generator is disconnected from the utility grid, the blades are feathered (pitched so no power output is possible) and the rotor is allowed to coast to a stop. All the steps of startup, synchronization, power control, and shutdown are automatically controlled by a microprocessor.

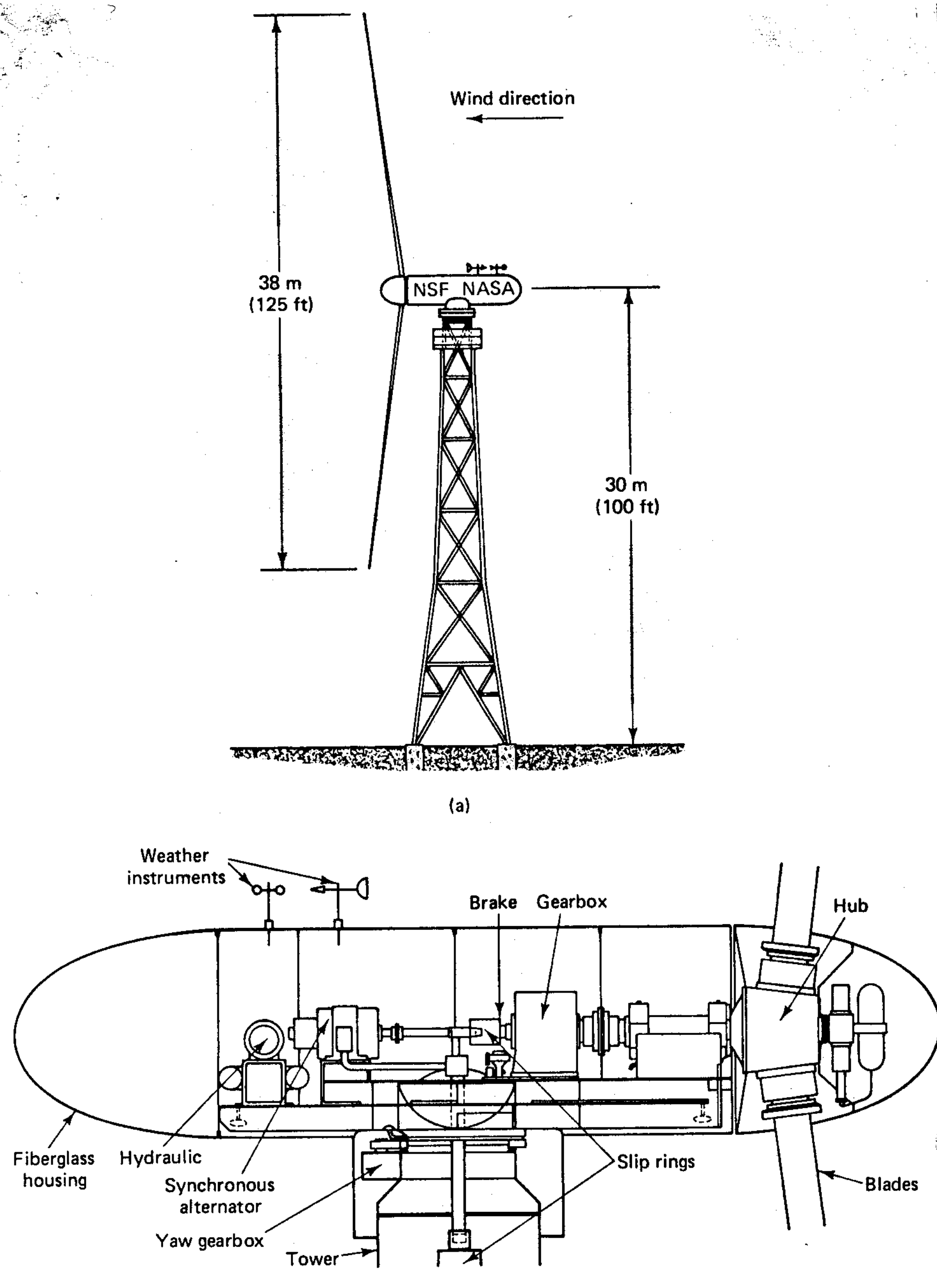

Figure 1: NSF–NASA MOD-0 wind power system: (a) general view; (b) superstructure and equipment. Rated power output, 100 kW; rated wind speed, 8 m/s (18 mi/h). (Courtesy of DOE.)

The stresses in the aluminum blades were too high when the unit was first placed into operation, and it was determined that the tower shadow was excessive. The tower was blocking the airflow much more than had been expected. A stairway inside the tower which had been added late in the design was removed and this solved the problem.

Except for this tower blockage problem, the MOD-0 performed reasonably well, and provided a good base of experience for designing larger and better turbines. The decision was made in 1975 to build several of these turbines, designated as the MOD-0A. The size of tower and rotor remained the same, but the generator size was doubled from 100 to 200 kW. The extra power would be produced in somewhat higher wind speeds than the rated wind speed of the MOD-0. The Westinghouse Electric Corporation of Pittsburgh, Pennsylvania was the prime contractor responsible for assembly and installation. The blades were built by the Lockheed California Company of Burbank, California. The first MOD-0A was installed at Clayton, New Mexico in late 1977, the second at Culebra, Puerto Rico in mid 1978, the third at Block Island, Rhode Island in early 1979, and the fourth at Kahuku Point, Oahu, Hawaii in early 1980. The first three machines used aluminum blades while the Kahuku MOD-0A used wood composite blades. The wooden blades weighed 1360 kg each, 320 kg more than the aluminum blades, but the expected life was longer than their aluminum counterparts. A MOD-0A is shown in Fig. 2.

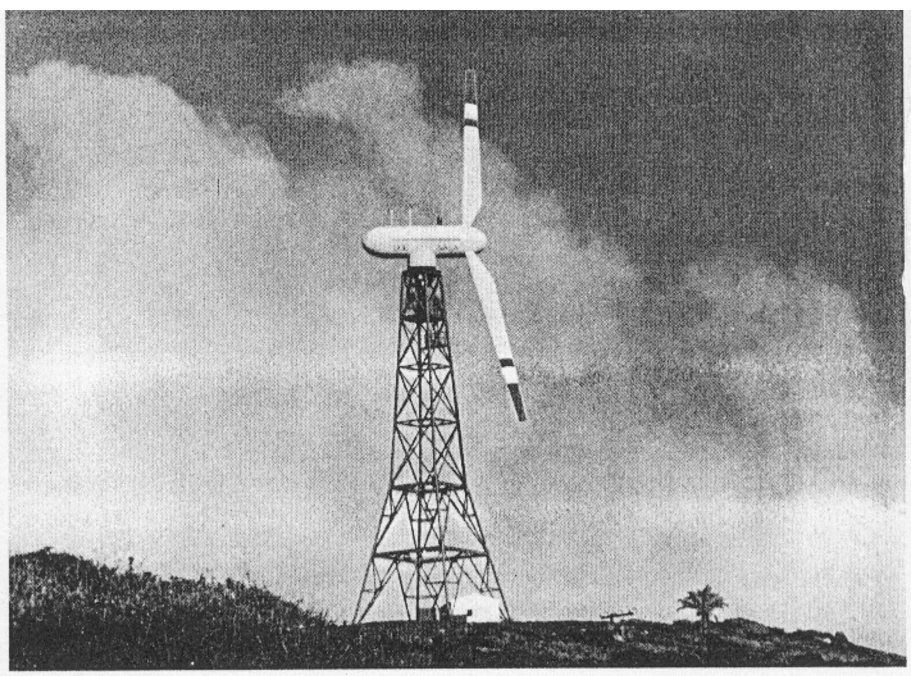

Figure 2: MOD-0A located at Kahuku Point, Oahu, Hawaii. (Courtesy of DOE.)

The Kahuku machine is located in a trade wind environment where relatively steady, high speed winds are experienced for long periods of time. The machine produced an average power output of 178 kW for the first 573 hours of operation. This was an outstanding record compared with the output of the other MOD-0A machines of 117 kW at Culebra, 89 kW at Clayton, and only 52 kW at Block Island during the first few months of operation for these machines. This shows the importance of good site selection in the economical application of large wind turbines.

Following the MOD-0 and MOD-0A was a series of other machines, the MOD-1, MOD-2, etc. Design parameters for several of these machines are shown in Table 1.1. The MOD-1 was built as a 2000-kW machine with a rotor diameter of 61 m. It is pictured in Fig. 3. Full span pitch control was used to control the rotor speed at a constant 35 r/min. It was built at Howard's Knob, near Boone, North Carolina in late 1978. It may be noticed from Table 1.1 that the rated windspeed for the MOD-1 was 14.6 m/s at hub height, significantly higher than the others. This allowed the MOD-1 to have a rated power of 10 times that of the MOD-0A with a swept area only 2.65 times as large.

Figure 3: MOD-1 located at Boone, North Carolina. (Courtesy of DOE.)

TABLE 1.1 Specifications of ERDA and DOE
Two-Bladed Horizontal-Axis Wind Turbines

	MOD-0	MOD-0A	MOD-1	MOD-2
Rotor r/min	40	40	34.7	17.5
Generator output power (kW)	100	200	2000	2500
Rotor coefficient of performance, $C_{\text{p,max}}$	0.375	0.375	0.375	0.382
Cut-in wind speed at hub height (m/s)	4.3	5.4	7.0	6.3
Rated wind speed at hub height (m/s)	7.7	9.7	14.6	12.4
Shutdown wind speed at hub height (m/s)	17.9	17.9	19.0	20.1
Maximum wind speed (m/s)	66	67	66	66
Rotor diameter (m)	37.5	37.5	61	91.5
Hub height (m)	30	30	46	61
Coning angle	7^o	7^o	12^o	0^o
Effective swept area (m^2)	1072	1140	2920	6560
Airfoil section, NACA-	23,000	23,000	44XX	230 XX
Weight of two blades (kg)	2090	2090	16,400	33,200
Generator voltage, line to line	480	480	4160	4160

The gearbox and generator were similar in design to those of the MOD-0A, except larger. The tower was a steel, tubular truss design. The General Electric Company, Space Division, of Philadelphia, Pennsylvania was the prime contractor for designing, fabricating, and installing the MOD-1. The Boeing Engineering and Construction Company of Seattle, Washington, manufactured the two steel blades.

As the MOD-1 design effort progressed, it became clear that the MOD-1 would be relatively heavy and costly and could not lead to a cost competitive production unit. Weight and cost were being determined by a number of factors, the most significant of which were the stiff tower design criteria, the full span pitch control which required complicated, heavy mechanisms and excessive space in the hub area, and a heavy bedplate supporting the weight on top of the tower. A number of possible improvements in the design became evident too late to be included in the actual construction. Only one machine was built because of the predicted production costs. Like the MOD-0, it was operated as a test unit to help the designs of later generation turbines.

One early problem with the MOD-1 was the production of subaudible vibrations which would rattle the windows of nearby houses. The rotor would interact with the tower to produce two pulses per revolution, which resulted in a vibration frequency of about 1.2 Hz. Techniques used to reduce the annoyance included reducing the speed of rotation and replacing the steel blades with fiberglass blades. Other operational problems, including a broken low speed shaft, plus a reduction in federal funding, caused the MOD-1 to be disassembled in 1982.

The next machine in the series, the MOD-2, represented an effort to build a truly cost competitive machine, incorporating all the information gained from the earlier machines. It was a second generation machine with the Boeing Engineering and Construction Company serving as the prime contractor. The rotor had two blades, was 91.5 m in diameter, and was upwind of the tower. Rotor speed was controlled at a constant 17.5 r/min. Rated power was 2500 kW (2.5 MW) at a wind speed of 12.4 m/s measured at the hub height of 61 m. In order to simplify the configuration and achieve a lower weight and cost, partial span pitch control was used rather than full span pitch control. That is, only the outer 30 percent of the span was rotated or pitched to control rotor speed and power. This construction feature can be seen in Fig. 4. To reduce the loads on the system caused by wind gusts and wind shear, the rotor was designed to allow teeter of up to 5 degrees in and out of the plane of rotation. These load reductions saved weight and therefore cost in the rotor, nacelle, and tower. The word *teeter* is also used for the motion of a plank balanced in the middle and ridden by children so one end of the plank goes up while the other end goes down. This described the same type of motion in the rotor except that motion was around a horizontal pivot point rather than the vertical one used on the playground.

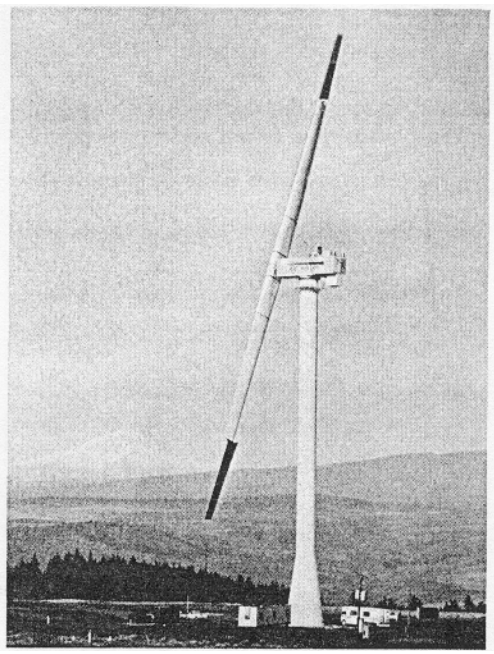

Figure 4: MOD-2 located at the Goodnoe Hills site near Goldendale, Washington. (Courtesy of DOE.)

The MOD-2 tower was designed to be soft or flexible rather than stiff or rigid. The softness of the tower refers to the first mode natural frequency of the tower in bending relative to the operating frequency of the system. For a two-bladed rotor, the tower is excited (receives a pulse) twice per revolution of the rotor. If the resonant frequency of the tower is greater than the exciting frequency, the tower is considered stiff. A tower is considered soft if the resonant frequency is less than the exciting frequency, and very soft if the resonant frequency is less than half the exciting frequency. The tower of the MOD-2 was excited at its resonant frequency for short time periods during startup and shutdown, so extreme care had to be taken during these times so the oscillations did not build up enough to damage the tower.

The MOD-2 tower was a welded steel cylindrical shell design. This design was more cost effective than the stiff, open-truss tower of the first generation machines. The MOD-2 was significantly larger than the MOD-1, yet the above ground mass was less, 273,000 kg as compared with 290,000 kg.

The first installation of the MOD-2 was a three machine cluster at the Goodnoe Hills site near Goldendale, Washington, built in early 1981. Two additional units were built, one in Wyoming and one in California.

The numbering system hit some difficulties at this point, since the next machine after the MOD-2 was the MOD-5. Actually, this third generation machine was designed by two different companies, with the General Electric version being named the MOD-5A while the Boeing version was named the MOD-5B. Objectives of the MOD-2 and MOD-5 programs were essentially identical except that the target price of electricity was reduced by 25 percent, to 3.75 cents per kWh in 1980 dollars.

The General Electric MOD-5A design called for a rotor diameter of 122 m (400 ft) and a rated power of 6.2 MW. Rated power would be reached in wind speeds of 13 m/s (29 mi/h) at the hub height of 76 m (250 ft). The wood rotor would turn at two rotational speeds, 13 or 17 r/min, depending on wind conditions.

The Boeing MOD-5B was designed to be an even larger machine, 7.2 MW with a rotor diameter of 128 m (420 ft). The rotor was designed to be built of steel with wood tips. A variable speed generator was selected as opposed to the fixed speed generator used on the MOD-2.

Federal research on the MOD series of turbines was terminated in the mid 1980s, and all the turbines have been scraped. One reason was that smaller turbines (in the 100-kW range) could be built at lower costs and with better performance than the large turbines. Many of us underestimated the difficulty of building large reliable wind turbines. The technology step was just too large.

A second reason was that the American aerospace industry did not have a desire to produce a cost effective commercial product. Wind turbine research was viewed as just another government contract. A given company would build a turbine on a cost plus basis. When it broke, it would be repaired on a cost plus basis. When the federal money ran out, the company's interest in wind power vanished. Hindsight indicates it would have been far better to have spent the federal money on the small, mostly undercapitalized, companies that were dedicated to producing a quality wind turbine.

A third reason for the lack of interest in wind was the abundance and depressed costs of petroleum products throughout the 1980s and into the 1990s. In the mid-1970s, it was standard wisdom that we were running out of natural gas. Many utilities converted from burning natural gas as a boiler fuel, instead using coal or nuclear energy. The price of natural gas increased substantially from its artificially low values. But by the mid-1980s, it was discovered that we had substantial reserves of natural gas (at this higher price), and utilities started converting back to natural gas as a fuel, especially for peaking gas turbines. The development of wind power has certainly been delayed by these various actions of the government, aerospace, and oil industries.

4 DARRIEUS WIND TURBINES

Most wind turbines designed for the production of electricity have consisted of a two or three bladed propeller rotating around a horizontal axis. These blades tend to be expensive, high technology items, and the turbine has to be oriented into the wind, another expensive task for the larger machines. These problems have led many researchers in search of simpler and less expensive machines. The variety of such machines seems endless. One that has seen considerable development is the Darrieus wind turbine. The Darrieus was patented in the United States by G. J. M. Darrieus in 1931[9]. It was reinvented by engineers with the National Research Council of Canada in the early 1970's. Sandia Laboratories built a 5 m diameter Darrieus in 1974, and has been strongly involved with further research on the Darrieus turbine since that time[11].

Fig. 5 shows a 17 meter Darrieus built at Sandia. The diameter of the blades is the same as the height, 17 m. The extruded aluminum blades were made by Alcoa (Aluminum Company of America, Alcoa Center, Pennsylvania). This machine is rated at 60 kW in a 12.5 m/s wind. Fig. 6 shows one of the blades during fabrication. Several models of this basic machine were built during 1980.

The Darrieus has several attractive features. One is that the machine rotates about a vertical axis, hence does not need to be turned into the wind. Another is that the blades take the shape of a jumping rope experiencing high centrifugal forces. This shape is called *troposkein*, from the Greek for turning rope. Since the blade operates in almost pure tension, a relatively light, inexpensive blade is sufficient. Another advantage is that the power train, generator, and controls are all located near ground level, hence are easier to construct and maintain. The efficiency is nearly as good as that of the horizontal axis propeller turbine, so the Darrieus holds considerable promise as a cost effective turbine.

One disadvantage of the Darrieus is that it is not normally self starting. That is, if the turbine has stopped during a period of low wind speeds, it will not usually start when the wind speed increases. Starting is usually accomplished by an induction motor connected to the local utility network. This is not necessarily a major disadvantage because the same induction motor can be used as an induction generator to supply power to the utility network when the turbine is at operating speed. Induction machines are simple, rugged, and inexpensive, requiring essentially no controls other than a contactor to connect the machine to the utility network. For these reasons, they are seeing wide use as wind turbine generators.

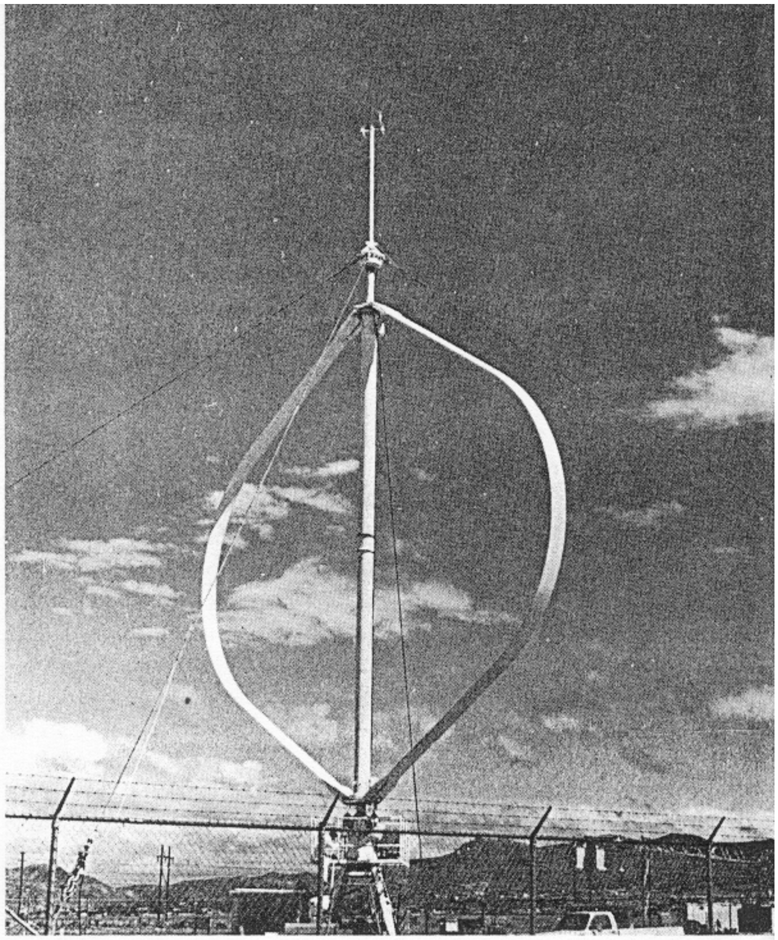

Figure 5: Sandia Laboratories 17-m Darrieus, rated at 60 kW in a 12.5-m/s wind. (Courtesy of Aluminum Company of America.)

The first large Darrieus constructed was a 230-kW machine on Magdalen Island, Quebec, Canada in May, 1977 by Dominion Aluminium Fabricators, Limited of Ontario, Canada. The average power output of this machine was 100 kW over the first year of operation, which is quite good. Then a noise was observed in the gearbox so the machine was stopped for inspection and repairs. During the inspection process, the brakes were removed, which should have been safe because the turbine was not supposed to be able to self start. Unfortunately, on July 6, 1978, the turbine started, and without a load or any way of stopping it, went well over the design speed of 38 r/min. The spoilers did not activate properly,and when the turbine reached 68 r/min a guy wire broke, letting the turbine crash to the ground. Perhaps the main lesson learned from this accident was that the Darrieus will sometimes start under unusual gust conditions and that braking systems need to be designed with this fact in mind.

A major design effort on Darrieus turbines has been made by Alcoa. They first designed

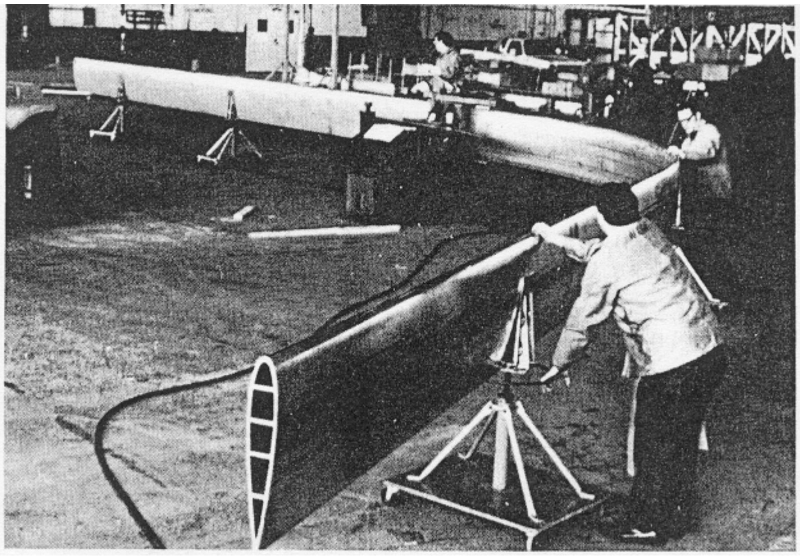

Figure 6: Extruded aluminum blade of 17-m Darrieus during fabrication. (Courtesy of Aluminum Company of America.)

a 5.5 m diameter machine which would produce about 8 kW of power, but dropped that size in favor of more economical larger machines. Other sizes developed by Alcoa include a 12.8 m diameter (30 to 60 kW), 17 m diameter (60 to 100 kW), and a 25 m diameter (300 or 500 kW depending on the gear ratio).

The Alcoa effort has been plagued by a number of accidents. A 12.8 m diameter machine collapsed at their Pennsylvania facility on March 21, 1980, when its central torque tube started vibrating and eventually buckled when the machine was running above rated speed. Then in April, 1981, a 25 m machine crashed in the San Gorgonio Pass east of Los Angeles[17]. The machine itself worked properly to a speed well above rated speed, but a software error in the microcomputer controller prevented proper brake application in high winds. When the machine rotational speed reached 60 r/min, well above the rated speed of 41 r/min, a bolt broke and allowed a blade to flare outward and cut one of the guy wires. The machine then crashed to the ground.

Accidents like these are not uncommon in new technology areas, but they are certainly frustrating to the people involved. It appears that the various problems are all solvable, but the string of accidents certainly slowed the deployment of Darrieus turbines as compared with the horizontal axis turbines.

Sandia continued work on the theory of the Darrieus turbine during the 1980s, with the result that the turbine is well understood today. It appears that there is no reason the Darrieus could not be an important contributor to the production of power from the wind. It just needs a large aluminum company that is willing and able to do the aluminum extrusions and possibly wait for several years before seeing a significant return on investment.

5 INNOVATIVE WIND TURBINES

Another type of turbine developed at about the same time as the Darrieus was the Savonius turbine, developed in Finland by S. J. Savonius[10]. This is another vertical axis machine which needs no orientation into the wind. Alternative energy enthusiasts often build this turbine from used oil barrels by cutting the barrels in half lengthwise and welding the two halves back together offset from one another to catch the wind. A picture of a somewhat more advanced unit developed at Kansas State University, Manhattan, Kansas, is shown in Fig. 7.

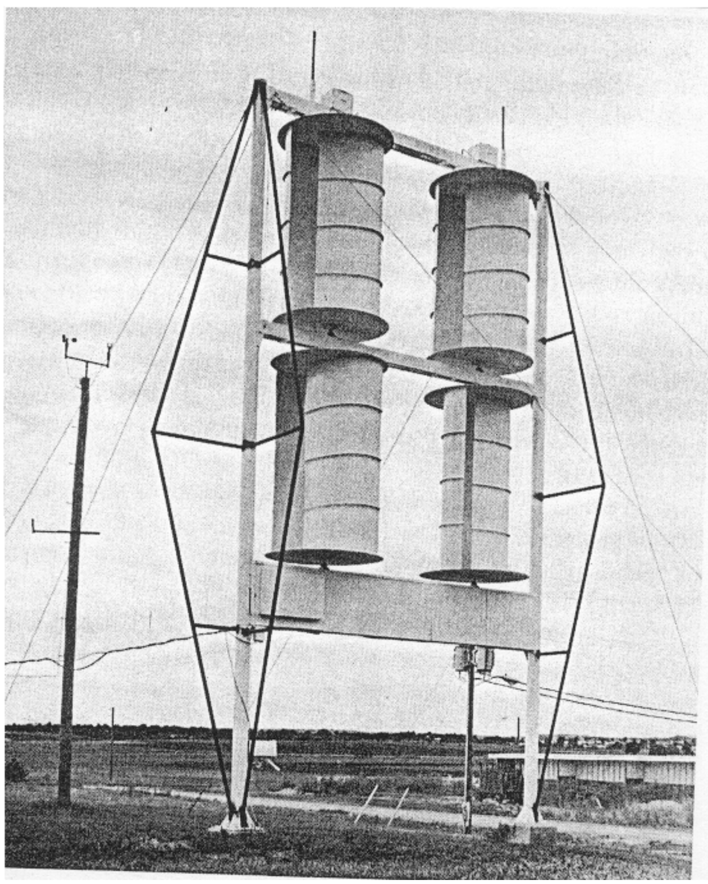

Figure 7: Kansas State University Savonius, rated at 5 kW in a 12-m/s wind.

The tower of the KSU Savonius was 11 m high and 6 m wide. Each rotor was 3 m high by 1.75 m in diameter. The rotors were connected together and drove a single 5 kW, three-phase, permanent magnet generator. At the rated wind speed of 12 m/s, the rotor speed was 103 r/min, the generator speed was 1800 r/min, and the frequency was 60 Hz. Output voltage and frequency varied with wind speed and load, which meant that this particular turbine could not be directly paralleled with the utility grid. Applications for this *asynchronous* (not synchronized with the utility grid) electricity are limited to electric heating and driving three-phase induction motors in situations which can tolerate variable speed operation. These include heat pumps, some water pumps, and fans. Such applications consume large quantities of electrical energy, so variable frequency operation is not as restrictive as it might appear. Asynchronous systems do not require complex blade pitch, voltage, and frequency controls, hence should be less expensive.

The main advantages of the Savonius are a very high starting torque and simple construction. The disadvantages are weight of materials and the difficulty of designing the rotor to withstand high wind speeds. These disadvantages could perhaps be overcome by good engineering if the turbine efficiency were high enough to justify the engineering effort required.

Agreement on the efficiency of the Savonius turbine apparently has finally been reached a half century after its development. Savonius claimed an efficiency of 31 per cent in the wind tunnel and 37 per cent in free air. However, he commented:[10] "The calculations of Professor Betz gave 20 % as the highest theoretical maximum for vertical airwheels, which under the best of circumstances could not produce more than 10 % in practical output." The theoretical and experimental results failed to agree. Unfortunately, Savonius did not specify the shape and size of his turbine well enough for others to try to duplicate his results.

A small unit of approximately 2 m high by 1 m diameter was built and tested at Kansas State University during the period 1932-1938[6]. This unit was destroyed by a high wind, but efficiencies of 35 to 40 % were claimed by the researchers. Wind tunnel tests were performed by Sandia on 1.5 m high by 1 m diameter Savonius turbines, with a maximum efficiency measured of 25 % for semicircular blades[1]. Different blade shapes which were tested at the University of Illinois showed a maximum efficiency of about 35 %[5]. More Savonius turbines were tested at Kansas State University, with efficiencies reported of about 25 %[13, 4]. It thus appears that the Savonius, if properly designed, has an efficiency nearly as good as the horizontal axis propeller turbine or the Darrieus turbine. The Savonius turbine therefore holds promise in applications where low to medium technology is required or where the high starting torque is important.

A chart of efficiency of five different turbine types is shown in Fig. 8. The efficiency or power coefficient varies with the ratio of blade tip speed to wind speed, with the peak value being the number quoted for a comparison of turbines. This will be discussed in more detail in Chapter 4. It may be noticed that the peak efficiencies of the two bladed propeller, the Darrieus, and the Savonius are all above 30 %, while the American Multiblade and the Dutch windmills peak at about 15 %. These efficiencies indicate that the American Multiblade is not competitive for generating electricity, even though it is almost ideally suited and very competitive for pumping water.

The efficiency curves for the Savonius and the American Multiblade have been known for a long time[6, 10]. Unfortunately, the labels on the two curves were accidentally interchanged in some key publication in recent years, with the result that many authors have used an erroneous set of curves in their writing. This historical accident will probably take years to correct.

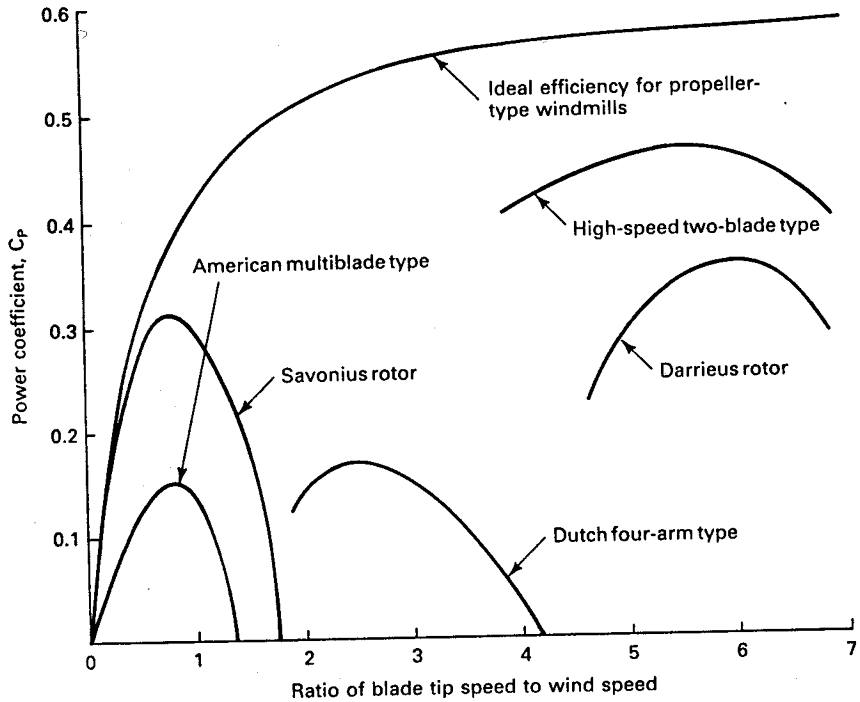

Figure 8: Typical performances of wind machines.

Another vertical axis machine which has interested people for many years is the Madaras rotor. This system was invented by Julius D. Madaras, who conducted considerable tests on his idea between 1929 and 1934. This concept uses the *Magnus effect*, which refers to the force produced on a spinning cylinder or sphere in a stream of air. The most familiar example of this effect is the curve ball thrown by a baseball pitcher. The Madaras rotor is a large cylinder which is spun in the wind by an electric motor. When the wind is from the left and the cylinder is spinning counterclockwise as shown in Fig. 9, the cylinder will experience a lift force in the direction shown. There will also be a drag force in the direction of the wind flow.

If the cylinder is mounted on a special type of railroad car and if the wind speed component perpendicular to the railroad tracks is sufficiently strong, the lift force will be adequate to move the car along the tracks. The basic idea is shown in Fig. 10. The railroad car or tracked carriage must be heavy enough that it will not overturn due to the drag forces. Power can be extracted from the system by electrical generators connected to the wheels of the tracked carriage. The cars roll around a circular or racetrack shaped track. Twice during each orbit of a rotor car around the track (when the wind is parallel to the track), each spinning rotor in turn must be de-spun to a stop, and then spun-up in the opposite direction. This cycle is necessary in order to assure that the propulsive force changes direction so that all rotors are propelling the train in the same angular direction.

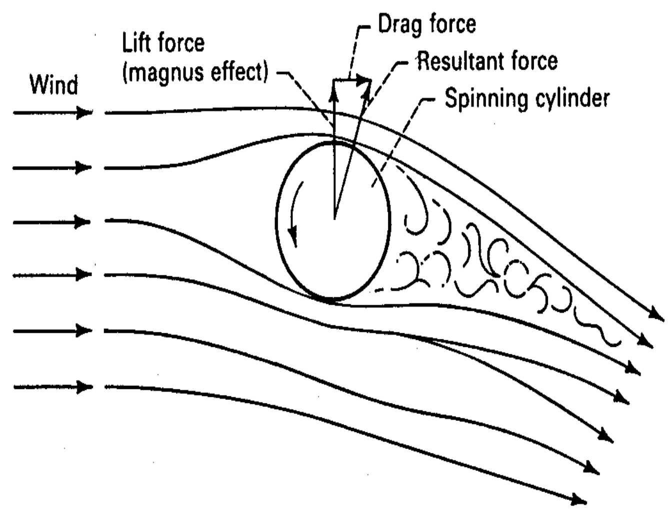

Figure 9: Magnus force on a spinning cylinder.

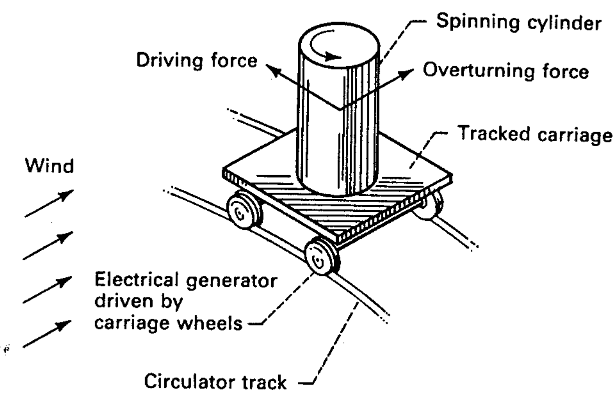

Figure 10: Madaras concept for generating electricity.

The original system proposed by Madaras consisted of 27 m high by 6.8 m diameter cylinders which were vertically mounted on flat cars and rotated by electric motors to convert wind energy to Magnus-effect forces. The forces would propel an endless train of 18 cars around a 460 m diameter closed track. Generators geared to the car axles were calculated to produce up to 18 MW of electric power at a track speed of 8.9 m/s in a wind speed of 13 m/s.

More recent studies[15, 16] have shown that energy production is greater with a racetrack shaped plant perhaps 3 km wide by 18 km long which is oriented perpendicular to the prevailing winds. This modern design includes cylinders 4.9 m in diameter by 38.1 m tall, cars with a length of 19.2 m and a width of 17.4 m, and a track with 11 m between rails. Individual cars would have a mass of 328,000 kg. Each rotor would be spun with a 450 kW, 500 volt dc motor. Each of the four wheels would drive a 250 kW induction generator. There would be about 200 cars on the track with a total rating of about 200 MW. Power would be extracted from the system by a 4160 V, three-phase, 500 A overhead trolley bus.

Cost estimates for the electricity costs from this large system were comparable to those from the MOD-1. Wind tunnel tests and field tests on a rotating cylinder on a fixed platform indicate that the concept will work. The questions remain whether the aerodynamic, mechanical, and electrical losses will be acceptable and whether the reliability will be adequate. Only a major development effort can answer these questions and there will probably not be sufficient interest in such a development if the horizontal axis wind turbines meet the basic requirements for cost and reliability.

All the wind turbines discussed thus far have a problem with capital costs. Although these machines work satisfactorily, capital costs are large. The Darrieus may become more cost effective than the two-bladed propeller turbine, but neither is likely to produce really inexpensive electricity. There is a desire for a breakthrough, whereby some new and different concept would result in substantial cost reductions. One candidate for such a wind machine is the augmented vortex turbine studied by James Yen at Grumman Aerospace Corporation[18]. An artist's concept of the machine is shown in Fig. 11.

The turbine tower has vertical vanes which direct the wind into a circular path around the inside of the tower. Wind blowing across the top of the tower tends to pull the air inside in an upward direction, causing the entering air to flow in a spiral path. This spiral is a vortex, which is characterized by a high speed, low pressure core. The vortex is basically that of a confined tornado. The pressure difference between the vortex core and outside ambient air is then used to drive a relatively small, high speed turbine at the base of the tower. The vortex machine is extracting power from pressure differences or the potential energy in the air, rather than directly from the kinetic energy of the moving air. The potential energy in the air due to pressure is vastly more than the kinetic energy of the air in moderate wind speeds, so there is a possibility of large energy outputs for a given tower size which could result in very inexpensive electricity.

One problem with the vortex machine is the potential for spawning tornadoes. If the vortex extending out of the top of the tower should become separated from the tower, grow a tail, and become an actual tornado, a permanent shutdown would be highly probable. In fact, based on the experience of the nuclear industry, fear of such an occurrence may prevent the implementation of such a wind machine.

Many other wind machines have been invented over the last few hundred years. The propeller type and the Darrieus have emerged as reasonably reliable, cost competitive machines which can provide a significant amount of electrical energy. Barring a major breakthrough with another type of wind machine, we can expect to see a wide deployment of these machines over the next few decades.

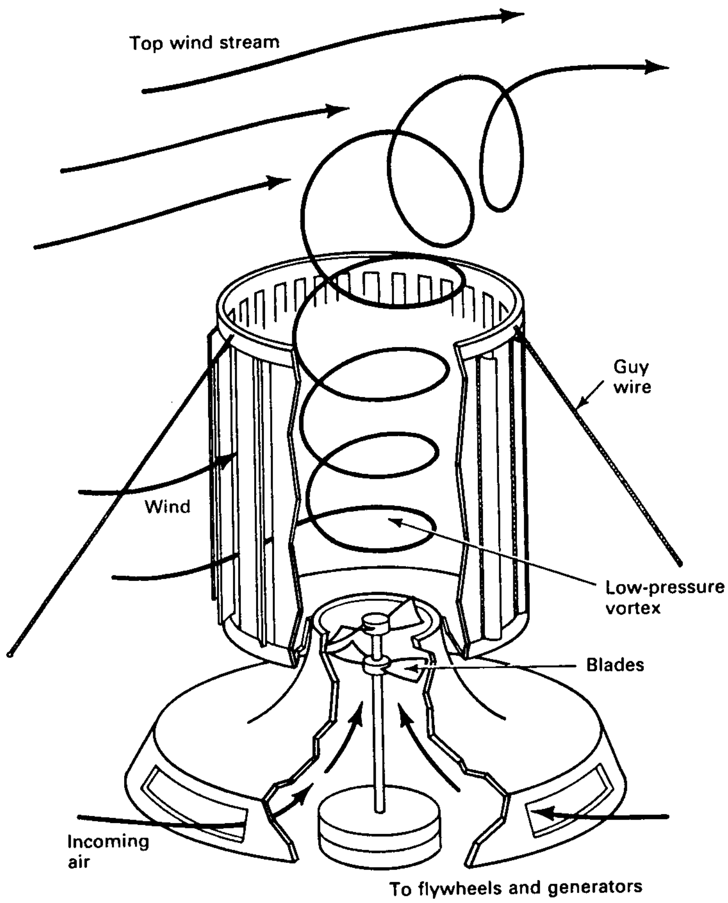

Figure 11: Augmented vortex turbine. (Reprinted from *Popular Science* with permission. ©1977 Times Mirror Magazines, Inc.)

6 CALIFORNIA WINDFARMS

Over 1500 MW of wind turbines have been installed in California, starting about 1980. On average, wind energy supplies around 1 % of California's electricity demand. Among electric utilities, Pacific Gas & Electric (PG&E), one of the largest in the country, uses the most wind power. At peak times during the summer, as much as 7 % of its demand is supplied by wind[2].

These are primarily horizontal-axis turbines, with two- or three-bladed rotors. Power ratings are in the range of 100 to 250 kW, with some smaller older units and a few larger new units. These turbines are deployed in large arrays known as windfarms. In addition to tower foundations and interconnecting cables, windfarms require construction and maintenance roads, a central control station, a distribution substation, and transmission lines. Some of the costs are fixed, so the larger the windfarm the lower the overall cost of electricity produced. The rule of thumb is that a windfarm must have at least 100 machines, corresponding to a peak output of at least 20 MW, to hope to be economical. We shall see details of some of these costs in Chapter 9.

Cost of energy from these windfarms is approximately \$0.07–\$0.09 per kWh[7]. These costs can be reduced by at least 40%, and perhaps 60% by the use of innovative, light-weight designs and improved operating efficiencies. If the cost can be reduced below \$0.05/kWh, and this figure appears well within reach, wind-generated electricity will be very competitive with other types of generation.

Lynette[7] indicates that new airfoils can increase energy capture by 25–30%, variable-speed generators can increase production by 5–15%, advances in control strategies by 3–5%, and taller towers by 10–20% (and sometimes more as we shall see in Chapter 2). The corresponding increase in turbine costs will be about 15–20%. Costs have been reduced dramatically since the early 1980s and should continue the trend for some time.

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