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ABSTRACT

Recent studies have shown wind power to be an eminently practical and potentially substantial source of electricity and direct mechanical power. Wind machines range from simple water-pumping devices made of wood and cloth to large electricity producing turbines with fiberglass blades nearly 300 feet long. Wind is in effect a form of solar energy--approximately two percent of the sunlight that falls on the earth's surface is converted to the kinetic energy of wind through a system in which warm and cool air move in different patterns. Wind power, which was first considered by planners and the business community as a serious power source only after the oil embargo in 1973, is already an economically attractive source of energy in many regions. It has been estimated that approximately one million mechanical wind pumps are in use today, predominantly in Argentina, Australia, and the United States. To help realize the full potential of wind power technology, several developments are necessary, including new designs which can operate in the often harsh conditions of developing nations and an increased infrastructure that includes a market for spare parts and repair services. The conclusion is that wind power and other renewable energy sources can make a substantial contribution to energy needs in the near future. The implication is that governments should continue to fill wind power research gaps and should increase support of development efforts. (DB)

Wind Power: A Turning Point

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Wind power may be a breath of fresh air on the world energy scene during the eighties. Already in 1981, wind energy is a rapidly expanding field with far more immediate potential than most people realize. The ambitious and largely successful research and development efforts of the seventies gave rise to a variety of commercial ventures and utility programs to harness the wind. In many countries, substantial numbers of wind machines are being installed for the first time in over 50 years. Behind these developments are a wealth of recent studies showing wind power to be an eminently practical and potentially substantial source of electricity and direct mechanical power.

Combining ancient ideas with modern materials and principles of aeronautical and electrical engineering, current wind-power technology is a model of what a marriage of old and new can yield. Today's wind machines range from simple water-pumping devices made of wood and cloth to large electricity-producing turbines with sleek contours and fiber-glass blades nearly 100 meters long. Different machines suit different uses, locations, and wind regimes, and improvements on the various designs are being made rapidly. Although considerable research remains to be done, even today—only eight years after the oil embargo first encouraged planners and the business community to consider wind power seriously—the wind is an economically attractive source of energy in many regions.

A sizable and growing market for wind machines exists in remote areas where diesel engines and small electricity grids provide expensive pumping power and electricity. In Australia, South Africa, and parts of Africa, Asia, and Latin America, wind-driven irrigation pumps are enjoying a renaissance. Small electricity-generating machines are also becoming popular, particularly in parts of North America and northern Europe. These technologies are fairly mature, having been in use for decades, but significant cost reductions lie ahead as they are improved and as more are produced. Many farms and homes may soon use the wind to generate electricity for less than it costs from the local utility.

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It will take just slightly longer for large wind turbines to make a significant contribution to the world's energy supply. They are not simple machines: they involve sophisticated engineering as well as microprocessor-based control systems. Yet large wind machines are well within the reach of modern technology and they are reaping the benefits of advances made in a range of related fields over the last few decades. Economic analyses and early test results indicate that when these turbines are manufactured commercially, they will produce electricity at a price that makes them attractive to many utility companies.

There are still some important unanswered questions concerning this renewable source of energy. Preliminary findings indicate that many countries could harness enough wind to meet a sizable proportion of their electricity needs, but only a few nations have even begun thorough wind-resource assessments. And important institutional, legal, and environmental constraints could limit the spread of this technology. As wind power challenges the traditional monopolization of electricity production, enlightened utility policies are one prerequisite to the advance of wind energy. Television interference and land-use competition are among the environmental problems to be considered if the wind is to become a major source of power.

Individual, government, and business initiatives over the next few years will determine whether the wind's considerable potential is turned into useful forms of energy. At the latest count, over 100 manufacturers worldwide were producing small wind machines for the commercial market. In the United States and a few other countries, many utility companies have wind-energy research projects and several plan to rely extensively on this power source. More than a dozen countries now have national development programs under way—twice as many as in the mid-seventies. The United Nations Conference on New and Renewable Sources of Energy in August 1981 is likely to be a watershed event in the evolution of wind power. Its experts will no doubt strongly endorse its potential, and a variety of national and international programs should result from the conference.

The conditions are ripe for this technology to move quickly from the research and planning stages to commercial reality. Tens of millions of small wind turbines and pumps may soon serve the rural areas of the world, and clusters of large wind machines could be linked to utility grids. Wind power will never be able to supply most of the world's electricity. But in combination with an expanded use of hydropower and the development of new renewable sources of energy, such as photovoltaic cells, much of the world's additional electricity needs can be met. By the early part of the next century many nations could obtain between 20 and 30 percent of their electricity by harnessing the wind.[1] Although perhaps lacking the aesthetics of the traditional Dutch windmill, modern wind-power technologies that take advantage of this clean, economical, and renewable source of energy are certain to have a place in the post-petroleum world. 7

Harnessing the Wind

Wind is in effect a form of solar energy. Sunlight falls unevenly on different areas of the earth, causing some parts of the atmosphere to be heated more than others. Since warm air is lighter than cool air and tends to rise, air moves as a result of this varying heating pattern. Approximately 2 percent of the sunlight that falls on the earth's surface is converted to the kinetic energy of the winds.[2] This is a tremendous amount of energy—much more than is consumed worldwide in any given year. The winds are the engine behind the world's storm systems, bringing rain to areas that would otherwise be dry and occasionally devastating communities in the form of hurricanes or tornadoes. This life-and-death power has assured the wind a place of importance in religions and mythologies throughout the world.

Two basic meteorological phenomena give rise to the bulk of the world's winds. One large pattern of global air circulation stems from cool polar air being drawn toward the tropics to replace lighter, warmer air that rises and then moves toward the poles. Areas of high and low pressure naturally develop and the force of the earth's rotation causes air to circulate clockwise in the southern hemisphere and counterclockwise north of the equator. These broad patterns are responsible for major weather features such as the persistent trade winds in the tropics and the prevailing westerlies found in the northern temperate regions. The second cause of extensive winds is the fact that the air over oceans is not heated as much as the air over land. Coastal winds occur as the cool ocean air flows inland to replace the rising warm air.[3]

8 The net result is dynamic, unstable weather systems of enormous complexity. The thermal energy of sunlight is constantly converted to the kinetic energy of the winds, but wind energy is simultaneously dissipated via friction with the earth's surface and within the wind itself. Only a very small portion of the wind's energy can actually be used. Most winds occur at high altitudes or over the oceans and are therefore inaccessible. Even the most ambitious wind-energy schemes would tap only a small fraction of the total resource, somewhat akin to occasionally lifting a bucket of water out of the Amazon River. The wind is one of the most abundant and easily usable forms of solar energy. It is constantly renewed and, for all practical purposes, nondepletable.

Harnessing the energy of the wind is not, of course, a new idea. Throughout history, sailing ships have transported goods and people, opening up new lands and carrying invading armies to distant shores. Windmills—machines that capture the wind's power to perform a variety of mechanical tasks—were developed later, although the precise time and place of their invention are uncertain. The first references to windmills appear in the writings of medieval Arabs, who described primitive wind machines in Persia in the seventh century A.D. These were apparently developed as early as 200 B.C. and were used to grind grain, a practice that later spread throughout the Middle East. They resembled a merry-go-round with sails and are known as vertical-axis machines, since the sails turn a perpendicular shaft in the center that is attached to a millstone that does the actual grinding. Similar devices were developed independently in China and used there at least 2,000 years ago.[4]

Windmills were introduced in Europe sometime before the twelfth century, apparently by returning crusaders. Although not an indigenous technology, they soon took on an unprecedented importance in medieval Europe, first for grinding grain and later for sawing wood, making paper, and draining water from low-lying farmland. These wooden windmills were horizontal-axis machines, with a drive shaft parallel to the ground and four large blades that could be rotated manually to face the wind. A system of gears connected the spinning shaft to a grinding stone or other device that used the mechanical force. It

"The wind
is one of the most abundant
and easily usable forms
of solar energy."

is this design that evolved into the Dutch version that most people visualize when they think of a windmill.[5]

Sophisticated versions of this technology were found throughout Europe by the fifteenth century. Windmills and waterwheels became the chief supplements of human and animal power, allowing the more efficient performance of routine tasks and greatly increasing the productivity of agrarian economies. At their peak in the seventeenth century there were about 10,000 windmills in England, each with a capacity of perhaps 10 to 20 horsepower, which represented a substantial portion of total energy use in those days. In the Netherlands, which undoubtedly harnessed more wind per person than any other nation, an estimated 12,000 machines were in use at this time, mainly reclaiming inundated cropland.[6]

By the early nineteenth century the use of wind power in European industry began to decline. Steam engines run on coal provided an economical substitute for many of the tasks windmills once performed, although in some nations wind's role continued to grow. Denmark, which largely lacks indigenous fossil fuels, developed improved windmills and used them to supply one-quarter of the country's industrial energy in 1900. In Australia and North America, pioneers in isolated arid regions found windmills were the only way they could obtain precious irrigation and drinking water. Small horizontal-axis machines with a dozen or more metal blades were quickly developed and an estimated six million water-pumping devices were in use in the United States by the late nineteenth century. According to wind-machine expert Peter Fraenkel, the windmill was as important as the Colt revolver in opening the American West to cattle ranching.[7]

An electricity-generating wind machine was developed by an engineer in Denmark in 1890 just shortly after a steam engine first produced electricity. Hooking a windmill up to a generator was not in itself a major technological breakthrough, but it opened up a range of new uses for wind power—from operating light bulbs to running a variety of industrial machinery. A healthy market for these new wind turbines sprang up in Denmark, the United States, and a few other countries during the twenties and thirties. Most of these small machines produced electricity on farms and at other remote locations that lacked access to utility lines. Although the market was not a large one, it was big enough to encourage steady improvements in design and manufacturing techniques.[8]

These wind turbine generators, as they were soon called, were an entirely new breed of wind machine. Engineers soon realized that to produce electricity efficiently fewer and thinner blades were needed. They developed blades that resembled airplane propellers, avoiding the wind drag caused by sail-like blades and allowing for a rapid rotation speed. The new blades were made of improved metals or laminated wood, a material with ample flexibility as well as strength. And the latest technology in generators and transmission systems was incorporated in the new machines.[9]

Yet the golden age of wind power did not last long. From the twenties onward rural electrification quickly eliminated the need for wind machines in much of the world. The new hydroelectric dams and fossil-fuel–based power plants were relatively cheap sources of electricity, in part because they benefited from large government subsidies as the widespread use of electricity became a popular economic goal. The large windmills of Europe soon became historic relics and in North America the farmland of the Midwest was dotted with abandoned machines. The wind continued to provide power mainly in isolated areas where electricity was expensive or not yet available.

Some inventors held on to their belief in wind power, however, and even during the heyday of cheap electricity in the middle of this century, projects to develop larger, more economical wind turbines were launched in a few countries. Researchers in Britain, Denmark, France, the Soviet Union, the United States, and West Germany designed wind turbines with blade diameters of 20 meters or more and with over 100 kilowatts of electrical capacity. These efforts were unfortunately sporadic since there was no sense of urgency to sustain them. The prevailing view of future energy trends left little role for a seemingly antiquated energy technology such as wind machines. Coal- and oil-fired power plants were providing electricity at low and declining prices, and nuclear power was expected to yield unlimited amounts of electricity at a reasonable price. The economics of wind power appeared so poor that the slightest technical difficulties were seen as reason enough to kill most development efforts.[10]

The fate of the Smith-Putnam wind turbine, developed in the United States in the forties, is typical of what happened to most research projects during this period. This wind machine was a technical wonder driven by huge stainless steel blades and with a capacity of 1,250 kilowatts, a figure unmatched by another machine until the seventies. The Smith-Putnam turbine was erected on a Vermont hillside in 1941; it was in operation for only a short time before a structural weakness caused it to lose a blade. The next logical step in any serious development program would have been to improve the design by learning from the problems of the first turbine. In this case, however, an economic assessment carried out by the machine's inventors found that even an improved turbine could not compete economically with prevailing electricity prices. The Smith-Putnam wind machine was scrapped.[11]

The wind-power field lay dormant throughout the next two decades—and it would have remained undeveloped were it not for the energy shocks of the seventies. The current renaissance of wind power can be traced directly to the 1973 oil embargo and the subsequent spiraling energy costs. Dozens of small wind-machine manufacturers have gone into business since then, and research on larger, more sophisticated turbines has been undertaken by both private companies and national governments. Behind these developments is the now widespread belief that wind turbines and mechanical windmills can indeed be economical sources of power in the years ahead.

There is a certain elegance to well-designed wind machines that has helped convince many scientists and engineers of the considerable promise this renewable energy technology holds. The blades of a wind machine typically occupy only a small space, yet theoretically they can harness as much as 60 percent of the wind passing through the area they sweep. Most commercial wind machines are only 20 to 40 percent efficient, but this is a good performance when compared with other energy-conversion technologies. Given the amount of energy they capture, both the material and energy requirements for the manufacture of wind machines are impressively low. As a result, wind machines normally generate enough power to pay back their initial energy investment in less than five years—much quicker than most other solar technologies.[12]

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The fact that wind machines require relatively little energy to build is a major reason for their economic attractiveness. Today's wind-energy technology is already economically competitive in some areas of the world that face high fuel prices. Not only are the machines simple and efficient, but their operation is based on well-established technologies, such as electric generators, propellers, and pumps, that need relatively minor modification. Even more encouraging are expected advances in technologies and production techniques that will bring onto the market machines that are significantly more reliable and less costly than today's models. Just how quickly these improvements will be made is linked to key institutional developments and policy decisions over the next few years.[13]

The bottom line in determining wind power's potential, however, is the dimensions of the resource. The amount of energy available in the wind is critically dependent on its speed—increasing by a factor of eight every time wind speed doubles. A simple calculation shows that a 12-mile-per-hour wind contains fully 70 percent more power than does one of 10 miles per hour. A variation in wind speed of just two miles per hour can therefore easily mean the difference between the failure or success of a wind-energy project. Average annual wind speeds vary from less than six miles per hour in a few regions to nearly 20 miles per hour in some mountainous and coastal areas. The average wind speeds of 12 miles per hour or greater needed for an electricity-producing wind machine to be economical can be found over wide areas. Mechanical water-pumping wind machines can be successfully operated in areas with winds that average as low as eight miles per hour, which includes all but a few parts of the world.[14]

The timing and location of winds are also important determinants of their energy potential. Winds are rarely constant, varying with both the season and the time of day. In general, the more intermittent winds are, the less valuable they are as an energy resource. A second consideration is the correlation between the need for power and the timing of the wind. For instance, wind power may be more economical in northern Europe, where peak electricity demand coincides with higher winter winds, than in parts of the eastern United States, where the greatest need for electricity occurs during the summer doldrums. Geographically speaking, wind energy is of course most valuable in areas where people live and where energy use is high. The enormous

"Today's wind-energy technology is already economically competitive in some areas of the world that face high fuel prices."

wind-energy potential of the Himalayas, for example, is unlikely ever to be tapped to a large extent.

Although they may be constraints on the development of this energy source, the timing and location of the wind do not present the impenetrable barriers that were once assumed. The wind in many populated areas has been assessed as steady enough to be quite a reliable resource. Recently developed analytical techniques can easily determine the potential value of wind power in a particular region based on fairly simple data about air currents gathered over the course of a year. Only a few good inventories have been done as yet, but the information that has been gathered is encouraging. Adequate average wind speeds of 12 miles per hour are quite common and many high-potential sites with far greater winds have been pinpointed. In fact, wind energy is more widely available than most conventional energy resources. Few countries are completely windless, something that cannot be said for coal, oil, or uranium. In many areas there is actually more energy potential in the wind than there is directly from the sun. This is in part because the wind blows at night as well as during the day.[15]

Wind availability is, of course, very localized, and it will be important for each country to get a more accurate reading of the size of this resource and its distribution. Initial assessments in North America and Western Europe indicate that in most northern temperate regions there are good and extensive winds to be harnessed and that some sites, such as mountain passes and coastlines, are exceptionally well suited to wind-power technologies. Preliminary data indicate that many tropical countries located in the trade-wind belt benefit from some of the steadiest winds in the world. Other areas, such as parts of Central Africa or the southeastern United States, appear to have little wind-energy potential.[16]

The next step for most countries is to identify specific areas with good winds and to match them up with energy needs. Because the wind's power can be harnessed by a variety of machines that are suited to different wind regimes and to particular energy requirements, there is a wide range of options. In farming regions where pumping water for irrigation or for livestock is a primary need and where winds are moderate but steady, mechanical wind pumps would be most appropriate. For rural areas with higher winds and expensive electricity, individual residences and businesses might use small wind turbines to meet their power needs. In regions with large urban populations and nearby undeveloped windy sites, a collection of large wind turbines might be suitable. The winds of change are certainly blowing in the right direction, and all three of these methods of harnessing wind energy should develop rapidly in the years ahead.

A Renaissance for Wind Pumps

The technology that opened the American West in the mid-nineteenth century may turn out to be a lifesaver for many semiarid parts of the world during the late twentieth century. Diesel and electric pumps have become prohibitively costly during the last decade, and a cheaper way must be found to bring up the water so desperately needed for irrigation, livestock watering, and general household use, particularly in developing countries. Fortunately, wind pumps are a well-established technology suitable in areas where wind speeds average as little as eight miles per hour, and they are especially appropriate to the modest water needs of homes or small farms. Wind power is also well matched to the task of providing water, since during a brief windless period the user can simply draw on water pumped into a storage tank when the wind was ample. Storing water is far cheaper than storing electricity.

Approximately one million mechanical wind pumps are in use today; most of them are located in Argentina, Australia, and the United States, where they mainly provide water for household use and for livestock. With a pump connected to a well in the ground, the user does not have to depend on a utility company for either water or the energy to raise it. No good estimates are available on the amount of energy supplied by these windmills, but the figure is probably not large. Mechanical wind machines generally have an energy capacity of less than half a kilowatt, so at best the world's wind pumps supply a few hundred thousand kilowatts of power—less than the capacity of a single large thermal power plant. Nevertheless, mechanical wind pumps play a crucial role in the many areas where they are the only economical way to draw water. Coal-fired electricity does not reach parts of the Australian outback, for instance, and getting it there would be prohibitively expensive.[17]

"Mechanical wind pumps play a crucial role in the many areas where they are the only economical way to draw water."

Most mechanical wind machines use anywhere from 4 to 20 blades to capture the wind's energy, which is then transferred by a drive shaft to a pumping mechanism below. The machines can be made of wood, cloth, metal, plastic, or a combination of these materials, with the particular mix depending on the availability of materials locally and their cost. The most common wind pump in use today is the American multibladed fan-type machine. This horizontal-axis design, little changed since its invention in the nineteenth century, is extremely rugged and will operate effectively at average wind speeds of less than ten miles per hour. Most of the parts of these machines, including the blades, are made of metal, and the diameter varies from two to several meters. The cost of wind pumps now sold commercially runs from around $4,000 to over $10,000.[18]

The market for these conventional wind pumps is fairly large and well established. Along with manufacturers based in Argentina, Australia, and the United States, a healthy wind-machine industry can be found in New Zealand, the Philippines, South Africa, and West Germany. Although sales declined somewhat during the fifties and sixties, particularly in the United States, many remote areas never gained access to cheap fuel supplies and continued to rely on wind power. The wind-pump industry has been particularly strong in Australia and South Africa, where the machines are standard equipment on farms and where there is an infrastructure that includes a market for spare parts and repair services.[19]

Since the early seventies the market for wind pumps has increased, although it remains concentrated in those regions where wind machines have traditionally been used. Although the market will continue to grow, it is somewhat limited by the fact that the large farms and deep wells typical of today's agriculture require a larger pumping capacity than windmills can supply. The technology could be used widely in developing countries, but the market there is hampered by its fairly high cost and the absence of institutional mechanisms to encourage its use. Efforts to import machines from other countries for development projects have frequently foundered because the designs were inappropriate for the wind available in the area or were poorly suited to local economic and social customs. Once the well-intentioned outside technical expert has left, the wind pumps sometimes stop working because they need a few minor spare parts or an oil change. In one project in Zambia, the windmills were eventually dismantled piece by piece by local people and used for other purposes.[20]

Solving these problems would both assure a large role for wind pumps and improve the living standards of millions of people in
.6 developing countries. Affordable irrigation projects are one of the most pressing needs in much of Africa as well as in many parts of Asia and Latin America. The diesel pumps that spread rapidly throughout rural areas of the Third World in the sixties and seventies are quite inefficient and increasingly costly, and mechanical wind machines appear to be the most viable near-term alternative. Today, windmills in areas with average wind speeds of at least ten miles per hour provide pumped water at approximately half the cost that diesels do. Recent studies in India found that even in less windy parts of that country, wind pumps are now cheaper to use than diesel ones.[21]

To realize the full potential of this technology in the Third World, new designs for wind pumps are needed—designs that are more appropriate to people's needs and to the often harsh conditions under which the machines must operate. A great deal of research has gone into this problem in recent years, mainly by private appropriate technology organizations supported by national governments and international aid agencies. Some of the most promising programs are those of the Intermediate Technology Development Group (ITDG) in Great Britain, the Steering Committee on Wind Energy for Developing Countries in the Netherlands, and Volunteers in Technical Assistance (VITA) in the United States. Wind-pump experts have considered designs from all over the world and then adapted them to a variety of local conditions and needs.

The sailwing or Cretan windmill, first developed in the Greek islands but now used in several Mediterranean countries, is one traditional design that has received a great deal of attention. This horizontal-axis windmill consists of a rotor with several metal or wooden spokes that have cloth sails stretched between them; the sails are, in effect, the blades of this machine. Cretan windmills are typically from three to six meters in diameter and their sails can be furled or removed during periods of high wind. Although the cloth must be replaced every two to three years, the rest of the machine can last 10 to 15 years if it is well constructed. Thousands of these windmills still provide irrigation water for farms in the arid Mediterranean region. A similar machine is used widely in Thailand, with the sails constructed of bamboo mats, a plentiful local material. Several thousand are in use, mainly for rice-paddy irrigation.[22]

Researchers have been particularly drawn to the sailwing windmill because the design lends itself to local manufacture out of a variety of indigenous materials. Improved versions of this traditional design have been built in Colombia, Ethiopia, Gambia, and India to meet the needs of local farmers. The Omo River project in Ethiopia, for example, significantly improved the sailwing's efficiency by adapting the Greek design and by using a double-acting pump. Similar machines have been tested in Canada, Malaysia, and Sri Lanka recently. India's National Aeronautical Laboratory is one of several institutions in that country doing wind-energy research, and it has built a ten-meter-diameter sailwing windmill that reportedly is more efficient than previous models.[23]

Another innovative design based on traditional windmills is the Savonius rotor. This is a vertical-axis machine typically made of two oil-drum halves mounted around a perpendicular shaft so as to catch the wind. The machine is relatively simple and inexpensive to make but has the disadvantage of being heavy and inefficient. In addition, Savonius rotors have no built-in protection from high winds, so they must be attached to very sturdy towers, which adds to the cost. One partial solution to this problem is to use a wire frame and cloth sails instead of oil drums. Despite these drawbacks, the Savonius rotor does have a considerable number of proponents, and examples of it can be seen at development projects in several countries.[24]

Many windmill development programs in recent years have relied on a variety of materials such as thatch and wood that are both cheap and locally available. This contrasts with earlier projects that emphasized the need to import the latest technologies from industrial countries. The advantage of this new approach is that the projects often directly involve and benefit the rural poor who are most in need of an inexpensive nearby source of energy. Wind pumps can be considered a prime example of what E. F. Schumacher called an "intermediate technology"—one that employs some modern engineering and that is well suited to the capacities and needs of the rural poor, providing jobs and creating a self-reliant community.

Researchers and government planners are now turning their attentio from individual prototype projects to the goal of making wind ma chines an integral part of development in the Third World and t building an indigenous manufacturing capability. To accomplish this they must address a number of problems encountered in some earl projects. Improving the ruggedness and lengthening the life of th machines is the first priority, since a windmill that lasts only a fev years or that falls over in a major storm is rarely economical. Mos wind-machine experts agree that improved engineering and the de velopment of somewhat more modern production facilities will giv windmills a longer life and will allow the quality control needed t turn out a consistently good product.[25] Larger scale production ca also in many cases lower the cost of wind pumps. Fortunately, a num ber of the designs developed recently are well suited to productio in rural workshops or village factories. Some of the parts can be im ported if necessary, but most of the manufacturing is well withi the range of rural industries.

Las Gaviotas, a rural development institute in Colombia funded by th United Nations and the Colombian Government, has taken a leader ship role in this area. Researchers there spent six years carefully de signing a reliable and inexpensive fan-type wind pump that function in low winds and that is well suited to providing a family's wate supply or to small-scale irrigation. A medium-sized production facil ity has been built to turn out 1,400 windmills a year, and the govern ment is placing the wind machines in rural areas throughout th country. The Las Gaviotas factory takes advantage of plentiful loca labor to produce an inexpensive machine that is also technologicall one of the best anywhere. This program is unique in both its scal and approach, and it has been widely acclaimed by experts througho the world.[26]

A similar strategy is now being emphasized by the London-based Intermediate Technology Development Group, which has developed a prototype fan windmill it hopes one day will be produced by local industries in many different countries. ITDG's machines are some- what larger and more expensive than the Las Gaviotas model, but they are impressively rugged and cost considerably less than most other machines on the market. A small firm in Kenya has begun man- ufacturing an ITDG-designed wind machine, and is successfully mar- keting it to commercial ranchers and development projects in that country. Similar machines are likely to be manufactured in India and Pakistan in the near future. Researchers at ITDG note candidly that their machines are still too expensive for most Third World peasants to buy without subsidization, but they believe that establishing an industry and a market that serves the slightly wealthier farmers is a necessary prelude to getting low-cost machines to the rural poor.[27]

Other appropriate technology groups are less convinced that this is the most effective way to increase the use of wind machines in developing countries. Some veteran windmill advocates, such as Ken Darrow of Volunteers in Asia, believe that the factories should be smaller, that they should depend more on local materials, and that the prospective user of the wind machine should be more directly involved in the manufacturing process.[28] This approach has, for instance, been successful in Thailand, where inexpensive wind pumps are now widely used. In fact, varying approaches will probably work best in different societies and economic conditions, and it is impossible to prescribe a single strategy that will work everywhere. Quite a number of innovative and at least partially successful programs are now in place around the world, providing data and ideas that others can benefit from as they build their own programs.

It seems clear that whatever specific approach is followed, a number of changes will be critical for a broadly successful wind-energy effort in any developing country. The manufacturing must almost certainly occur within the country itself in order to provide employment, to mobilize local interest, and to keep costs low given the expense of transporting materials. Moreover, an infrastructure for the maintenance of machines and the provision of spare parts is also essential. Programs that train people to install and repair wind machines should be part of that infrastructure. In addition, some form of low-interest loan or subsidization will have to be provided if the rural poor are to use this technology extensively.

Both in industrial and developing countries, wind pumps have a bright future. Greatly expanded use of these machines can be expected in parts of the United States and the Soviet Union where small-scale pumping is needed as well as in remote areas of Africa and Asia. The main difference is that the market in industrial countries can expand without much government support, for the technology and the industry are well established. In developing countries, however, there are millions of people who could benefit immensely from windmills that provided water for drinking or for irrigation, but who lack the money to buy the machines themselves. National and international assistance programs are essential if wind pumps are to be used widely throughout the Third World.

Turning the Wind into Electricity

The key to making the wind an all-purpose power source is of course using it to generate electricity. Wind electric generators have been manufactured since the twenties, but because electricity from other sources was cheaper a large market for such turbines never developed. Since the early seventies, however, there has been an encouraging resurgence of interest in wind generators, and a growing number of companies are producing them. On farms and near homes in rural areas, small wind turbines may be a common sight before the turn of the century. They offer not only the possibility of reasonable and stable electricity prices, but also an undeniably appealing symbol of energy independence. Wind turbines will probably be the first technology that allows a substantial proportion of electricity users to produce their own power.

Small wind turbines come in many sizes and shapes, with most of the manufacturing activity centered on machines capable of generating from 1 to 15 kilowatts and with blade diameters of less than 12 meters. The typical American home located in an area with average wind speeds of greater than 12 miles per hour could meet most its electricity needs with a three-to-five-kilowatt wind turbine. A wind-energy system designed to serve such a household currently costs between $5,000 and $20,000, a figure that is expected to decline rapidly in the next decade.[29]

Although the small-turbine industry has begun to innovate recently, most of the machines on the commercial market still differ only slightly from those of the past. With a few exceptions they are horizontal-axis turbines and have two to four thin, propeller-type blades that rotate at variable speeds depending on the strength of the wind. Most small wind turbines face upwind of the tower, and have a tail of some sort mounted behind the rotor to help maintain the upwind position. A few models face downwind, which eliminates the need for a tail but sometimes causes turbulence problems because the wind hits the tower before it intercepts the machine's blades. Metal, wood, and fiber glass are among the materials in the blades of currently marketed machines, with most manufacturers seeking a strong, economical, and yet lightweight blade. With lighter parts the stress on the machine is reduced while the power output is maintained. 21

Before the seventies, most small wind turbines were used at remote sites that lacked access to an electricity grid, and the machines were designed specifically with that market in mind. A typical remote-site turbine is quite small and rugged, and generates direct current that can be stored in batteries for use when the wind is not blowing. Approximately 20,000 remote-site wind turbines are in use today, at fire lookouts, remote airfields, and the like. They can be seen on isolated ranches in parts of Australia, on buoys off the coast of Chile, and at mountain chalets in Switzerland. Active wind-turbine industries are found in Australia, Denmark, the Netherlands, Sweden, the United States, and a few other countries.[30]

The market for remote-site wind machines continues to grow, mainly in developing countries that are still without electricity grids. Particularly in areas where very little electricity is required, wind turbines are usually cheaper to use than diesel generators. Still, these small-wind-energy systems are expensive; they typically generate electricity for well over 20¢ per kilowatt-hour—much more than centrally produced power costs in most countries.[31] Not only are the machines produced in limited quantity, but the power they generate must be stored in batteries, which is very costly. Unless an unexpected breakthrough in battery technology greatly lowers costs, this type of wind-energy system will have a limited market potential.

In recent years, however, a quite different system has been developed, one that can be used in conjunction with utility-derived power. Rather than generating direct current, these new wind turbines are attached to an induction generator that produces alternating current—the same electricity found in most utility lines. Other new machines use a synchronous converter to perform the same task. With these technologies, a household or business can use central-grid electricity along with wind power. Instead of having to rely on batteries when the wind is not blowing, the user draws power from the utility company's lines just like a normal customer. And when there is ample wind but little electricity needed, the excess power can be fed back into the utility lines, reversing the customer's meter. The wind-machine owner becomes a producer as well as a consumer of electricity, and the utility grid is in effect the customer's storage battery.

These new technologies, in conjunction with soaring prices for electricity derived from conventional sources, have opened up a large market for wind energy. Worldwide, approximately 100 firms now manufacture wind turbines and the number is still growing. In the United States alone, approximately 40 manufacturers expect to sell between 1,000 and 2,000 of these machines in 1981. China and the Soviet Union are among the many countries that have recently taken an interest in small wind machines.[32]

The industry is a young one and still subject to normal growing pains—some firms are barely surviving, selling only a handful of wind machines a year, while others market well over 100 of them. As the market expands, the industry will change as some companies increase in size rapidly and less-competitive firms are forced out of business. The quality of the machines being sold is still uneven. A U.S. Government report in the late seventies found that some machines on the market "reflect 1930's technology but lack the reliability and longevity of their predecessors."[33] That situation is being remedied by a number of companies, although the industry has not yet done all that is possible with modern technology to develop improved wind turbines.

Today, reducing costs and improving reliability are the main goals of many wind-turbine manufacturers. Until recently, sales have been so low that manufacturers could not even afford to introduce improvements they knew could greatly boost performance. As a result, many of the components of current wind machines are "off-the-shelf" hardware that was not engineered specifically for wind-turbine use. Improving this equipment could lower the cost of wind-derived electricity considerably. Engineers who have examined the technology note that these changes can be based entirely on known materials and concepts that have not yet been applied to wind machines. Some of the improvements being implemented by private and government research programs are increased rotor efficiency and more-reliable transmissions and generators. Lightweight, inexpensive, yet rugged

"The wind-machine owner
becomes a producer
as well as a consumer
of electricity."

blades are needed; fiber glass and molded plastic are two materials with considerable potential. In addition, lightweight and flexible towers designed specifically with wind turbines in mind could be cheaper and more aesthetic than those typically used to support today's models. It should also be possible to simplify the control systems for small turbines.[34]

These improvements must of course be based on detailed engineering assessments, since cutting corners in the wrong place can cause problems. Some of the wind turbines on the market today are quite unreliable, and even a very inexpensive machine is not going to be a good investment if it lasts only five years. It is generally accepted that wind machines should have life spans of at least 20 years if they are to break into the mass market. Ned Coffin of the Enertech Corporation, a leading U.S. firm, notes: "The key to our business is making a windmill that is idiot proof. It has to be maintenance-free like an icebox."[35] Only a few of today's small turbines meet this criterion, and the pace at which reliability improves will be crucial in determining how quickly the market develops.

With continued research, turbines may eventually be developed that are even more efficient and less expensive than those described above. Small vertical-axis wind machines that are shaped somewhat like merry-go-rounds are being marketed by one company in Great Britain and another in the United States. These designs will require further research, however, to determine whether they can become competitive. Another alternative, the sailwing turbine developed at Princeton University, has two curved blades made of wire and cloth, and some researchers believe that it has considerable potential. Private industry as well as several governments are testing a number of other designs that may one day reach the market.[36]

One particularly promising idea has to date received relatively little attention: using wind turbines to heat water for space heating. Devices recently developed, called heat churns, use mechanical power directly to heat water. They are much cheaper than electricity generators, and they are well suited to a rotating wind turbine. Estimates have shown that in windy regions, such a device is already cheaper than electric resistance heating and may very soon cost less than fossil-fuel heating in most areas. These systems are particularly appropriate in areas such as Canada and northern Europe, where heating is one of the largest energy users and the cold winter climate is accompanied by strong winds.[37]

The change that will perhaps do most to lower costs and expand the market will be the use of large-scale production and assembly techniques in the wind-turbine industry. The largest firms in business today are producing only a few hundred machines per year, which means that each turbine is essentially handmade, with a high labor cost. The wind-turbine field is currently about where the auto industry was before Henry Ford introduced the Model T. Indeed, the automobile assembly process provides a good example of the improvements that could be made in this industry. Manufacturing wind turbines on an assembly line would be relatively easy compared with assembling cars. A production line turning out several thousand wind machines a year could reduce costs substantially even without other improvements in the technology.[38]

The most advanced wind turbines on the market today produce electricity for around 15¢ per kilowatt-hour. However, detailed projections made by wind-turbine experts in the United States indicate that improvements like those described above could bring costs down to approximately 5¢ per kilowatt-hour in areas where winds average 12 miles per hour. With a combination of technology improvements and mass-production techniques, this fledgling industry could reach an almost unlimited market in rural areas of the world.[39]

It is difficult to predict how quickly these improvements will occur. The changes needed are not particularly complex but they will require a considerable initial investment both in engineering research and in the establishment of large manufacturing plants. The current market does not justify that scale of investment and in any case most wind-turbine manufacturers do not have access to sufficient capital. The market is growing, however, and it may not be long before one or two companies, perhaps in league with venture-capital firms or large corporations, are willing to make the investment gamble required. In the United States, the Bendix Corporation, a large, diversified firm, recently purchased 30 percent of the Enertech Corporation, an investment that will allow the already successful turbine manufacturer to expand production greatly. The potential payoff for such investments is certain to be large, since cheaper machines would allow a rapid

"The wind-turbine field is currently about where the auto industry was before Henry Ford introduced the Model T."

expansion of the market, and companies that gain a foothold now would have an advantage for years to come.[40]

Few good estimates are available on how extensively small wind turbines might one day be used. In addition to the economic considerations discussed, there are still major institutional and even psychological uncertainties. Wind-resource surveys in the United States indicate that approximately 25 percent of the continental land area is suitable for small wind generators, but wind machines are unlikely to turn up on every site with sufficient wind.[41] Assessing wind power's true potential requires an understanding of who the potential users are, what their future energy requirements will be, and the likelihood that they will consider the wind an attractive energy source.

The most extensive survey conducted so far was one by the Solar Energy Research Institute in the United States in 1980. It included a detailed evaluation of the many considerations that affect market potential in different locations—including wind speed, utility rates, income level, and housing density. The investigators found that cities and suburban areas were unlikely to use wind turbines extensively, and that regions with little wind or with low income levels also had little potential. The study nonetheless concluded that there are 3.8 million homes in rural parts of the United States that are particularly good locations for small wind generators. And over 370,000 farms and many commercial businesses could also benefit from this energy source. Clearly, wind machines will not be established at all these locations in the near future, but in the long run the potential is enormous. Based on this study it can be estimated that the United States could one day have as many as five million small wind turbines in use, providing about 25,000 megawatts of generating capacity—half as much as nuclear power currently provides.[42]

Although few good surveys have been done yet, it seems likely that many other rural areas of the world could put large numbers of wind turbines to good use. Already, a small boom in sales has occurred on some Caribbean islands buffeted by both high electricity prices and strong trade winds. Denmark, which has good winds plus a government interested in this technology, now has the world's most active wind-turbine industry. Several hundred wind machines can now be seen on Danish farms. These recent developments portend a rapid increase in small-wind-turbine sales worldwide. Both the economic arguments for using the wind to generate electricity and the interest of its potential users are on the rise.[43]

6 Wind Power for Utilities

Although the wind may seem like a quintessentially decentralized source of energy, centralized wind-power systems may in fact provide a substantial amount of energy in the coming decades. Since the early seventies, engineers in several countries have been working to develop large, technologically sophisticated turbines that would dwarf the monsters Don Quixote encountered at la Mancha. These research efforts, although largely ignored by governments and the popular press, have been quite successful. Some utility planners in both Europe and North America are convinced that this may be a major area of growth for their companies during the next decade. By the end of the century, clusters of 50 or more large wind turbines on what have been dubbed "wind farms" may be a common sight in some parts of the world.

There are several reasons wind farms may have a bright future. Small wind turbines, although they are increasingly economical in some regions, are not feasible in many others. Nearby hills, trees, and other obstructions greatly reduce their effectiveness. Even the most ardent wind-machine advocates now recognize that windmills will never cover most rooftops in cities and suburban areas. The wind in such areas is often insufficient, and the cost of building towers high enough to capture it would be prohibitive. Yet cities or suburbs could for a reasonable price obtain electricity from a group of large turbines located on a nearby windy ridge or other open space. Indeed, many of the world's windiest locations remain undeveloped because living in an area with 20-mile-an-hour average winds would be, to say the least, unpleasant. Wind farms may be the only way the energy potential of such locations can ever be tapped fully. In addition, economies of scale support the concept of wind farms using large turbines. Most engineers working on these projects believe that, once the technology is mature, large wind machines will be the cheapest source of wind-derived electricity available. Whether that promise will be realized is still uncertain, but there are some impressive plans on the drawing board and considerable progress has been made already.[44]

In terms of basic appearance and function, large and small turbines
are quite similar. But there the common ground between the two tech-
nologies ends. Large wind machines are essentially an aerospace tech-
nology; they require meticulous engineering and must meet rigid
specifications. The blades are typically as long as a jumbo jet's wings
—usually over 50 meters—and the latest computer technology controls 2
their angle and rotational speed. The stress on these blades is enor-
mous, and designing them to hold up in heavy winds has been a
real challenge. The complex nature of the technology has meant that
most of the research on large turbines has been done by high-tech-
nology firms. Alcoa, Boeing, General Electric, Lockheed, and Westing-
house are all involved in programs funded by the U.S. Government
and directed by the National Aeronautics and Space Administration
(NASA). Both in the United States and Europe, engineers who cut
their teeth on jet-aircraft technology are directing large-turbine re-
search efforts.[45]

Technically, a large wind machine is one that has a capacity of 100 kilowatts or more, but much of the development work has focused on machines capable of generating at least 1,000 kilowatts (one megawatt). Five distinct multimegawatt wind machines are currently being developed in three countries, and a number of machines that could produce 200 to 1,000 kilowatts are also being worked on. To put this in perspective, a 1,000-kilowatt wind machine could supply power for approximately 400 typical American homes, and for perhaps twice as many residences in some other countries.[46] It would take a wind farm with 250 large turbines, each capable of producing 4,000 kilowatts, to yield as much power as one of the largest thermal power plants in use today. Engineering constraints make it unlikely that wind machines with a capacity much greater than 4,000 kilowatts will ever be practical.

The United States holds the lead in developing large wind machines. NASA, employing the engineering skills of private industry, began work in 1975 on a series of progressively larger horizontal-axis turbines. Now under the supervision of the Department of Energy, this program recently sponsored the construction of three 2,500-kilowatt turbines in the windy Columbia River valley in the Pacific Northwest. Designed by Boeing, the Mod-2 is a breathtaking machine with two narrow blades that describe an arc nearly 100 meters in diameter. The turbines are so large that they can be seen from five miles away on a

clear day. The steel blades face upwind of the tower and rotate at a constant speed. Power is harnessed by a synchronous generator that feeds directly into the electricity grid of the Bonneville Power Administration. Designed to operate in a location with at least 14-mile-per-hour average winds, the Mod-2 is expected initially to generate elec-
8 tricity for approximately 8¢ per kilowatt-hour, with the cost dropping rapidly if 100 or more of the machines are eventually built. NASA had hoped to develop other, more advanced wind turbines, but proposed budget cuts by the Reagan administration make that unlikely.[47]

Since the U.S. program was launched, other industrial nations have begun to develop large turbines. National research programs in Canada, Denmark, Great Britain, the Netherlands, the Soviet Union, Sweden, and West Germany are well under way. The machines come in a variety of sizes and employ different technologies, depending on local conditions and the engineers' judgment on appropriate design. One of the more impressive efforts is taking place in Denmark, where officials hope a 630-kilowatt machine they have developed will be on the market soon. They believe that as many as 2,000 of these machines could be built along the Danish coastline. In England, Taylor Woodrow Construction, Ltd., a major engineering firm that also builds nuclear power plants, is designing a 3,000-kilowatt wind turbine with government funding. British engineers are confident this machine will be reliable and economical. According to one report, Taylor Woodrow sees the 3,000-kilowatt machine as a standard piece of generating equipment for utilities and the company expects the turbine to be in large-scale production by the late eighties.[48]

Although the major thrust of most research programs is horizontal-axis wind machines, another design is also receiving attention. The National Research Council of Canada and the U.S. Department of Energy have separately financed the development of a vertical-axis design called the Darrieus wind turbine, which resembles a large inverted eggbeater. Darrieus machines have two or three curved aluminum blades turning a central upright shaft that is attached to a transmission and generator on the ground. The Darrieus design is well suited to areas with high winds and one of its advantages is that the rotor does not have to be turned to face the wind. One problem with the current design, however, is that the blades extend close to the ground, where there is less wind to be captured. The blades must also withstand varying levels of force as they pass into and out of the "eye" of the wind. Perhaps these difficulties can be resolved, but it remains to be seen whether Darrieus machines will ever be as widely used as horizontal-axis turbines.[49]

The large-wind-turbine industry could become a very competitive one by the late eighties. In addition to the government-sponsored programs, at least two companies are tackling the market with privately financed research efforts. The Bendix Corporation and the Hamilton Standard Company in the United States have developed horizontal-axis machines with capacities of 3,000 and 4,000 kilowatts, and both have contracts for the testing of their turbines by utilities. These programs are costly ones, and the fact that these established firms are willing to commit millions of dollars to large turbines indicates a hefty measure of confidence in the market potential. Hamilton Standard recently built the world's first factory for the blades these large machines need, and the company hopes to be able to produce two wind machines per month by late 1981. That would be quite an achievement and could revolutionize the market.[50]

Large-wind-machine technology is still in its adolescence, and both the direction and the pace of future developments are uncertain. As there has been no long-term testing of any designs, a number of technical issues need to be resolved. Engineers are still debating about how many blades the machines should have, what the nature of the transmission systems should be, and whether towers should be rigidly constructed or somewhat flexible. The question of which materials to use is also critical, and while several alternatives are technically adequate, it is unclear which will be most reliable and yet economical in a commercial market. The blades for the large turbines are currently being made of steel, laminated wood, fiber glass, or a combination of these materials and they must be able to withstand an enormous amount of stress. As the blades account for a significant portion of the total machine cost, the answer to this question is particularly important.

Probably the most encouraging thing about large wind turbines today is the sheer breadth of the research efforts. Independently engineered machines of quite different design are being developed simultaneously, and the occasional failure of a particular model by no means jeopardizes the entire effort. Bolstering these research programs is a substantial amount of information exchange and comparison of designs

among engineers both at the national and international level. A few years ago researchers feared that the U.S. Government program might be too narrow, but the appearance of many other privately and publicly financed efforts has made it a wide open field. Extensive international competition for a share of the market can be expected in the
 near future.

As research on the machines themselves continues, attention is already turning to the next stage of the development process—the establishment of arrays of large wind machines on wind farms. Even though the technology is not yet fully mature, many utility planners in the United States and Western Europe believe that enough information is available to begin making plans and anticipating problems that could arise. Ninety-one U.S. utilities had wind-energy programs as of 1980, and 42 of those are looking into the development of large wind machines. Moreover, it is a field of rapid growth, with the number of projects having increased 80 percent between 1979 and 1980. In Great Britain, the Central Electricity Generating Board—the second largest utility in the West—is actively involved in the country's development efforts. And in Sweden the utilities have assumed an important role in the country's extensive large-turbine development program.[51]

California is the site of perhaps the most ambitious wind-farm development effort in the world so far. The state is blessed with a number of excellent locations for wind farms, mainly in mountain passes that separate the coast from the hot interior valleys. Innovative leadership in both the public and the private sectors has also been helpful. All the large utility companies in California now have development programs and have signed contracts to build wind farms. Pacific Gas & Electric and Southern California Edison seem to be playing a game of leapfrog as each attempts to one-up the other in a fight for leadership and public recognition in wind-energy development. SCE now plans to have 120 megawatts of wind-energy capacity by 1990, while PG&E in conjunction with the California Department of Water Resources is considering an even more ambitious goal of 350 megawatts. The latter target would require approximately 100 of the largest wind machines that are currently being developed. The state government has supported these efforts with wind-resource assessments and tax incentives, and has encouraged California's financial community to invest in the programs. Russell Schweikart, chairman of the Cali-

"Ninety-one U.S. utilities had wind-energy programs as of 1980, and 42 of those are looking into the development of large wind machines."

fornia Energy Commission, believes that "wind energy has reached a turning point in California. . . . We hope to lead the nation in the development of wind farms."[52]

Much of the early work in developing wind farms in the United States will be carried out by small innovative firms that have been formed specifically to serve utilities interested in this energy source. Companies such as U.S. Windpower Inc. and Windfarms Limited have started signing contracts with utility companies to supply power at a certain price. These small-wind-energy entrepreneurs hope to locate their own financing, buy the necessary land, and build the machines, thereby offering the utilities a risk-free way of tapping the wind. Aided by generous federal and state tax incentives that make wind farms a good tax shelter, these new firms are playing an important pioneering role.

U.S. Windpower, based in Massachusetts, has already developed the world's first wind farm. It is located in New Hampshire and has 20 turbines capable of producing 30 kilowatts each, for a total capacity of 600 kilowatts. The company manufactures its own machines and now has a "statement of principles" with the Department of Water Resources in California for a 100,000-kilowatt (100 megawatt) wind farm. A California outfit, Windfarms Limited, plans to establish farms that use large multimegawatt turbines purchased from manufacturers such as Boeing and Hamilton Standard. The firm has signed an agreement with the Hawaiian Electric Company for an 80-megawatt wind farm and has a preliminary agreement with PG&E and the Department of Water Resources for one of 350 megawatts—the biggest planned so far. This large project, to be completed in 1989, would by itself supply half the capacity called for in the U.S. Wind Energy Systems Act of 1980. Typical of the wind farms now being planned, this will be located in a windy pass and the power produced will mainly substitute for oil-fired electricity. Pacific Gas & Electric will pay Windfarms Limited the same price it would normally pay for oil-based generation of electricity—currently over 6¢ per kilowatt-hour.[53]

Some observers consider these projects bold and timely efforts while others label them premature, risky gambles. The Windfarms Limited contracts in particular, have raised eyebrows since the large machines they expect to use are a still-untested technology. Yet Wayne Van Dyck, president of Windfarms, is confident that the turbines will be developed in plenty of time. Claiming that the only barriers are institutional, he says, "We will fill the gap between the manufacturers and the utility companies." Certainly, filling that gap is essential, for the president of Hawaiian Electric has observed: "We have no risk capital so we cannot buy wind farms ourselves at this stage. We are a regulated utility and must wait for the kinks to get worked out until we invest." American wind-energy entrepreneurs are simultaneously helping to advance wind-power technology and providing important early lessons about the design of a wind farm. If Van Dyck and others like him succeed, utility customers throughout the world will eventually benefit.[54]

The emergence of wind power as a major energy resource for utilities hinges on the economic performance of these large wind machines and on the availability of good sites for wind farms. The large turbines developed so far are still just prototypes, but they can already produce electricity for as little as 10¢ per kilowatt-hour when placed on a site where the wind averages over 16 miles per hour. Such machines may be within economic reach of the utility market in a few windy areas where electricity prices are already very high, but their wider use must await further cost reductions. Studies in Denmark, England, and the United States indicate that electricity that costs between 3¢ and 7¢ per kilowatt-hour should be produced by the next generation of turbines once they are manufactured in quantity for a steady market. With the price of electricity escalating in most parts of the world, achievement of those cost goals would soon make wind farms an economically viable alternative to conventional power plants.[55]

It is hoped that these second-generation wind turbines will be economical at sites with average wind speeds as low as 14 miles per hour. This would expand greatly the number of potential locations for wind farms; but careful selection of good sites and farsighted planning will still be necessary. In some parts of the world the number of prime locations for wind farms is quite limited, and other claimants on the land such as public parks and suburban sprawl may present additional constraints. On the sites that are chosen it therefore makes sense to install as many turbines as possible, being careful that they do not interfere with one another because of wind turbulence. Extensive searches for wind-farm sites have already begun in California, Oregon, and a few other areas of the United States, and preliminary surveys have been made by some West European countries as well as

> "North Sea wind may one day rival North Sea oil as an energy resource in Great Britain."

the Soviet Union. The Soviets have apparently found some excellent locations for wind farms near the Barents Sea and in several other areas.[56]

For coastal nations with few good sites for wind farms, one possibility may be to place the turbines offshore. The most extensive feasibility study for such a scheme has been carried out in Great Britain, with quite favorable conclusions. The North Sea area has a large continental shelf, shallow water, and wind speeds that average as high as 20 miles per hour. Platforms similar to those used for oil drilling could be built, and a submarine cable would conduct power to a central relay station onshore. The study concluded that even with all the extra costs entailed in working at sea, offshore wind farms will soon be economically competitive with nuclear power. Most importantly, the wind resource off England's shores is huge. North Sea wind may one day rival North Sea oil as an energy resource in Great Britain.[57]

Although many people remain skeptical of the potential contribution of wind farms, the various engineering and economic studies done over the last few years have won a sizable number of converts. More convincing still is the growing number of machines in operation and the willingness of some major firms to invest large amounts of money in their development. In less time than it takes to plan and build a conventional power plant, the first large wind farms should be in operation.

Wind's Energy Potential

Understanding the potential for wind energy and drawing up reasonable goals are of course prerequisites to the policy changes and the investment decisions that are needed. Until recently, very little such information was available. But today, in the emerging mosaic of a renewable energy future, some elements of the wind-energy prospect are clearly visible. Wind power is a robust and economical energy alternative in many countries and its future is certain to involve diverse technologies, each of which will serve particular needs and be affected by a distinct set of economic and institutional considerations.

Simple mechanical windmills hold tremendous promise for the many rural areas of the world where lifting water from wells or small reservoirs is a critical energy need. The six million water-pumping windmills that once dotted the then-poor rural areas of North America are testimony to their potential contribution to an area's development. Today, a major opportunity to expand the use of wind pumps exists on every continent, constrained mainly by institutional barriers and a shortage of investment money among the people who could most benefit from their use.

One of the most promising characteristics of wind pumps is their adaptability to a wide range of wind conditions. They can be used effectively in areas with average wind speeds as low as eight miles per hour, which includes well over half the earth's total land area. There are relatively few countries that cannot make at least limited use of mechanical wind pumps. The most notable exceptions are some tropical areas that lack good trade winds, such as parts of the Amazon Basin, of Central Africa, and of East Asia. Many of the semiarid regions of the world that desperately need affordable pumps have a more than adequate wind resource. Australia offers a particularly good match between wind availability and pumping needs. Africa, for the most part a semiarid continent, has a tremendous and almost entirely untapped potential for the use of wind pumps. Parts of South America provide an equally bright opportunity.[58]

In these and other parts of the world, obtaining enough water for people to drink and for irrigation is one of the most serious resource problems. In many developing countries, the establishment of economical irrigation systems could improve agricultural productivity considerably and serve as a catalyst for rural development. The small-plot agriculture of South and Southeast Asia is particularly well adapted to the pumping capacity of wind machines, and diesel pumps are far too expensive for the average farmer in those areas. In parts of Africa water could be stored in small reservoirs during the short rainy season and then wind pumps could be used to irrigate the fields during the generally windy dry months. Tens of millions of small wind pumps might be in operation one day—in virtually all parts of the world. How much energy these machines could collectively supply is difficult to estimate. In comparison with major commercial energy sources, the amount is probably not large, but in terms of the number of people whose lives could be improved, the contribution would be tremendous. By the turn of the century, over a hundred million farmers, villagers, and rural poor could be benefiting from wind energy. In human rather than economic terms, mechanical windmills may be one of the most important renewable energy technologies.[59]

The use of electricity-producing wind machines may expand even more rapidly. The potential market is a diverse one, and critical variables such as the future price of electricity and the degree to which utility companies encourage or hinder the use of wind machines are unclear. There are many encouraging signs, however. Electricity prices are rising, the cost of wind machines is falling, and the utilities are gradually becoming more receptive to the idea of individual power producers being hooked up to the electricity grid.

Rural farming regions in developed countries offer perhaps the best initial opportunity for large-scale use of wind turbines. On modern farms, electricity requirements are often quite high—particularly on dairy and poultry farms—and there is plenty of open space for the machines to be constructed on. One of the advantages of wind turbines is that they do not preclude the simultaneous use of land for other purposes such as cattle grazing. Much of the U.S. Great Plains as well as parts of the Northeast and Midwest, where wind speeds average over 12 miles per hour, appear to be excellent sites for wind turbines on farms. Although few detailed surveys have been done, the same can probably be said for parts of Canada, China, northern Europe, and the Soviet Union, as well as the countries where wind machines have been used traditionally, such as Argentina, Australia, and South Africa.[60]

Given the recent and projected increases in rural populations in some countries, more people will be in a position to use small wind turbines. In the countryside the wind can be used for everything from operating milking equipment to running household appliances, and both the residential and agricultural markets are expected to grow rapidly. Most of the turbines manufactured will probably be relatively small, capable of generating perhaps two to five kilowatts, which can meet most of one household's needs. There will also be a growing market for intermediate, 10-to-50-kilowatt machines—considerably less complex than the giant turbines being developed for utility use and yet able to generate cheaper electricity than the small wind turbines for residences do. Intermediate-sized wind machines would be appropriate for industries, large farms, or towns located in areas with steady winds. Businesses in a particularly windy region could supplement their income by selling power back to the utility.[61]

36 One determinant of whether people install wind turbines—either small or intermediate-sized ones—is the prevailing price of electricity, which varies by more than a factor of ten in different parts of the world. There are parts of Canada where hydroelectric plants still generate electricity for only a penny or two per kilowatt-hour and small wind turbines are unlikely to be economical there in the near future. Where large oil-fired power plants are common, however, electricity prices range from 6¢ to well over 10¢ per kilowatt-hour. In these areas, small wind machines may be a good buy quite soon. Expensive electricity is one important reason that wind-turbine sales have soared in Denmark.[62]

The small electricity grids that serve many islands, most cities in the developing world, and rural communities everywhere present a third tier of electricity prices, ranging from 15¢ to over 50¢ per kilowatt-hour.[63] These small grids are notoriously inefficient and are usually based on costly diesel generators. In many of these areas, wind-derived electricity is already competitive. No studies have been done on the size of this potential market, but it is undoubtedly large. The trade-wind belt that circles the globe near the Tropic of Cancer includes, for example, many islands and coastal nations that are paying a great deal for diesel-derived electricity. The Caribbean region, the Pacific Islands, and the northwest coast of Africa all hold considerable potential for the use of wind power.

The incentive for utilities to develop wind energy will be quite different, but the future may be equally bright in this sector. The decisions to employ large machines will be made by a relatively small group of planners who base their choice on the reliability of the large-turbine technology as well as on strict economic criteria. The cost of electricity from conventional sources will be an even greater consideration here than in the case of small turbines. Also important will be the availability of good sites with strong winds. It is no accident that the wind-farm boom in California is occurring in a state that has both expensive oil-fired electricity and some superb locations for installing arrays of large wind turbines.

"Many countries can eventually meet between 20 and 30 percent of their electricity needs with a combination of small and large wind turbines."

Utilities in parts of New England, northern Europe, and the Soviet Union, where similar conditions prevail, should also soon be interested in this concept. And if the technology matures as rapidly as many engineers project and cost goals of less than 5¢ per kilowatt-hour are reached, wind farms could become a viable alternative to conventional power plants in many parts of the world by the nineties. Coastal areas of Asia, Australia, and South America, for instance, could use wind farms to good effect. Offshore wind farms may later become a popular power source for the many countries that lack enough good sites on land. Along with the excellent potential for the several European nations that border the North Sea, portions of the northeast and Gulf coasts in the United States may be suitable sites for offshore wind farms.[64]

The size of the wind-energy potential varies greatly among countries, and different nations will undoubtedly rely on different technologies. It is therefore quite difficult to specify how much of the world's electricity needs wind will meet in the future. However, based on economic trends and some broad estimates of the resource available, it seems clear that many countries can eventually meet between 20 and 30 percent of their electricity needs with a combination of small and large wind turbines. Relying more than this on wind power would in most cases be difficult due to insufficient wind resources and to problems of intermittency of power supply. Nonetheless, the 20- to 30-percent figure represents a sizable share of the total need for electricity, and is more than nuclear power provides in most countries. If fully developed, wind power could meet a significant fraction of many nations' requirements for additional generating capacity over the next 30 years.[65]

Wind energy is by no means a simple plug-in panacea that can solve all of the world's energy problems. There are many areas that lack sufficient wind and many energy needs for which wind power is inappropriate. However, in most countries wind energy could play a valuable role—providing precious electricity or pumping power that cannot be obtained economically by any other means. Improved wind-energy technology will for the first time allow many individual consumers to produce their own power. The combination of wind energy and the expanded use of hydropower could very well meet more than half of the world's additional requirements for electricity capacity over the next two decades. These two renewable energy resources may be the cornerstones of a new strategy to put the world's electricity supply on a sustainable basis. Later, photovoltaic power, ocean thermal energy, and other solar resources can provide additional building blocks.

The fact that wind power is a plentiful and economical energy resource is of course no guarantee that it will be widely used anytime soon. One of the clearest energy lessons of the last decade is that the technologies a particular society relies on often bear little relation to either economic rationality or human needs. Technocrats and politicians have promoted a range of policies in the face of mounting evidence that they are no longer appropriate. Approaches that are suited to the new era of renewable energy are only beginning to emerge.

The legacy of outdated policies could impede the spread of wind machines in several ways. Few nations, for instance, have gathered enough wind-resource information to even begin formulating long-term plans. Utilities in some countries have objected strongly to small-wind-turbine owners feeding any excess electricity they produce back into utility lines. And technical research on wind machines is not proceeding as rapidly as it could, in part because attracting sufficient capital to the wind-power industry has been difficult in many regions. These problems must be solved if wind power is to reach its full potential.

For many nations one of the first priorities should be a thorough wind assessment. Wind surveys have been carried out haphazardly so far, and many governments have only sketchy knowledge of their country's wind-energy potential. This is unfortunate, since the amount of wind available is critical and it can vary widely over short distances. Ideally, local governments should publish general information on the amount of wind in an area as well as loan wind-measuring equipment to individuals or utility companies that want to evaluate a particular location. Inventories will be essential in mapping out wind-energy development programs and could help mobilize early political support for these efforts.

Wind-energy assessments have been an important part of California's successful program. Until a few years ago, most experts doubted that California had much wind-power potential. That belief was based on historical data recorded at airports—yet these sites are often chosen specifically because they lack wind. Contrary to the gloomy conclusions of those early estimates, meteorologists conducting wind assessments for the California Energy Commission have discovered a veritable gold mine. In a few short years, they have found sites for wind farms that, combined, could generate 5,500 megawatts, mainly in windy mountain passes that are relatively unpopulated and yet reasonably close to major urban centers. Not only is "wind prospecting" a rapidly expanding business in California, but the early assessments have set off a small land rush in some parts of the state.[66]

The international sharing of information on wind availability and of ways to obtain the data would be helpful. As the United States is now in the process of a rather thorough inventory of its wind resource, it will be in a good position to help other nations that want to do the same. The U.N. World Meteorological Organization has recently become involved in wind-energy assessments and has just published a map showing the general distribution of wind resources throughout the world. This agency and relevant professional organizations need to pursue these efforts to exchange information and to draft internationally standardized assessment procedures.[67]

As windmills of various shapes and sizes become more widely available, some problems must be faced that a short time ago seemed inconsequential. One of those is the environmental impact of wind machines. Although a few experimental turbines can be erected without disrupting the environment significantly, having millions of wind machines in place would be another story. Environmentalist Roderick Nash observed recently that "most people do not yet fully realize that obtaining a meaningful amount of power from the wind involves far more than a few picturesque structures surrounded by tulip beds."[68]

The most serious environmental concerns will probably involve land-use issues that are raised by wind farms. Placing wind turbines in valuable or scenic areas could lead to serious controversy. Fortunately, many of the best sites for wind farms are not particularly valued for agricultural or residential uses, and cattle grazing and some other activities can be established on these farms along with the wind turbines. However, in scenic coastal areas and some mountainous regions, conflicts may arise. One local group in Vermont has mobilized opposition to the U.S. Department of Energy's plans for a large experimental wind turbine atop a very visible mountain in a national forest. Such conflicts are rare so far, and careful land-use planning can ensure that windmills do not intrude on wilderness areas or valuable cropland.[69]

Other possible wind-power problems include noise, safety, and television interference. The noise from a few of the experimental large turbines annoyed nearby communities, but engineers believe that careful design can eliminate this. The latest wind turbines are hardly audible unless the person is standing directly beneath them. Safety is also an important issue: clearly, large wind machines should not be right next to buildings and roads, since an accident in which a blade is lost is possible. Small turbines in towns and farming communities will have to be regulated by installation codes and other measures to ensure safety. Indeed, some communities already have such ordinances. Television interference may turn out to be a somewhat more difficult problem. All wind turbines—but particularly larger ones with metal blades—tend to interfere with television signals, causing picture distortion within a range of up to a few kilometers. Possible solutions include using blades made of synthetic materials or not installing wind turbines near communities. Cable transmission of television programs may, however, be required in the few houses located near large wind machines. Although television interference is unlikely to be a major constraint on the spread of wind power, the issue does deserve attention.[70]

In communities in the United States where wind turbines have already been erected and public opinion surveys carried out, the machines have been generally well received. In environmental terms, wind energy is a refreshing contrast to the climate-altering effects of large coal plants and the safety and health hazards of nuclear power. Most people seem to think even the larger wind machines are quite aesthetic, and they enjoy having such a clear symbol of pollution-free energy production nearby. However, virtually all technologies have trade-offs, and continued attention to wind power's environmental impact will be essential if it is to be a major and beneficial energy source. One of the encouraging aspects of the wind-power field is

"In environmental terms, wind energy is a refreshing contrast to the climate-altering effects of large coal plants and the safety and health hazards of nuclear power."

the extent to which such concerns are being aired so early in the development process.[71]

One critical influence on wind power's future is the attitudes and programs of electric utilities. The most economical way to use both large and small turbines is to connect them to electricity grids and so avoid separate and expensive storage of wind-generated electricity. Utilities the world over will have to decide what to pay for any electricity they receive from individual power producers as well as what fee to charge for hooking up to the grid. The establishment of wind farms will be affected even more directly by utility policies, since in most cases investment by the utility will eventually be required. As precedents are set and guidelines established, the utilities will be learning valuable lessons that can be applied to other renewable sources of electricity, such as small-scale hydropower and photovoltaic cells.

A new era is clearly dawning for utilities. While the ways electricity can be generated have increased, many companies face financial crises and are short on investment funds. Careful planning is called for to channel limited capital into the most economical technologies. Wind farms will present a challenge, but they should not be a radical departure for utilities, since in planning and financial terms they can be treated like conventional power plants. The widespread use of small wind turbines by individual owners, however, presents an entirely new problem. A large number of independent power producers could emerge in the next several years, breaking open the electricity market and fundamentally challenging the current monopoly of the utilities. Perhaps in fear of such a development, some utilities have introduced discriminatory hookup fees and higher rates for small-wind-tubine owners who want to be linked to the electricity grid.[72]

Fortunately, these misguided policies are beginning to disappear in many areas. Although it is appropriate to have technical guidelines and a reasonable fee that covers the cost to utilities of hooking up small turbines to electricity lines, it makes economic sense for power producers to be paid the full value of any electricity they provide. This encourages more generation of power by the lower-cost producers and in the long run will have a favorable effect on electricity prices. And buying wind power gives utilities an opportunity to obtain additional small amounts of electricity that are matched to their now sluggish growth in demand—without a heavy capital expenditure.

One question often raised regarding utility reliance on this renewable resource is how to assess wind energy's value compared with other power sources. Wind, by its very nature, is intermittent, and some skeptics have argued that this greatly reduces its value as an energy source, since utilities must not only purchase wind machines but also have additional generating capacity for the times when the wind is not blowing. Recent studies have largely laid those concerns to rest. Much of the value of wind power comes from the savings it allows when more-costly power plants can be turned off. Some parts of the world still use oil-fired power plants extensively, and in such areas the fuel-saving value alone is enough to make wind machines economical. Meteorological data have also shown that in many regions the wind can be quite a steady provider of power, with fairly predictable fluctuations. Moreover, utility grids have always had to handle considerable variability, since electricity demand and supply are never constant. Wind's intermittency is not really so different from that of conventional sources of power, which can be relied upon only to a limited extent given unexpected plant shutdowns for repairs. Sophisticated computer controls allow constant adjustment for these variations, and power is routinely purchased from adjacent utilities as need arises.[73]

A few utility companies, particularly in California, have already begun planning how best to integrate wind power with their electricity grids. One promising strategy is for utilities to operate wind turbines in conjunction with hydropower plants. These are typically run on an intermittent basis anyway, to meet fluctuating electricity demand. By operating the hydro facilities at full capacity when the wind is not blowing and by slowing them down when the breezes are abundant, maximum benefit can be gained from the wind machines. The northwestern United States, the James Bay region of Eastern Canada, most of Scandinavia, and many parts of the Soviet Union are among the regions where the integration of wind and hydropower makes considerable sense. In addition, electricity-pricing policies could encourage the use of power when it is least costly to produce—that is, when the wind is blowing. In fact, the introduction of wind power should ideally be part of a wider transition to the more efficient use of electricity.[74]

"The introduction of wind power should ideally be part of a wider transition to the more efficient use of electricity."

In most parts of the world, utilities are government-owned; even in the United States, where utilities are mainly in private hands, state regulatory commissions retain important leverage. Increasingly, governments and consumers are insisting that utilities be more responsive to innovations that are in the long-term interest of the customers. In Denmark, where wind turbines have become quite popular, small-scale power producers have been welcomed by the utility and are well reimbursed for the electricity they feed back into the grid. American utilities have been slower to adjust, but they are being pushed along by the Public Utility Regulatory Policies Act (PURPA) of 1978, which includes a section requiring utilities to pay small-power producers the "avoided cost" of power that would have been produced from other sources. Although not yet fully implemented, the PURPA regulations have stimulated a reevaluation of policies by many utility companies and state utility commissions. Several state governments have recently introduced their own laws favoring small-wind-turbine owners.[75]

In addition to the policies of utilities, the support of national governments will be important to the future of wind power. Since the 1973 oil embargo many nations have adopted the development of alternative energy technologies as a national goal. The widely varying approaches of different countries is clearly evident in the wind-power field. Some governments have concentrated on the research of their national laboratories. Others have supported private industry research or have used tax policies to encourage investments by manufacturers and individual users.

These various approaches—accommodating different energy needs, resources, and philosophies on the role of the government—are providing a wealth of policy options for countries to choose from in the future. Compared with the status of many other new sources of energy, the technology for harnessing the wind is quite advanced. Although it is not currently a major energy source, as hydropower is, wind energy needs much less fundamental research or major technological breakthroughs before it can be used than, for example, ocean thermal energy or photovoltaic electricity do. In the long run, therefore, less research funding may be needed, although in the short run well-financed and targeted programs can have a tremendous impact and are well worth the effort. In general, the wind is an underrated energy resource, and some governments have spent a great deal more on grandiose and impractical solar-concentrating systems for electricity generation. Certainly each nation must carefully allocate scarce funds to the development of the many renewable energy technologies that have promise. Yet most governments will undoubtedly find that wind power deserves a somewhat larger share of future budgets.

In terms of research and development, government support has been the key to the rapid progress made since 1973, particularly in the field of large wind machines. Wherever significant strides have been made, governments have taken an early and active interest in the technology. In both Denmark and the Soviet Union, the government itself is developing large turbines; in Sweden and the United States, the government is directing and funding research being carried out by private industry. Observers of the wind-energy field generally agree that private industry would never have undertaken similar programs on its own, given the amount of risk involved in the early stages and the limited short-term payoff. Even in the United States, where privately financed large-turbine development efforts are now under way, federal programs were the essential catalyst that convinced industry planners the technology had promise. Indeed, government research on these large machines has so far been a notable, though unheralded, success story with long-term benefits that should far outweigh its relatively low cost.[76]

Governments have done much less to support research on wind pumps or small turbines, apparently for political as well as technological reasons. The technical argument is that these machines are simpler and further along in the development process, and so require less assistance. While this is to some extent true, it fails to explain the great disparity in funding levels. These smaller machines could become a major source of power, and it is quite clear that even a little government support, properly targeted, could give the industry the boost it needs. The technologies are not nearly as far along as they could be, and significant progress will depend on the small manufacturers in the business having access to desperately needed capital. Unfortunately, most governments seem more attracted to high-technology programs that follow the conventional pattern of a few utility companies supplying power for many users, something large wind turbines are best suited for.

This unbalanced situation may be finally starting to change in many countries. China, India, and the Soviet Union, among others, now have a few small-wind-power development projects. In Europe and North America, small programs have been started to assist private companies in the advancement of the technology. Denmark and the United States have each established small-wind-turbine test centers that allow private companies to test their machines free of charge. The results assist the manufacturer as well as potential users. These programs, though still new, have been quite successful and are widely acclaimed by industry. Cooperation between manufacturers and the government on other aspects of the design and use of small wind machines would certainly speed the spread of this technology.[77]

Bolstering some governments' support of wind-energy technology are a range of financial incentives in the form of tax credits. Denmark and the United States each have generous tax provisions that help individual wind-machine installers as well as new wind-farm entrepreneurs. The basic principle behind these tax credits is that the government should share some of the burden of bringing risky new technologies to the commercial market. The tax credits greatly improve the short-term economics of investing in wind turbines, and although their full impact is not yet clear, they could help the market develop quickly. Another area that needs financial support is the distribution of wind pumps and turbines in many rural areas of developing countries. Millions of people could benefit immediately from such efforts, and the indigenous manufacturing and maintenance industries that could be developed would make a valuable contribution to the local economy. Already, many Third World governments and international aid agencies finance the import of diesel generators and other less economical technologies, so their funding of wind energy would be more a matter of a shift in emphasis than an entirely new program.[78]

As the eighties began, there was considerable debate in some industrial countries about whether governments were doing too much to develop alternative sources of energy. The Reagan administration in the United States, for one, argued that government support be limited to basic research on technologies that industry has not been interested in so far. The administration maintains that the energy business is primarily a private one, and claims that misdirected government programs have promoted inefficiency. There is some truth to these arguments. Many government programs to develop new technologies have been economic disasters. The Concorde supersonic plane developed by England and France is one example and nuclear energy threatens to be a second. Government development efforts, particularly if they must work with private industry, need to have specific and realistic goals and must be well managed. Yet some wind-energy development programs have matched that recipe perfectly, and economic analyses indicate these projects—far from being a financial waste—should yield handsome returns during the eighties.[79]

Wind energy is now financially attractive enough that industry is making a major investment in it; yet there is still an important role for government to play in filling some research gaps and in speeding the development effort. In fact, wind energy has so much potential that a small amount of government support over the next several years might yield a vibrant and self-sufficient industry that could continue the effort on its own. Failing to continue government support right now would be like stopping work on a major bridge when it is only a few meters short of completion. Governments that limit their research funds to the most undeveloped and problematic technologies will miss the opportunity to provide a final push to wind power and to other renewable energy sources that could make a substantial contribution in the next two decades.

Along with national governments, the international community will play an important role in converting promise into progress. The wind-energy field has so far profited from a substantial flow of information between researchers and planners in different countries through both informal contacts and bilateral and multilateral agreements that have brought engineers together. Sweden, for instance, is using technologies developed in the United States and West Germany in the large turbines it is developing. The International Energy Agency now has a cooperative program in which four countries are exchanging information on the development of large wind turbines. The U.S. small-wind-turbine test center in Colorado has received hundreds of international visitors who take home information about the technology as well as the operation of this innovative center. The impressive global communications system has eased the exchange of information, and the research frontier in wind energy has become a truly international one.[80]

The United Nations Conference on New and Renewable Sources of Energy in August 1981 will strengthen these international links and focus worldwide attention on wind energy. A preliminary report prepared for the meeting recommends that formal channels be opened to exchange information on wind energy, employing the resources of national governments and international organizations.[81] The report also recommends the establishment of wind-energy research centers and training programs. This would be particularly helpful to developing countries that lack expertise and experience in wind energy, yet it would also yield important data for all wind-energy developers. Accurate assessments of all countries' wind resources should be a top priority, since effective programs cannot be developed without this information. And bilateral and multilateral aid agencies should begin funding the many renewable energy technologies that have promise, rather than focusing only on conventional and grandiose projects. The recently proposed energy affiliate to the World Bank would be a perfect channel for international wind-energy funding.

The technology for harnessing the wind has come a long way in the last decade, but the progress made so far could be dwarfed by the advances in the next 10 to 15 years. There are encouraging signs that some of the credibility problems that originally plagued this energy technology are being overcome. Cautious engineers and technocrats who earlier steered clear of "unconventional" technologies are now enthused about wind power. From rural development planners to utility executives, many people are now convinced that wind energy's time has come. If the impressive technical achievements of the recent past are matched by effective industry and government policies, wind power could develop very rapidly. From all signs, the wind-energy field has reached that all-important turning point.

1. This estimate is discussed more fully in the section "Wind's Energy Potential."

2. M. R. Gustavson, "Limits to Wind Power Utilization," *Science*, April 6, 1979.

3. Carl Aspliden, "Technical Note on Wind Energy" (preliminary) World Meteorological Organization, Geneva, July 1981; Nicholas P. Cheremisinoff, *Fundamentals of Wind Energy* (Ann Arbor, Mich.: Ann Arbor Science Publishers, Inc., 1978).

4. Walter Minchinton, "Wind Power," *History Today*, March 1980; E. W. Golding, *The Generation of Electricity by Wind Power* (London: E. & F. N. Spon Ltd., 1955).

5. Minchinton, "Wind Power"; Golding, *Generation of Electricity by Wind Power;* Volta Torrey, *Wind-Catchers: American Windmills of Yesterday and Tomorrow* (Brattleboro, Vt.: Stephen Greene Press, 1976).

6. Minchinton, "Wind Power"; Golding, *Generation of Electricity by Wind Power;* Torrey, *Wind-Catchers.*

7. Frank R. Eldridge, *Wind Machines* (New York: Van Nostrand Reinhold Company, 1980); Peter L. Fraenkel, "The Use of Wind Power for Pumping Water," a contribution for the British Wind Energy Association Position Paper on Wind Power, 1980.

8. Eldridge, *Wind Machines.*

9. Cheremisinoff, *Fundamentals of Wind Energy.*

10. National Aeronautics and Space Administration, "Wind Energy Developments in the Twentieth Century," revised, Lewis Research Center, Cleveland, Oh., 1979.

11. Torrey, *Wind-Catchers.*

12. William D. Metz and Allen L. Hammond, *Solar Energy in America* (Washington, D.C.: American Association for the Advancement of Science, 1978). The five-year energy payback period is a conservative estimate, in most cases it will be even lower; see Lockheed California Company, "Wind Energy Mission Analysis, Executive Summary," Burbank, Calif., October 1976, and Institute for Energy Analysis, "Net Energy Analysis of Five Energy Systems," Oak Ridge Associated Universities, Oak Ridge, Tenn., September 1977.

13. The prospects for improving the economic attractiveness of each of the three major wind-energy technologies is discussed in detail in sections 3, 4, and 5.

14. Cheremisinoff, *Fundamentals of Wind Energy*; a broad view of worldwide wind availability is included in Pacific Northwest Laboratory of Battelle Memorial Institute, "World-Wide Wind Energy Resource Distribution Estimates," a map prepared for the World Meteorological Organization, 1981.

15. Pacific Northwest Laboratory, "World-Wide Wind Energy Resource Distribution Estimates."

16. *Ibid.*; resource availability is discussed in more detail in the section "Wind's Energy Potential."

17. The figure of approximately one million wind pumps is widely used (see, for example, Fraenkel, "The Use of Wind Power for Pumping Water") but is not based on an actual survey; the energy-capacity estimates are based on data from Kenneth Darrow, Volunteers in Asia, private communication, May 28, 1981.

18. A good overview of wind-pump technology and related issues is found in Steve Blake, "Wind Driven Water Pumps—Economics, Technology, Current Activities" (prepared for the World Bank), Sunflower Power Company, Oskaloosa, Kansas, December 1978.

19. Material on worldwide wind-pump industry from Alan Wyatt, Volunteers in Technical Assistance, and Péter Fraenkel, Intermediate Technology Development Group (ITDG), private communications, April 28 and May 13, 1981.

20. These points are supported in Marshal F. Merriam, "Windmills for Less Developed Countries," *Technos*, April/June 1972, and in H. J. M. Beurskens, "Feasibility Study of Windmills for Water Supply in Mara Region, Tanzania," Steering Committee on Wind-Energy for Developing Countries, Amersfoort, Netherlands, March 1978; Zambia example from Alan Wyatt, Volunteers in Technical Assistance, private communication, April 28, 1981.

21. Peter L. Fraenkel, "The Relative Economics of Windpumps Compared with Engine-Driven Pumps," ITDG, London, unpublished, 1981; the estimate on cost of pumping water using wind power from Peter Fraenkel, ITDG, private communication, May 13, 1981; studies in India are described in Preparatory Committee for the United Nations Conference on New and Renewable Sources of Energy, "Report of the Technical Panel on Wind Energy," United Nations, New York, April 1981.

22. Ken Darrow, "Locally Built Windmills as an Appropriate Technology for Irrigation of Small Holdings in Developing Countries," Volunteers in Asia, Stanford, Calif., unpublished, February 26, 1979.

23. *Ibid.*; the Omo River project is described in Peter Fraenkel, *Food from Windmills* (London: ITDG, 1975).

24. Blake, "Wind Driven Water Pumps."

25. This point is made most strongly in Peter Fraenkel, "An International Programme to Produce a Wind-Powered Water-Pumping System Suitable for Small-Scale Economic Manufacture," presented to the Second International Symposium on Wind Energy Systems, October 1978.

26. Victor Englebert, "The Wizard of Las Gaviotas," *Quest*, May 1981.

27. Fraenkel, "An International Programme"; Peter Fraenkel, ITDG, private communication, May 13, 1981.

28. Darrow, "Locally Built Windmills."

29. Small wind turbines are discussed in detail in Dermot McGuigan, *Harnessing the Wind for Home Energy* (Charlotte, Vt.: Garden Way Publishing, 1978), and in Jack Park and Dick Schwind, *Wind Power for Farms, Homes and Small Industry* (Springfield, Va.: National Technical Information Service, 1978). The description of the technology in this and following paragraphs is taken from these sources.

30. Carl Aspliden, U.S. Department of Energy, private communication, June 4, 1981.

31. Theodore R. Kornreich and Daryl M. Tompkins, "An Analysis of the Economics of Current Small Wind Energy Systems," presented to the Third Wind Energy Workshop, Washington, D.C., May 1978. A figure of 50¢ to $1.00 per kilowatt-hour is used in U.N. Conference on New and Renewable Sources of Energy, "Report of the Technical Panel."

32. The figure of 100 manufacturers is a rough but conservative estimate based on a figure of 40 for the United States and an estimate of at least 60 in Europe from Carl Aspliden, U.S. Department of Energy, private communication, June 4, 1981; U.S. figure from Rockwell International, "Commercially Available Small Wind Systems and Equipment," Golden, Colo., unpublished, March 31, 1981; 1,000 to 2,000 wind machines figure from Ben Wolff, former president of American Wind Energy Association, private communication, June 10, 1981; Kevin Fountain, "New Energy Sources in China," *China Business Review*, September/October 1979; Rolf Brünbaum, "Alternative Energy Sources in the USSR," *Ambio*, Vol. 7, No. 2, 1978.

33. Wind Energy Program, "Commercialization Strategy Report for Small Wind Systems," U.S. Department of Energy, Washington, D.C., unpublished, undated.

34. W. S. Bollmeier *et al., Small Wind Systems Technology Assessment: State of the Art and Near Term Goals* (Springfield, Va.: National Technical Information Service, 1980).

35. Frank Farwell, "New Energy: A Burgeoning Business in Windmills," *New York Times*, April 27, 1980.

36. Eldridge, *Wind Machines;* Kurt H. Hohenemser, Andrew H. P. Swift, and David A. Peters, *A Definitive Generic Study for Sailwing Wind Energy Systems* (Springfield, Va.: National Technical Information Service, 1979); Irwin E. Vas, *A Review of the Current Status of the Wind Energy Innovative Systems Projects* (Springfield, Va.: National Technical Information Service, 1980).

37. D. E. Cromack, *Investigation of the Feasibility of Using Wind Power for Space Heating in Colder Climates* (Springfield, Va.: National Technical Information Service, 1979).

38. Wind Energy Program, "Commercialization Strategy Report"; Bollmeier *et al., Small Wind Systems Technology Assessment.*

39. Cost-of-energy figures are at best approximate, and several manufacturers claim their machines can produce electricity for less than 15¢ per kilowatt-hour. The actual figures, however, are usually higher; see Bollmeier *et al., Small Wind Systems Technology Assessment,* and U.N. Conference on New and Renewable Sources of Energy, "Report of the Technical Panel."

40. "Bendix Converts $750,000 Loan into 30% Equity Holding of Enertech," *Solar Energy Intelligence Report*, June 15, 1981.

41. John A. Garate (of General Electric Company), "Wind Energy Mission Analysis," presented to the Third Wind Energy Workshop, Washington, D.C., May 1978.

42. Arthur D. Little, Inc., *Near-Term High Potential Countries for SWECS Final Report* (Springfield, Va.: National Technical Information Service, 1981).

43. Information on Denmark from B. Maribo Pedersen, "Windpower in Denmark," presented to the California Energy Commission Wind Energy Conference, Palm Springs, Calif., April 6-7, 1981 (referred to in following notes as Palm Springs Wind Energy Conference).

44. Economies of scale for large wind turbines are discussed in Lockheed California Company, *Wind Energy Mission Analysis*, and in Grant Miller, "Assessment of Large Scale Windmill Technology and Prospects for Commercial Application," working paper submitted to National Science Foundation, Washington, D.C., unpublished, September 8, 1980.

45. Large-wind-turbine technology is discussed in National Aeronautics and Space Administration, "Wind Energy Developments," in Eldridge, *Wind Machines*, and in "Going With the Wind," *EPRI Journal*, March 1980.

46. This figure is a conservative one based on the assumption that an average house uses 600 kilowatt-hours of electricity per month and that the wind machine operates at a capacity factor of less than 50 percent.

47. The NASA program is discussed in National Aeronautics and Space Administration, "Wind Energy Developments," and in Miller, "Assessment of Large Scale Windmill Technology."

48. B. Maribo Pedersen, "The Danish Large Wind Turbine Program," presented to the Wind Energy Workshop on Large Wind Turbines, NASA Lewis Research Center, Cleveland, Oh., April 1979; Pedersen, "Windpower in Denmark"; "Great Britain to Build 3 MW, 250 KW SWECS," *Wind Energy Report*, January 1981.

49. National Research Council of Canada, "Canadian Wind Energy Research and Development," Ottawa, unpublished, undated; Paul N. Vosburgh and John E. Primus, "Wind Energy for Industrial Applications," 1980 Fall IE Conference Proceedings, conference site and date unknown.

50. David Taylor, Bendix Corporation, private communication, March 23, 1981; Mr. Wolfe, Hamilton Standard Company, private communication, March 23, 1981.

51. The involvement of U.S. utility companies in wind-power projects is described in Mary C. Wentworth, *Electric Utility Solar Energy Activities: 1980 Survey* (Palo Alto, Calif.: Electric Power Research Institute, 1980); R. H. Taylor and D. T. Swifthook, "Windpower Studies in the C.E.G.B.," presented to the Fourth Biennial Conference and Workshop on Wind Energy, Washington, D.C., October 29-31, 1979; National Swedish Board for Energy Source Development, "The Swedish Wind Energy Program," Stockholm, unpublished, February 24, 1981.

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53. U.S. Windpower program discussed in Ellen Perley Frank, "Breaking the Energy Impasse," *New Roots*, (month unknown) 1979, and in "World's First SWECS Windfarm Built on Mountain Ridge in New Hampshire," *Wind Energy Report*, January 1981; Windfarms Limited projects are discussed in Jane Wholey, "Hawaii: New Dynasty in Renewable Energy," *Solar Age*, May 1981, and in Windfarms Limited, California Dept. of Water Resources, and Pacific Gas & Electric Co., "350,000-Kilowatt Wind Farm."

54. Wayne Van Dyck quote from speech at the Palm Springs Wind Energy Conference; Wholey, "Hawaii: New Dynasty in Renewable Energy."

55. Danish estimates described by Pedersen, "Windpower in Denmark"; British estimate from David Lindley of Taylor Woodrow Construction Ltd. at the Palm Springs Wind Energy Conference; U.S. estimate in Robert Lowe, "Expected Electricity Costs for the U.S. Mod-2 Windmill," *Energy Policy*, December 1980, and in Miller, "Assessment of Large Scale Windmill Technology."

56. Information on the Soviet Union from *Solar Energy Intelligence Report*, July 9, 1979.

57. North Sea study described by David Lindley of Taylor Woodrow Construction Ltd. at the Palm Springs Wind Energy Conference; Judy Redfearn, "The Prospect for Ocean-Going Windmills," *Nature*, April 24, 1980.

58. Information on availability of sufficient wind for wind pumps from Alan Wyatt, Volunteers in Technical Assistance, and Peter Fraenkel, ITDG, private communications, April 28 and June 2, 1981.

59. The importance of irrigation for agriculture in developing countries is discussed in Food and Agriculture Organization, *Energy for World Agriculture* (Rome: 1980).

60. Some of the best material on global wind availability is included in Pacific Northwest Laboratory, "World-Wide Wind Energy Resource Distribution Estimates"; this is a broad view of wind availability, and more detailed material is available only on a limited and regional basis.

61. The potential cost-effectiveness of intermediate-sized wind turbines is discussed in Bollmeier *et al.*, *Small Wind Systems Technology Assessment.*

62. The large variation in electricity prices and their impact on the economics of wind energy are discussed in U.N. Conference on New and Renewable Sources of Energy, "Report of the Technical Panel."

63. *Ibid.*

64. General data on wind availability from Pacific Northwest Laboratory, "World-Wide Wind Energy Resource Distribution Estimates."

65. The 20- to 30-percent figure is of course approximate and is based on estimates for particular areas made in Lockheed California Company, "Wind Energy Mission Analysis," in Matania Ginosar, "A Proposed Large-Scale Wind Energy Program for California," *Energy Sources*, Vol. 5, No. 2, 1980, in Michael Dubey and Ugo Coty, *Impact of Large Wind Energy Systems in California* (Sacramento, Calif.: California Energy Commission, 1981), and in Redfearn, "Prospect for Ocean-Going Windmills."

66. California Energy Commission, "Wind Energy Assessment of California," Sacramento, Calif., March 1981; Nancy Phillips, "Wind Farms Blow U.S. Land Prices Sky High," *Canadian Renewable Energy News*, April 1981.

67. World Meteorological Organization activities from Carl Aspliden, U.S. Department of Energy, private communication, June 4, 1981; the World Meteorological Organization map is Pacific Northwest Laboratory, "World-Wide Wind Energy Resource Distribution Estimates."

68. Roderick Nash, "Problems in Paradise: Land Use and the American Dream," *Environment*, July/August 1979.

69. General information on land-use problems from Robert Noun, Solar Energy Research Institute, speech at Palm Springs Wind Energy Conference; Lincoln Sheperdson, "Vermont Citizens Move to Protect National Forest from Wind Turbine," *Canadian Renewable Energy News*, December 1980.

70. Thomas O'Toole, "Windmill Experiment Ordered Limited," *Washington Post*, April 22, 1980; D. L. Sengupta and T. E. A. Senior, "Electromagnetic Interference to TV Reception Caused by Windmills," presented to the Third Wind Energy Workshop, Washington, D.C., May 1978.

71. Favorable results of surveys carried out at experimental turbine locations described by Robert Noun, Solar Energy Research Institute, speech at Palm Springs Wind Energy Conference.

72. "A High-Risk Era for the Utilities," *Business Week*, February 23, 1981; John E. Bryson, "Energy Utilities: The Next Ten Years," California Public Utilities Commission, San Francisco, Calif., unpublished, March 27, 1981; "Wind and Utilities," *Wind Power Digest*, Fall 1979.

73. "Wind and Utilities"; W. D. Marsh, *Requirements Assessment of Wind Power Plants in Electric Utility Systems* (Palo Alto, Calif.: Electric Power Research Institute, 1979); an energy analyst in Australia has calculated that for small electricity grids wind power has approximately the same reliability as a nuclear power plant, as reported in Mark Diesendorf, "Australian Wind Reliability," *Wind Power Digest*, Spring 1981.

74. Clifford Barrett, "Bureau of Reclamation's Wind/Hydroelectric Energy Project," presented to the Fourth Biennial Conference and Workshop on Wind Energy, Washington, D.C., October 29-31, 1979; Charles A. Lindley, "Wind Machines for the California Aqueduct," presented to the Third Wind Energy Workshop, Washington, D.C., May 1978.

75. Information on Denmark from B. Maribo Pedersen, Technical University of Denmark, private communication, April 6, 1981; Reinier H. J. H. Lock, "Encouraging Decentralized Generation of Electricity: Implementation of the New Statutory Scheme," *Solar Law Reporter*, November/December 1980; "P.U.R.P.A. and Small Systems," *Wind Power Digest*, Spring 1981.

76. The government programs in Denmark, Sweden, and the United States are described in International Energy Agency, *Large Scale WECS Annual Report* (Stockholm: National Swedish Board for Energy Source Development, 1981); information on the Soviet Union from *Solar Energy Intelligence Report*, July 9, 1979.

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78. B. Maribo Pedersen, Technical University of Denmark, private communication, April 6, 1981; U.S. Department of Energy, "Federal Wind Energy Program Fact Sheet," Washington, D.C., unpublished, June 25, 1980; Kent Rissmiller and Larry M. Smukler, "An Analysis of the Legislative Initiatives of the 96th Congress to Accelerate the Development and Deployment of Wind Energy Conversion Systems," Energy Law Institute, Concord, N.H., unpublished, June 17, 1980.

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80. International Energy Agency, *Large Scale WECS Annual Report;* Prince Jones, Rocky Flats Wind Systems Program, Golden, Colo., private communication, April 9, 1981.

81. U.N. Conference on New and Renewable Sources of Energy, "Report of the Technical Panel."

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