WIND ENERGY: APPLYING NEW TECHNOLOGY TO AN OLD IDEA

by

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ABSTRACT

Wind energy has been used by man since the first ships sailed the Mediterranean Sea more than four thousand years ago. In the last two thousand years, wind has been used as a motive force to pump water for the cultivation of arid regions of the world. Within the last one hundred years, the generation of electricity from the wind has had limited use in remote areas of the world. Since 1978, federal and state laws have encouraged investment in alternative energy technology. This investment has advanced wind power technology to a new level, involving innovative mechanical design and application.

Through the application of entrepreneurial and engineering innovation, a new electric power generation industry has been created. Over the last six years nearly 10,000 wind turbine generators, comprising well over 30 different designs, have been installed in California. These machines range in generator size from less than 1 kW to over 3200 kW; the rotor diameters range from less than 2 ft to over 300 ft.

Since 1973, this technology has taken two distinct development paths—a few large machines (100 kW or greater) developed with federal funds, and thousands of small machines (less than 100 kW) developed by the private sector. While both large and small machines have encountered technical and economic problems, only the small machine industry has progressed to commercialization under recent limited federal and state financial assistance.

An overview of the wind industry is presented, along with a review of the commercialization process. The operating history of a 15 MW project run by a power corporation is discussed. This project demonstrates a typical commercialization process for any new technology, where problems are assessed, designs evaluated and improved, and modified machines are deployed and successfully operated.

If federal financial assistance abruptly ends in 1985 (as presently planned), it could retard the rapid deployment of larger second generation machines (200 kW to 400 kW). If this occurs, it would be unfortunate, because these second generation machines, while a nonfirm resource, will cost less and can be constructed faster than most conventional oil, gas, nuclear, and coal resources through the end of this century. As a result, these second generation machines will continue to reduce future energy costs and, therefore, become an important part of utility resource plans.

INTRODUCTION

The 1973 energy crisis sent shock waves around the world and challenged previous views on the reliability and economics of certain conventional resources. The jump in energy prices in the United States also stimulated an increase in energy conservation, which has significantly reduced utility electrical demand growth rates.

The reduction in demand has provided a window of about ten years during which older existing units and new utility projects under construction can provide adequate energy supplies. The lower demand combined with the risks associated with new utility-financed coal and nulcear projects has resulted in the delay or cancellation of future projects [1]. As utility resource planning has moved from the early 1970s into the 1980s, there has been a growing awareness that renewable, less-polluting, quickly exploitable, and possibly less expensive alternative energy sources could provide a significant part of the nation's energy needs [2].

WIND ENERGY

Wind energy is one of these alternative sources. The wind energy potential in the United States is estimated at 68 quads (2 million MWs), and over 4,000 quads (13 million MWs) worldwide [3]. The principal reasons wind energy is considered useful are:

- Wind is widely available.
- Wind is very predictable on an annual basis.
- Wind energy is extremely clean.
- Wind energy is not a new technology, and thus represents a resource which can be commercialized in a relatively short period of time.

This last point is extremely important, because from a solid technology base in 1973, the federal government was able to quickly start funding programs for the development of large and some small wind turbine generators. A review of wind technology development history up to that point will show why modern wind turbine generators are simply applying new technology to an old idea.

DEVELOPMENT HISTORY OF WIND ENERGY TECHNOLOGY

The development history of wind energy is basically a review of improvements in blade design. Since the Persian Panemones of 200 B.C. (Figure 1), two principal factors have limited its use worldwide: limits in blade design, which have restricted machine efficiency, and the economics of other energy resources. The importance of blade design becomes very clear after a review of the equation for conversion of the kinetic energy of the wind to power.

$$P = \tfrac{1}{2}\rho A V^3 \qquad (1)$$

where

P = power
ρ = air density
A = area swept by rotor in square feet
V = wind speed in miles per hour [5]

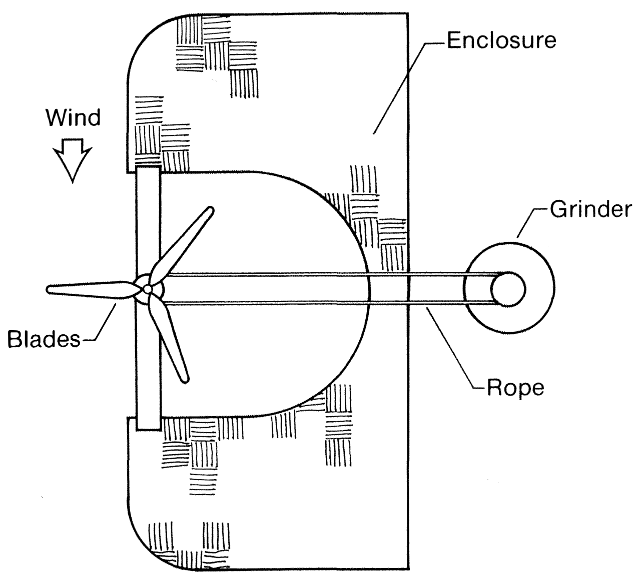


Figure 1. Schematic View From Above of a Persian Panemone—Designed and Operated About 200 B.C.

Because little can be done about air density or wind speed except locating a machine in a favorable site, most improvements in the efficiency of wind machines have concentrated on the blade design.

The Persians' first vertical axis wind machine (Panemones), while useful, had limited efficiency because only half of the total blade or paddle area could be exposed to the wind at a time. By 100 A.D., the first horizontal axis applications were in use around the Mediterranean Sea as water pumps. Using small cloth sails as blades, these machines represented a step forward in blade design, because the entire blade area was exposed to the wind [4].

Such advances in blade design first began to occur in northern Europe in 1200 A.D. Brought back from the Mediterranean by the Crusaders, these advances consisted of larger cloth sails which converted wind energy into mechanical energy for pumping water, grinding grain, and eventually running small industrial facilities. Having developed machines capable of delivering up to 90 hp in strong winds, the Dutch and Danish made dramatic advances in the application of basic horizontal axis technology, so that by the seventeenth century over 25,000 windmills were in use in northern Europe [4].

As the eighteenth and nineteenth centuries advanced, the invention of the steam engine, along with the shift from an agrarian to an industrial society, changed the economics of wind power. The invention of cheaper, more efficient, and more reliable steam energy technology created the first constraint to the use of wind power. By the 1800s, the number of wind machines in Europe had diminished to under two thousand. Ironically, it was in the 1800s that wind power first gained major influence in the United States [5].

Westward expansion into the more remote, arid parts of the United States demanded technology to pump water. In the early 1800s, the first American wind machines were developed for this purpose. These metal, multiblade machines were not very efficient, but their slow speeds and blade mass produced the torque needed to lift water. It is estimated that by the mid-1800s wind provided 25 percent of nontransportation energy. Hundreds of companies were producing thousands of water pumpers with many different models derived from the same basic theme. However, by the 1980s, the introduction of cheaper and more efficient electrical pumping brought economic factors into play that reduced the use of wind power in the United States, except in very remote rural areas [4].

BLADE TECHNOLOGY EVOLVES—THE AIRFOIL

By 1900, technological advances in Europe and the United States had set the stage for the next significant improvement in blade design, the application of a true airfoil. Prior to, and just after, World War I, development in aviation technology improved the wind machine blade efficiency. Wind machines, with fewer blades and reduced mass, allowed higher rotational speeds, which were better suited to the production of electricity.

Although wind turbine generators had become much more efficient in design, the economics of wood, oil, and natural gas as fuels limited the use of wind power to designs under 5 kW. Larger machine development was also constrained by the cost of the increased mass needed to support larger blades. A few exceptions to these constraints on large machine design were:

Denmark—Hundreds of medium-size machines (20-30 kW) were deployed prior to 1914 to provide the Danish dairy industry with remote power. These machines were refurbished and used during World War II when other energy sources were scarce [2].

Russia—In 1913, a 100 kW machine was built and operated on the shore of the Black Sea. The machine ran for a number of years in parallel with a 20 MW steam turbine some miles away [2].

The United States—The largest electrical generating machine developed prior to 1945 was installed at Grandpa's Knob in Vermont in 1939. Constructed and operated by the Smith-Putnam Company, the 1250 kW machine produced intermittent power from 1939 to 1945. In 1945, a blade root failure caused the loss of one of the two 8-ton blades. Ironically, the problem had been foreseen and new blades had been designed, and were to be manufactured after World War II. However, the accident, combined with post-World War II economics, did not justify repair and operation [6].

During World War II, world oil shortages caused many countries, such as Denmark, to reactivate and use old non-operating wind machines; however, economic factors changed after the war and limited efforts to develop wind power occurred.

During the period 1945-1973, the principal efforts to use wind power took place in Europe. The Danish built a 60 kW, a 70 kW, and a 200 kW WTG, the latter running from 1958 to

1967, when it was shut off because of cheap oil prices. It was placed back into service from 1977-1979 for research purposes. The Germans built a two-bladed, teetered, 100 kW unit that ran from 1957-1968, and the French built an 800 kW unit that ran from 1958 until the mid-1960s, when a blade failed and destroyed the machine [4].

By 1973, post-World War II advances in separate technical and engineering areas had provided the basic components for modern wind turbine generators. Principally, as the result of advances in helicopter rotor design and further advances in aerospace and wind tunnel applications, smaller, lighter, and more efficient blades were developed that allowed a reduction in the overall machine mass. The development of epoxies, plastics, and fiberglass contributed to continued blade advances. For example, the use of wood-epoxy laminating was found to be good for blades up to 200 ft long, and was better able to withstand the tremendous cyclic loads inherent in large machine operation [7].

MODERN TECHNOLOGY—REFINEMENT OF DESIGNS

The basic components of a modern horizontal axis wind turbine generator are shown in Figure 2—generator (both induction and synchronous), transmission, brake (airfoil and disk) and blades. In 1973, with a solid technical base, the economics of generating energy from the wind was the critical issue. The energy/economic shake-up of the early 1970s triggered extensive efforts to develop cost-effective wind turbine generators.

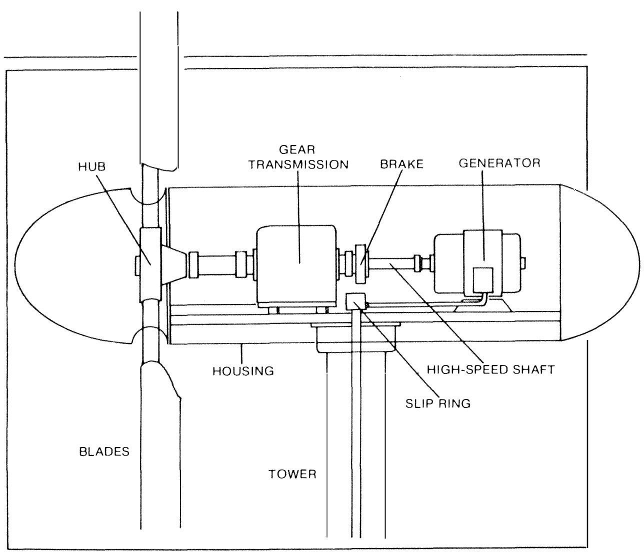


Figure 2. Major Components of a Modern Horizontal Axis Wind Turbine Generator.

Large Machines

With a sense of national emergency, the United States' federal government (Department of Energy and NASA) spent 250 million dollars beteween 1973 and 1980 on the development of wind energy [7]. The majority of that money went into the development of the first modern large wind turbines. The first of these machines, the MOD(el) 0, was deployed by NASA at their Lewis Research Center near Sandusky, Ohio. This 100 kW unit had a rotor diameter of 125 feet, the second largest ever built.

The MOD 0 used two blades, principally because in large machines (over 100kW) the blades and hub assembly tend to be the highest cost items. With two blades rather than three blades, unit costs are reduced. However, the use of two blades creates serious engineering problems with respect to dynamic loading and resonance. As a major research project, the operation of the MOD 0 provided technical review in the following areas [5]:

- Tests with utility grid interface
- Tests in an isolated system connected to diesel engine/generator
- Tests on blade dynamics, vibration, and fatigue
- Development of sophisticated analytical tools to evaluate and predict loads on large rotating structures.

The progression in large-scale wind turbine development from the MOD 0 to the MOD 5 is shown in Figure 3 [8]. The large machine research program prototypes are listed in Table 1 [4]. The results of the large-scale work done by DOE/NASA can best be summarized by the operating history of a Pacific Gas and Electric Company's (PGandE) MOD 2, which is installed in Solano County, California, 10 miles northeast of San Francisco.

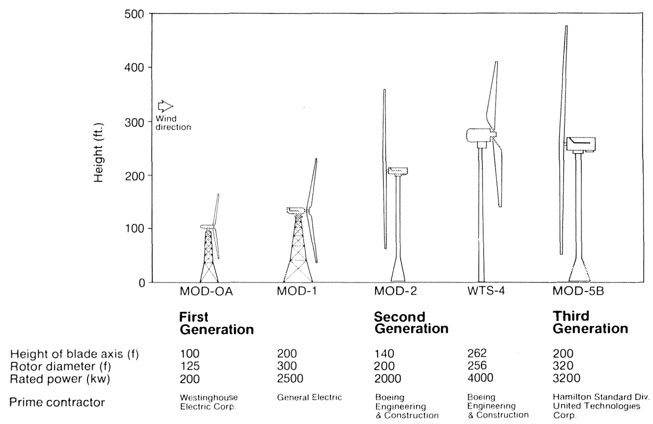


Figure 3. Various Large Wind Turbine Generators Developed Through the Federal Assistance Program.

Table 1. Federal Government Large Machine Research Program [4].

NASA R&D		PROTOTYPE		
HAWT	CAPACITY	BUILT BY	INSTALLED AT	FIRST TURNED
MOD-0	100 kW @ 14.5 mph	NASA	Sandusky, OH	Sept., 1975
MOD-0A	200 kW @ 18.3 mph	Westinghouse	Clayton, NM	March, 1978
(four machines)		Westinghouse	Culebra, PR	Jan., 1979
		Westinghouse	Block Isl., RI	Oct., 1979
		Westinghouse	Oahu, HI	May, 1980
MOD-1	2.0 MW @ 25.7 mph	G.E.	Boone, NC	Sept., 1979
MOD-2	2.5 MW @ 19.5 mph	Boeing	Goldendale, WA	Dec., 1980
(four machines)		Boeing	Goldendale, WA	Feb., 1981
		Boeing	Goldendale, WA	May, 1981
		Boeing	Medicine Bow, WY	early 1982
MOD-5A	6.2 MW	G.E.	design study only	
MOD-5B	7.2 MW	Boeing	design study only	

MOD 2

Built in 1981, the MOD 2 began operation in April 1982. Designed and built by an aerospace contractor, the MOD 2 represents the state-of-the-art in large multi-megawatt wind turbine generators (Figure 4). Specific information on the MOD 2 dimensions is listed in Table 2. Installed costs totaled over 12 million dollars or 4800/kW. Since beginning commercial operation in November of 1982, the PGandE MOD 2 has experienced various problems which have reduced production to 7000 MWhr, significantly below its theoretical limits [9].

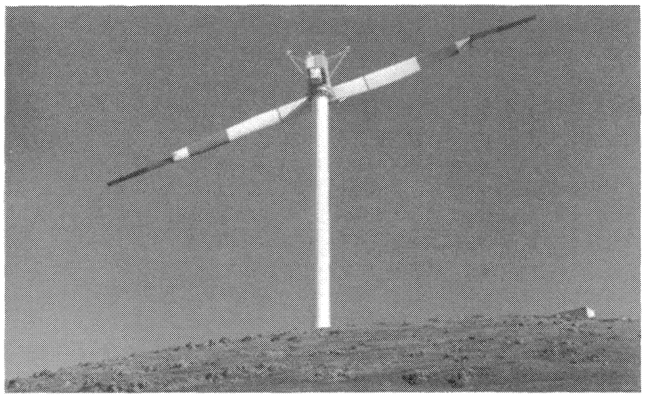


Figure 4. PGandE's 2.5 MW MOD 2, Solano County California, 1985.

Table 2. Information on PGandE's MOD 2 [7].

o	Generator Capacity	2500 kW
o	Generator Voltage	4160 V/115 kV
o	Generator Speed	1800 RPM
o	Rotor Length Tip-to-Tip	300 Feet
o	Rotor Weight	94 Tons
o	Rotor Speed	17.5 RPM
o	Tip Speed	190 MPH
o	Tower Height	200 Feet
o	Nacelle Weight	94 Tons
o	Total Weight of WTG	314 Tons (Approx.)
o	Cut-In Speed	14 MPH
o	Cut-Out Speed	60 MPH
o	Electronic Controls	Microprocessor

This low output and capacity factor (16 percent in 1984) are attributed primarily to various unforeseen problems with the machine that have occurred over the last two years. These include:

- The need to install small metallic strips as vortex generators to improve the aerodynamic efficiency of the blades
- Work on the variable pitch control system
- Blade stress situations that were related to differing wind speeds and directions at various levels across the blade
- Replacement of a cracked, low-speed shaft
- Overheating of the main shaft bearing caused by poor startup lubrication

Even though these problems were serious, they have been solved and 1985 performance has improved significantly over 1984. Ironically, while the PGandE machine has contributed valuable research information, two factors, which have indirectly come from its development and operation, will most likely limit the commercial development of large multi-megawatt wind turbines—cost, and the complexity of development of designing for a varied wind resource across large rotor areas.

Even in mass production, without federal assistance the costs to install and operate a MOD 2 type machine will not be competitive with smaller wind machines. For comparative purposes, the PGandE 2.5 MW MOD 2 cost $4800/kW installed and has produced 7000 MWhr in three years of operation. TERA Power Corporation has operated 50, 50-kW machines (2.5 MW) at an installed cost of about $3000/kW for only two years and has produced 8.5 million kWhrs. The principal reason for this better performance with smaller machines is availability. As will be discussed later, small machines have had a large number of problems, perhaps more than PGandE's MOD 2. However, the number of machines deployed per megawatt improves availability and thus production. For example, each problem on the MOD 2 takes 2.5 MW offline. Similar problems on a smaller machine take only 0.05 MW offline.

The second issue of the effects of a site's vertical wind resource on large blades poses tremendous uncertainty. As more data are collected, shifts in wind directions and speed at varying heights are showing that many wind sites may be limited to machines that remain within the first 200 feet above the ground surface. Because of these issues, multi-megawatt technology does not appear ready for commercialization. Small machine technology does appear to show promise.

Small Machines

Starting in 1973, federally funded research on small machines took place mainly at the DOE Sandia Laboratories in Albuquerque, New Mexico, and at DOE's Rocky Flats facility.

Vertical Axis Machines. Sandia focused principally on vertical axis technology. Vertical axis machines represent an important airfoil distinction because each blade section experiences a constant angle of attack during one rotation, whereas in horizontal axis machines, each section of blade experiences a varied angle of attack during one rotation [10]. With all major components on the ground (Figure 5), vertical axis machines

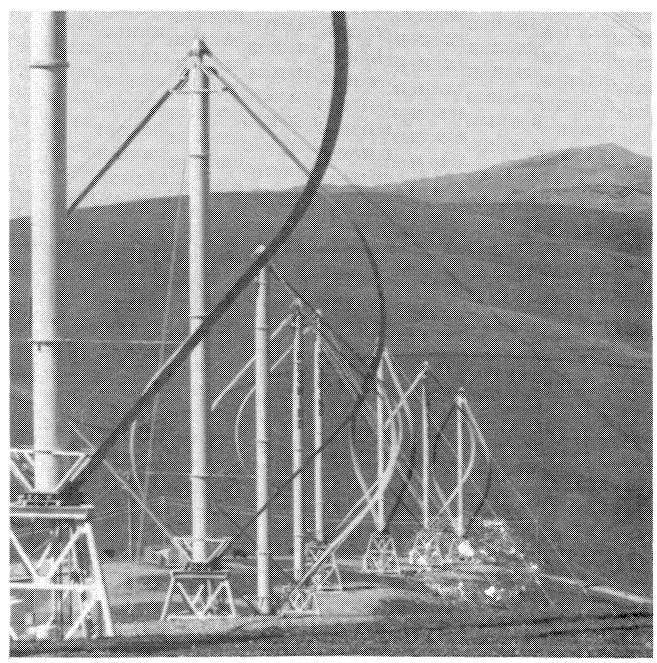


Figure 5. Typical Vertical Axis Machine.

held the potential for reduced maintenance costs. This advantage is discounted somewhat because the vertical axis machine, being close to the ground, has to deal with more turbulent winds.

Horizontal Axis Machines. The Rocky Flats R&D program provided the basis for the development of many of the existing small horizontal axis machines in use today. Working with 1 kW, 4 kW, 8 kW, 15 kW, and 40 kW capacity units, extensive testing in extreme weather conditions was conducted [4]. About 80 percent of the machines installed in California are horizontal axis machines.

Some of the major small machines designs in use today are shown in Figures 6 and 7. While the federal government has funded both large and small machine research, the private sector has advanced the small machine to commercial status. Because of the significant economic incentives provided by Congress in 1978, private investment has surged. The Public Utilities Regulatory and Power Plant Act of 1978 required all utilities to buy power from private generators at the utilities' avoided cost. That, in combination with large tax credits for alternate energy investment, has put over three billion dollars into California wind development since 1979 with almost all of that money going towards machines rated at under 150 kW [10]. This was principally due to the cost and perceived risk of large machines (six to ten million dollars for a MOD 2), compared to small machines (93,000 to 150,000 dollars for a 50 kW machine).

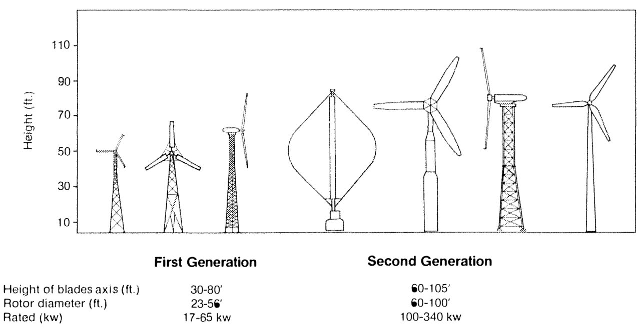


Figure 6. Various Small to Medium Size Wind Turbine Generators That Have Been Developed Through Federal Assitance and Private Investment.

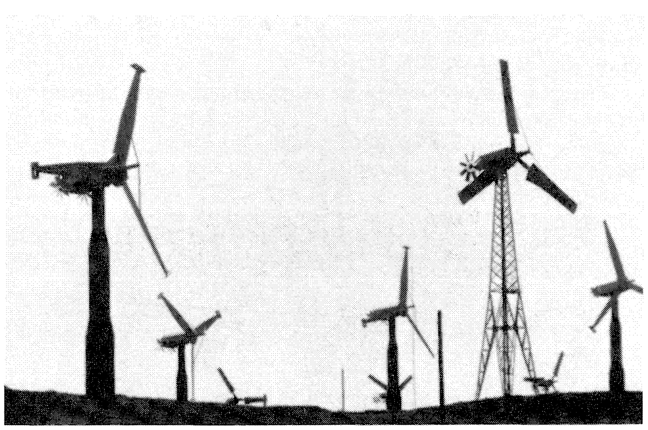


Figure 7. Various Small Wind Turbine Generators That Have Been Developed Through Private Investment.

CALIFORNIA PERSPECTIVE

The combination of high avoided cost, positive government regulation, and excellent wind resources located in lightly populated areas has placed California wind development in the leading position both in the United States, and the world. How the industry has grown since 1981 is shown in Table 3 [11]. Installed capacity is over 609 MW. This could possibly double by the end of 1985. The number of machines is approaching 10,000, and each year the average price per installed kW has dropped, from $3,113/kW in 1981 to $1,860/kW in 1984. Projects under construction in 1985 will be sold to investors at a price range of $1350-$1700/kW.

Table 3. Status of Wind Development in California [9].

	1981	1982	1983	1984
Number of Turbines Installed (Cumulative)	144	1,289	3,782	8,469
Number of MWs Installed (Cumulative)	7	71	243	609
Average Size of Turbines (kW)	49	56	69	78
Average Size of Projects (MW)	.9	2.4	7	11
Average Capital Cost (84$)	3,113/kW	2,175/kW	1,900/kW	1,860/kW
Kilowatt Hours Generated (Millions)	-	5	50	195

Such prices for wind generation compare very favorably with other electric-generating resources available in California or under consideration as future generation resources as shown in Tables 4 and 5 [1]. Competitive prices, short lead times for installation, and the use of third-party capital have led all major utilities in California to adopt aggressive alternative energy policies.

Table 4. Comparison of California Generation Alternatives 1984 Constant Dollars [1].

GENERATION RESOURCE	SIZE	COST OF POWER (¢/kWh)	CAPACITY COST ($/kW)
NUCLEAR	2 x 1,200 MW	13.84¢	$5,546
COAL			
California	2 x 800 MW	11.71	2,692
Non-California	2 x 800 MW	8.52	1,952
Fluidized Bed	2 x 500 MW	12.78	3,297
OIL FIRED	500 MW	15.97	858
COMBUSTION TURBINE	4 x 75 MW	17.72	459
HYDROELECTRIC			
Small	5 MW	8.52	3,379
Major	50 MW	10.65	3,308
WIND ENERGY	400 x 100 kW	9.50	1,550

Table 5. Comparison of California Generation Alternatives 1990 Nominal Dollars [1].

GENERATION RESOURCE	CAPITAL COST ($/kW)	COST OF POWER (¢/kWh)
NUCLEAR	$3,056 - 5,492	14.9 - 23.0
COAL	3,151	19.8 - 24.9
OIL	1,325	17.5 - 30.0
GAS	1,325	15.8 - 28.4
GEOTHERMAL	1,096 - 1,612	15.4 - 16.6
HYDROELECTRIC	911 - 3,068	5.4 - 16.2
WIND POWER	1,485 - 2,188	7.5 - 11.0

* Assumes power deliveries begin in 1990

For example, Figures 8 and 9 show that PGandE, after the additions of its Diablo Canyon Nuclear Plant and Helms Pumped Storage Project, plans for all new resources over the next ten years to be alternative energy resources (Figures 8 and 9). Wind will represent seven percent of PGandE's 1994 capacity [9]. This is in line with California's goal of producing ten percent of the state's energy from wind by the year 2000.

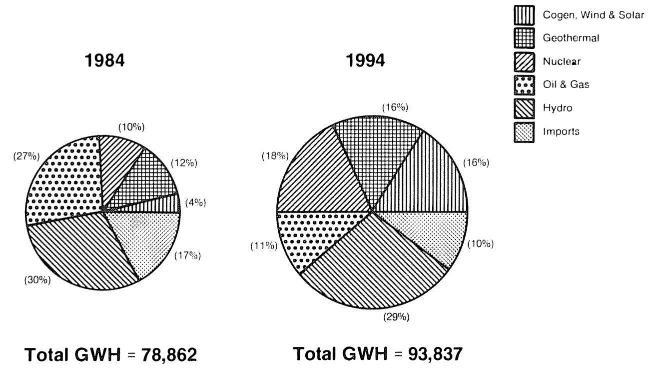


Figure 8. PGandE Energy Mix, 1984 and 1994.

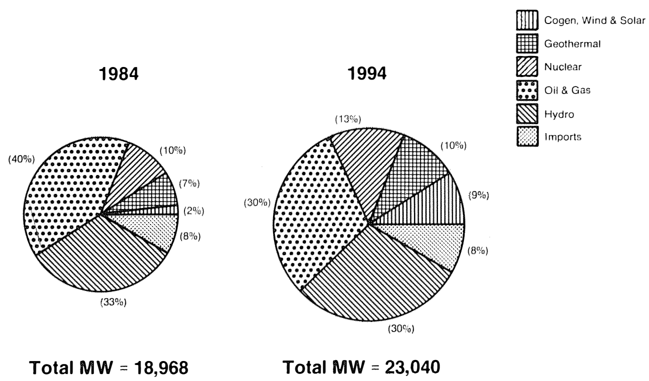


Figure 9. PGandE Capacity Mix, 1984 and 1994.

EARLY PROBLEMS

While these numbers are positive, many problems have occurred over the first few years of development. These include financial, technical, and land use issues.

Land Use. While wind power is considered environmentally clean (no air pollution) as compared to converted oil, gas, and coal plants, the installation and operation of thousands of turning machines has created some land use issues. In areas like the Altamont Pass (40 miles east of San Francisco) and the Tehachapi Mountains (south of Bakersfield), the remoteness of the location has reduced the concerns of erosion and noise impacts. As a result, wind power development has had its largest development in these areas.

Conversely, in San Gorgonio Pass, near Palm Springs, the proximity of a fairly large population has resulted in significant regulatory problems. The potential for major visual, noise and erosion impacts resulted in a two year permit process designed to plan and resolve potential issues. As can be seen from Figure 10, visual pollution is potentially a very strong issue with wind development. As a result, in 1985, with limited development in progress, a law suit by the citizens of Palm Springs over environmental review procedures, threatens to delay certain future development. Even with this possible constraint, over 150 MW of capacity is in operation in the San Gorgonio Pass area.

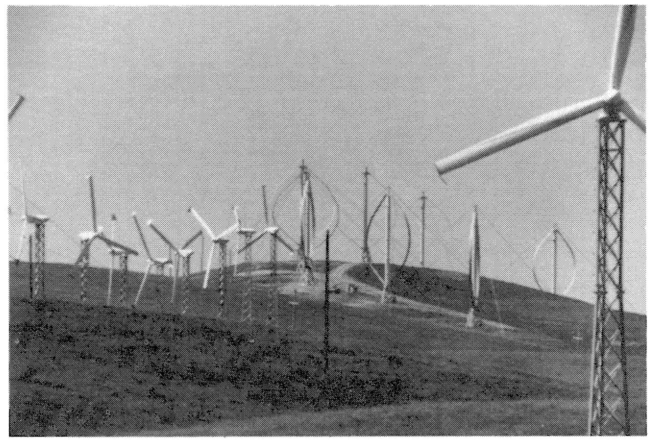


Figure 10. Potential Visual and Soil Erosion Impacts from Wind Development.

Technical. Concerning the technical problems, many designs have failed, some totally and some partially. In 1982, one day before a major state conference in Palm Springs on wind development, a 500 kW vertical axis test machine located at Southern California Edison's wind test facilities destroyed itself in less than three seconds. The problem was software-related in the brake control system. Later that same year, a young machine designer fell to his death while manually trying to turn one of his machines out of the wind after it and half a dozen other machines at the site had brake failures and began to lose blades (Figure 11). Other machines have experienced less dramatic problems that have required major retrofits as improvements have been developed. Some examples of these types of problems are outlined later. In many instances, certain designs have never been developed or, once developed, never worked properly. As of 1985, there are at least half a dozen solid domestic machines and an equal number of foreign machines that have successfully run in large numbers over the past three years.

Financial. Over the last six years, wind project financing has consisted of a number of forms:

- Limited partnerships to individuals or corporations
- Sales to large brokerage houses that in turn sell the machines as partnerships
- Leveraged lease deals with corporations
- Projects financed by banks or financial institutions and then sold to general partners

As the industry moves from a tax credit or shelter environment of a conventional financing environment, many problems may occur. Unless federal tax credits are extended, new wind projects will have to be financed from banks or other major

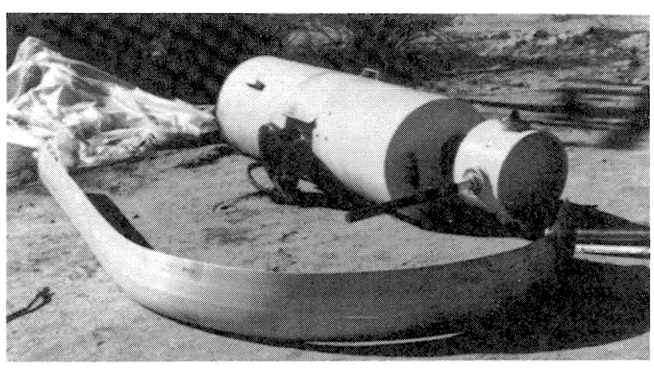


Figure 11. A Destroyed Machine and Twisted Blade After One of the Industry's Early Accidents.

financial institutions similar to real estate projects. The major problem that may occur will be the lack of extensive operational experience, particularly on later, improved scale-ups of small machines, to satisfy conservative lending institutions.

WIND PROJECT DEVELOPMENT—ALTAMONT PASS

Siting a Wind Project

In 1979, PGandE and the California Energy Commission began to conduct wind energy assessment studies in northern California. Using historical information, they selected various locations to install anemometers to measure annual wind speeds. In Altamont Pass, these studies were conducted until late 1981 and showed that Altamont Pass had an excellent wind resource with an annual mean wind speed in the range of 15 to 18.6 mph.

At this point, private developers began to negotiate for leases with land owners and to place their own anemometers on various pieces of land to assess the local wind resource. Given the vastness of the areas (thousands of acres), limited information was refined by going out on windy days to fly kites. While it may sound strange, kite-flying provides a fairly accurate means of assessing the affects of topography on local wind currents. Such methods were used to determine specific machine locations. Since in most major California wind areas, the wind blows in predominantly one direction, most machines are oriented in rows perpendicular to the wind. Down-wind spacing to avoid long-term rotor turbulence effects is usually between five to seven rotor diameters. A typical Altamont Pass wind farm with substation and parallel rows of machines is shown in Figure 12.

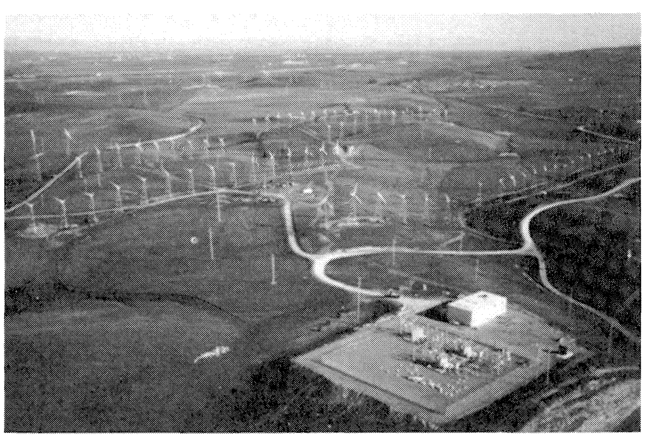


Figure 12. A Typical Wind Farm Layout with Substation and Rows of Machines.

The Wind Resource

The wind resource of the Altamont Pass is very reliable. Every year starting in March, the combination of warming temperatures in the California Central Valley (high pressure) and cool arctic currents off the coast (low pressure) of California, create conditions that draw cool heavy moist air into San Francisco Bay and through the low passes of the California coastal mountains. One such pass is the Altamont Pass near Livermore, California.

As spring progresses to summer, coastal water upwelling and temperatures in the high 90s and low 100s in Central California increase wind movement. The classic annual cycle of average monthly wind speed averages for Altamont Pass, along with a probability range for annual averages near TERA Power's Delta Energy Project Site is shown in Figure 13. During the summer months, monthly average wind speeds can range from 20 mph to 30 mph with some 24 hour periods equalling 40 mph. Peak gusts of 60 mph are not uncommon during certain weather cycles.

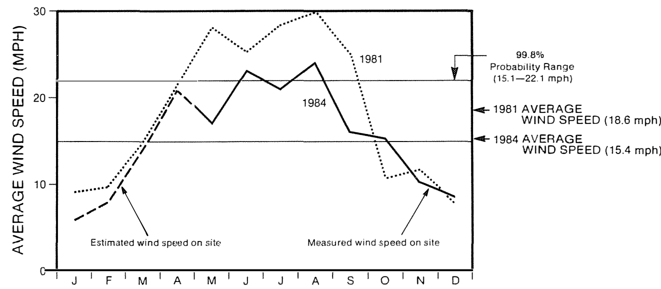


Figure 13. Typical Altamont Pass Annual Wind Cycle Shown with 1981 and 1984 Wind Data from TERA Power Corporations Delta Energy Project.

On a daily basis, winds in the Altamont Pass typically begin in the middle to late afternoon, peak from midnight to six a.m. and taper off by noon. While occurring on an average basis, this type of cycle does not happen every day. This points out one of wind power's major disadvantages, that it is a nonfirm resource for utility planning and as such cannot be dispatched.

Wind Resource Engineering

Since 1981, considerable amounts of data have greatly improved the understanding of the wind resource on a macroscale, and the microeffects of topography and machine siting on machine operations and performance. For example, TERA Power Corporation has installed a computerized project monitoring system that collects wind speed data from 132 locations, at its 500 acre Delta Energy Project site, eleven at independent locations and 121 at machine locations. The data from this system will expand the understanding of site-specific wind resource and machine interations, and improve siting techniques in the future.

These types of data helped PGandE determine possible causes for operational problems with the MOD 2. Their extensive wind data collection found that wind shear, which is the change in wind speed and direction at different elevations, significantly affected machine performance. On a large blade such as a Mod 2 (300 ft), different wind speeds in different directions create very complex loads on rotating equipment.

At TERA's Delta site, turbulence close to the ground could create long-term equipment fatigue on machines. The data produced by such wind resource evaluations are being factored into machine design and siting criteria so that long-term improvements in performance with reduced maintenance costs can be realized.

TERA POWER'S DELTA ENERGY PROJECT

In 1982, TERA Power Corporation installed the first five units of its 200 wind turbine generators at the Delta Energy Project. The project covers 500 acres of land which is leased from the Department of Water Resources (DWR). DWR is a state utility which conveys water and power throughout California. TERA sells power to DWR for use in its South Bay Pumping Plant, where the energy is used to pump water to the Santa Clara Valley (Silicon Valley).

Since 1982, TERA has installed 145 machines, with an additional 55 to be installed in 1985. The machines are downwind horizontal axis machines rated at 50 kW at 30 mph. The machines have a 54 foot rotor diameter, cut in at 14 mph and can generate a peak capacity of 95 kW in 45 mph winds (Figure 14). When completed, the Delta Energy Project will provide 15 MW of peak capacity and approximately 40 million kW per year of energy to the Department of Water Resources. As of May 1, 1985, the project has produced over 13 million kWhr, 50 percent of that energy being produced since August 1984. Machine availability for the project was above 90 percent for 1984.

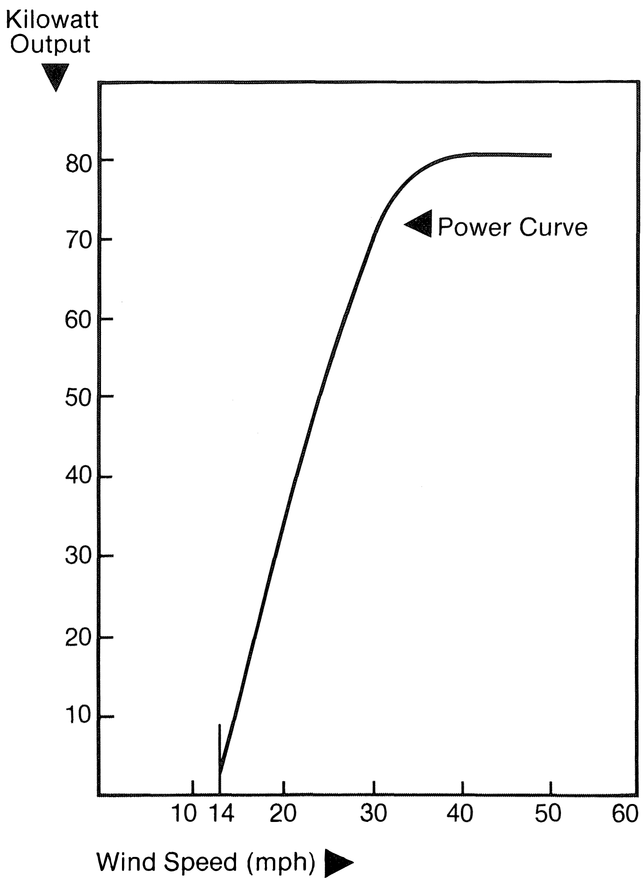


Figure 14. Power Curve for an ESI 54's Wind Turbine Generator.

Construction

Wind energy project construction is simple compared to conventional power station construction which TERA Corporation has managed in the past. Each machine requires a foundation of three 12 foot concrete piers. An 80 foot latticed tubular tower is bolted to the foundation and the machine and blades are mounted on the towers (Figure 15). Each tower is hinged so that it can be raised and lowered by a crane for major maintenance work. All electrical and control wire runs are underground in conduits and are collected in a cinder-block control building. Each machine control panel is mounted inside the control building and wired. Each control building handles eight to sixteen machines and has one or two pad-mounted 500 or 750 KVA transformers used for step-up from 480 V to 12.47 kV. Breakers at each control building range from 800 amps to 1600 amps.

A single three-phase pole line collects site generation and delivers power to a substation onsite, where 12.47 kV is stepped down to the 4160 V power needed to run DWR's pumps. Installation of 85 machines and support facilities was accomplished in six months.

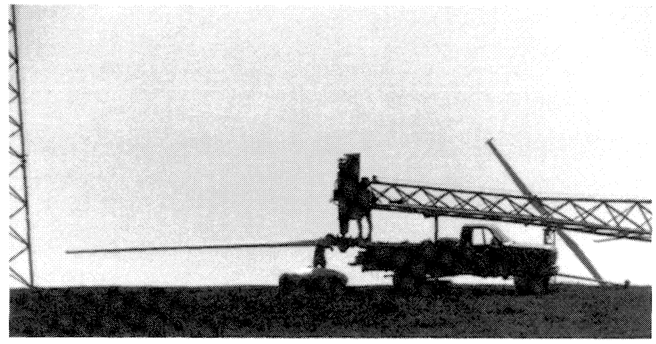
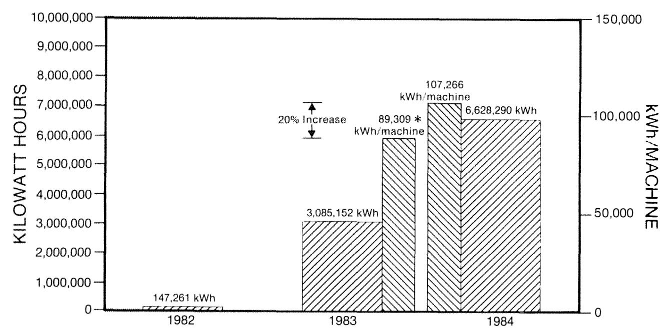


Figure 15. ESI Maintenance Crews on the Ground Conducting Major Maintenance Work.

Operational History

Annual energy production since 1982 for the Delta Energy Project is shown in Figure 16. Per machine production increased 20 percent from 1983 to 1984. This improvement resulted from improvements in maintenance and operating procedures. Since 1982, a number of problems have been encountered in the machines. As each problem has occurred, the user has worked with ESI to assess the problem and develop prudent analytical methods to solve the problem. A brief, but more detailed review of the major problems and solutions encountered over the past two years should provide an example of the wind industry's technical maturing process, and why future larger machines should be more cost effective.



* 1983 value has been extrapolated to reflect a full year's operation based on 6 months of actual operation.

Figure 16. Annual Energy Production, TERA Power Corporations Delta Energy Project.

PROBLEMS AND SOLUTIONS

The problems and associated solutions that TERA Power has experienced with its ESI-54 machines are listed in Table 6. Problems are to be expected with any new product. In any case, the manufacturer and TERA Power have responded to the problem by applying well-balanced engineering, testing, and management methods. It is important to note that the ESI-54 machine was a predecessor to the ESI-80, a 250 kW rated machine at 30 mph. This second generation scale-up of the ESI-54 has had all the improvements developed for the ESI-54 incorporated into its commercial design. The ESI-80 is being deployed in 1985 at a cost of between $1100 to $1500/kW, depending on the site wind resource and substation needs.

Cracked Transmission Feet

Problem. In late 1983, small cracks were discovered in gearbox feet on machines that had run more than 3000 hours. ESI engineers responded by strain gauging the troubled area and monitoring stress levels during various operating conditions. At the same time, a structural analysis was performed by using both textbook strength-of-material equations and finite-

Table 6. Problems and Solutions Encountered by TERA Power Corporation with the ESI 54 Wind Turbine Generator.

PROBLEM ENCOUNTERED		SOLUTION
1)	Cracked Transmission Feet	a) Design Improvement b) Material Improvement c) Tip Brakes to Reduce Peak Loads d) Low Power Braking e) Soft Starting
2)	Tip Brake Nuisance Deployment	a) Electromagnet Tip Mechanism
3)	Brake Failure	a) Alternate Supplier of an Industrial Rated Brake b) Reduce Braking Demands Using Active Control of Tip Brakes
4)	Coupling Failure	a) Proper Alignment Spe ification b) Accurate Alignment Technique
5)	Insect Degraded Performance	a) Use the Roughness Insensitive LS(1) Airfoil
6)	Lower than Projected Performance	a) Improved Availability Due to Fixed Problems b) Improved Airfoil Performance in Varied Environmental Conditions

element computer modelling of the foot with predicted loads applied. Since the gearbox supplier was responsible for the design of this custom housing for their standard gear package, the user had no previous analysis to fall back on.

After the foot design was studied, it became clear that the casting was poorly designed. The web that supported the foot was ⅜ in thick, while the main portion of the foot was a 1½ in thick cantilevered beam. Since the web was thin, it cooled quickly during casting, forming a fine-grained structure. This led to a brittle material. A thicker web would have reduced stresses and improved material properties.

Solution. The first, most obvious solution was to change the foot design to reduce the stresses. A solid web was installed on all new gearboxes and the material was changed to a ductile iron casting. Since implementing this new design, there have been no problems. To prevent cracks from occurring on existing units in the field, a torque bracket has been designed which shares the torque loads and reduces the foot stresses to 30 percent of their original values. This improvement on the larger ESI 80 (250 kW) machines is shown in Figure 17.

Tip Brake Nuisance Deployments

Problem. The purpose of tip brakes is to slow down the rotor speed in overspeed conditions. The first design used a tip brake deployment mechanism which relied on a shear wire to break if centrifugal loads exceeded a safe limit (Figure 18). After deployment in the field, it was found that, in very high winds, tip brakes would deploy even though no overspeed had occurred. Such deployments took machines out of service when they were producing most of their power. The normal resetting of these tips required maintenance personnel to climb machines in high wind and nighttime conditions.

To study the problem, ESI designed a strain gauge transducer to measure loads acting directly on the shear wire. After many hours of monitoring shear wire loads in various wind conditions, it was discovered that a 20 Hz oscillating load was superimposed on the steady centrifugal load. The amplitude of this oscillating load was only a few percent of the steady load in medium winds, while in high winds it increased to a peak-to-peak value of 30 percent of steady shearing load. This was enough to accelerate fatigue in the shear wire. Using accelerometers mounted in the blade, the source of this 20 Hz load was discovered to be a very minor edgewise acceleration in the blade, which excited the shear wire counterweight. These accelerations resulted in forces acting on the shear wire.

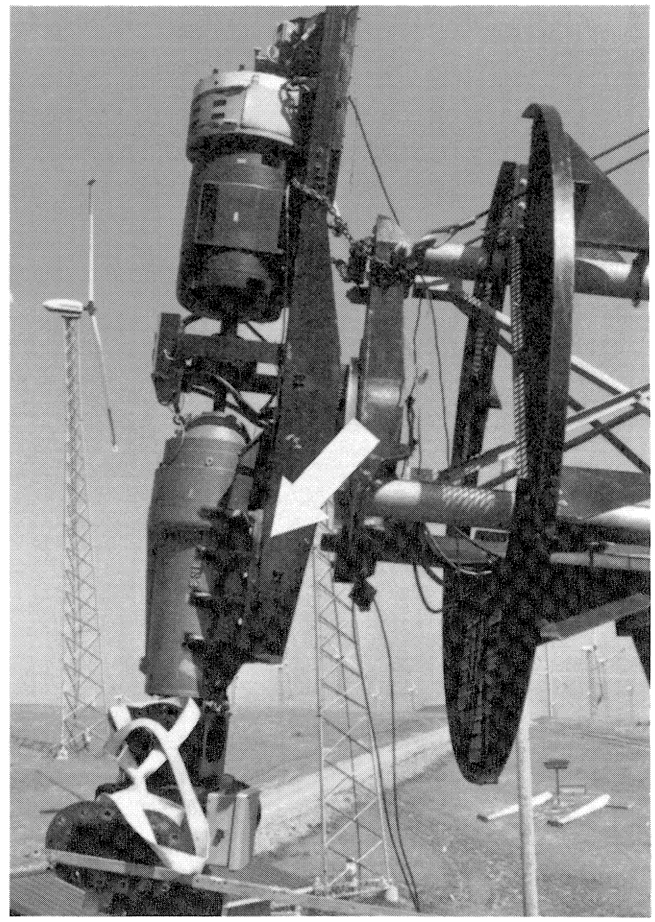


Figure 17. Improved Transmission Feet on an ESI-80.

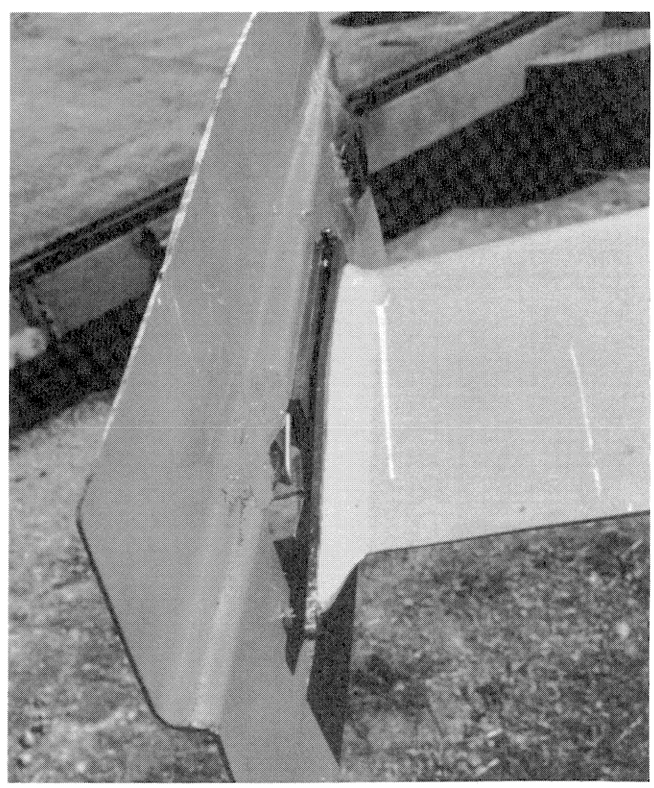


Figure 18. Old Style Shear Wire Tip Brake or Vane.

Solution. Use of an electromagnet to hold the tip vane in the run position eliminated the counterweight, which was sensitive to inertia loads. It also resulted in a system which is insensitive to fatigue. By killing power to the magnets, the systems can be used actively as an aerodynamic brake for the relatively infrequent high power stops, which are the only demanding stops on the mechanical brake.

By going to an electromagnetically held tip brake mechanism, nuisance deployments were solved, time-consuming manual resets were eliminated, and brake loading in high wind shutdowns was reduced (Figure 19). Using the electromagnetic braking has also indirectly solved braking problems outlined later in this paper. This system has been implemented on all new ESI machines and is being retrofitted onto older units. All parts are stainless steel except the magnet parts, which are plated. The vane is made of fiberglass for lightweight but stiff construction (Figure 20).

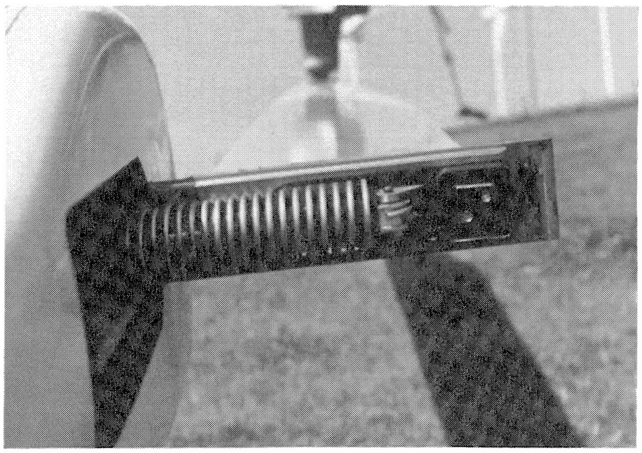


Figure 19. New Electromagnetic Tip Brake Assembly—Deployed Position.

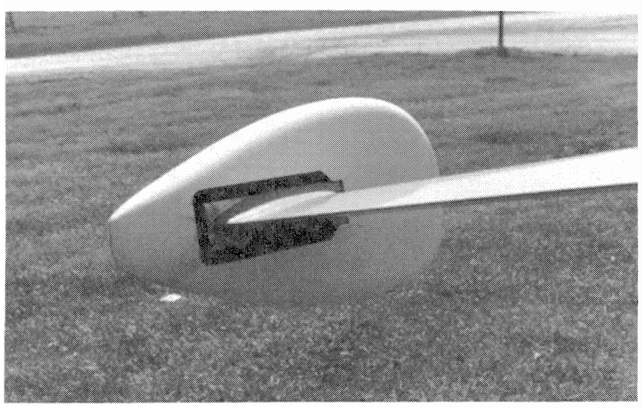


Figure 20. New Tip Brake in Operating Position.

Brake Failure

Early Problem. The original brake on the 1982 and 1983 ESI machines was a fluid disc brake. The brake was rated to stop the machine under full load; however, excessive wear on 100 percent of the units in operation caused excessive maintenance costs and downtime. After rechecking the original analyses to confirm the braking torque and braking energy required, and performing field tests, the manufacturer was confident that the specifications were correct.

Solution. The original brake was replaced by a friction plate brake after extensive proof testing. A test stand was designed so the manufacturer could cycle the brake at maximum braking energy once every two minutes for 1000 cycles. The friction surfaces were contaminated with grease to test loss of torque. All these tests demonstrated that this brake was appropriately sized and truly rated for the specific loads.

Field tests on operating machines proved to be consistent with the proof test results. Even after thousands of operating hours the brake demonstrated consistently less than 0.010 in wear.

Later Problems. Following the transmission and brake retrofits in late 1984, failures began in the high speed gear carriers on a few machines. These failures occurred mostly at the same location and resulted in the loss of drive train and primary braking systems (Figure 21).

Solution. To solve this problem, braking torques were reduced through the use of a low-speed braking system. Under prior operating conditions, air pressure was released instantaneously to apply the spring-loaded brake. With the new braking system, air is gradually released in two stages so that braking torque loads are spread out.

This solution, along with the addition of actively controlled tip brakes, has reduced the loads on the drive train and brake. This type of braking has been implemented on both new ESI-54 and ESI-80 machines with great success.

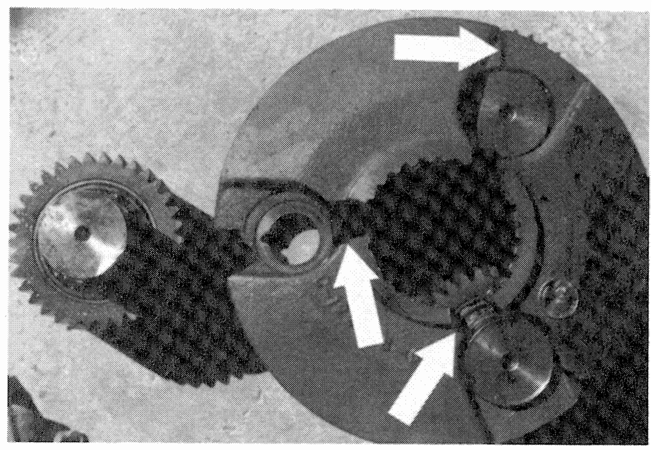


Figure 21. High Speed Carrier Gear Failure.

Coupling Failures

Problem. After several thousand hours of operation, about 20 to 30 of machines' gear couplings wore excessively. The cause was not obvious, because the coupling was rated for nine times the peak load being applied, and alignment was being performed to the manufacturer's written specification.

Consultation with the manufacturer revealed that the alignment specifications printed in their literature were ambiguous. A well-defined specification showed that maintenance personnel had been allowing too broad a tolerance on their alignment procedure. Another problem that occurred frequently was the loosening of the taper lock fittings and the slippage of the couplings along the shaft.

Solution. To more accurately align the couplings, a method was employed that used two dial indicators and a graph. Alignment measurements were plotted accurately on the graph to within 0.001 in of parallel and angular alignment. This method was far more accurate than the feeler gauge method previously used. The final alignment could be plotted graphically, ensuring documentation of quality control. This method is now universally used in production and in maintenance. To eliminate any potential taper lock fitting slippage, a heat shrink fit was substituted for the taper locks.

Insect Buildup on Blades

Problem. The ESI-54 was designed with a relatively high performance airfoil common to helicopter and gyrocopter design. This very common airfoil has been used on wind turbines because its high lift and low drag guarantee peak performance. After initial operation of a large number of machines in 1983, it was found that wind turbine performance was better than predicted until airborne insects built up along the leading edge of the airfoil. After significant insect build up, machine performance dropped dramatically as shown in Figure 22.

After some research, the manufacturer found that the airfoils performance was particularly sensitive to leading edge roughness. Because the pressure (suction) acting on the leading edge is very high compared to the trailing edge, any roughness would cause separation of the air passing over the leading edge, destroying a large percentage of the total lift on the

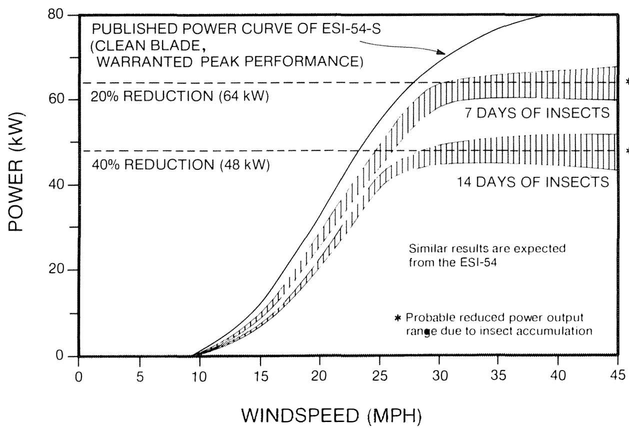


Figure 22. Effects of Insect Build-Up on Power Curve.

airfoil. This pressure distribution, which is normally good for clean blade performance, adversely affects performance on dirty blades.

Solution. Short-term, the blades were manually washed every three to ten days. By 1986, existing blades will be retrofitted with a polyurethane coating which will allow high pressure water to wash blades from the ground. Long term, the manufacturer has found an airfoil which is insensitive to the effects of insect accumulation or leading edge roughness. The new blade allows the pressure distribution to be flat from leading to trailing edge, instead of relying on leading edge pressure to develop most of the lift. This assures that the blade will stall from the trailing edge. This same airfoil has been used in aircraft to improve wet-weather flying performance.

This airfoil has been used on the ESI-80 and has proven to be a great improvement over the ESI-54 dirty blade performance. Bug, oil, or dust build-up have not degraded performance to any measurable extent on the ESI-80, while ESI-54s continue to require periodic cleaning.

CONCLUSION

As of 1985, a number of small wind turbine generators have been scaled up to medium size machines (200-400 kW). This scale-up has occurred based on sound operating history and design improvements. On TERA Power's Project, each month of operation is seeing continued improvements on machine performance and revenue generation. Availability is over 95 percent through April 1985 and no major problems have occurred since mid 1984.

The industry as a whole is struggling to make the transition to larger cost-effective machines before the federal tax credits disappear in late 1985. Those manufacturers and developers that have a good track record of performance and a scaled-up product should succeed in producing power from the wind at a reasonable cost.

As improvements on the second generation or medium size machines occur, utilities will begin to consider wind projects as viable investments. Using standard utility financing with a 30 year levelized price, these machines can be installed and operated between 7.5 and 9.5 cents per kWhr in 1984 dollars. With ever increasing fuel prices, using wind energy as a reliable part of this nation's electric generation resources will continue. The rate at which that occurs will depend primarily on the acceptance by financial institutions of the possible risks given the limited operating history of the second generation machines.

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