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Regional Wind Energy Development

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SERI

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ABSTRACT

Regional wind energy development is reviewed with emphasis on wind resources and applications in the western United States. The conclusions of existing major studies are noted to indicate the importance of wind energy as a major energy source, its relative place among the other solar technologies and expected social benefits. Problems of wind resource assessment of special importance to the West are described and previous work on wind energy, hydro-electric power, and water resources are summarized. The roles of the Regional Solar Centers and the National Solar Energy Research Institute are discussed and possible areas of interaction in the western region are indicated. Further activities in the development of wind energy technology and its utilization are also described.

I. THE IMPORTANCE OF WIND ENERGY

Several recent studies [1, 4, 5] have taken a new look at all solar technologies and at the relative cost, social benefits, and energy potential at each. Although the detailed projections of these studies differ, each has indicated a very important role for wind energy. A comparative analysis of solar technologies and the potential market impact of each was recently completed by the MITRE Corporation [1]. The societal and ecological benefits of using solar energy instead of relying on coal or nuclear fuels were not included in this study. This analysis was based on computer simulations of solar energy utilization and market impact by region and market sectors up to the year 2020. The broad conclusions of that study were the following: solar energy may eventually displace significant quantities of both fossil and nuclear fuels; significant solar contributions are expected in all regions; federal incentives to promote solar-electric technologies could strongly accelerate their acceptance and use; and most solar systems generally have a rapid net energy payback that should result in a long-term reduction in resource consumption.

Market Penetration

At the present rate of solar development, the projected solar contribution was 0.2 quads by 1985, 6 quads by 2000, and 34 quads of energy displacement per year by 2020. It is of interest to note that nuclear power--after 20 years of development--now contributes less than half of the 6 quads projected for solar after an equal period of development. Wind energy was expected to be the second largest source of solar power by the year 2020 through production of utility electricity in a fuel-saver mode. The projected market response for wind energy by 2020 was more than 6 quads per year of energy displacement.

The four market sectors considered in developing these projections were low temperature heat, process heat, electric utilities, and synthetic fuels. Wind energy was compared with several solar technologies--solar thermal, photovoltaics, biomass, ocean thermal--only for the generation of electric utility power, but dispersed wind energy was not considered. Competing conventional systems included combinations of coal, oil, and nuclear power. Wind energy devices were assumed to have a lower capital cost per kilowatt hour and a capacity factor at least as high as other solar technologies. In addition, wind energy was assumed to be available wherever windy sites occurred, whereas solar-thermal and photovoltaic systems were projected for use only in the Southwest. Wind energy was projected to be cost-competitive in areas with winds averaging about 7 m/s or more. It is estimated [2] that approximately 407,000 square kilometers within the United States have such winds and that approximately 14% of this area is potentially available for development. Deployment of over 100,000 units at high wind sites could displace 6.6 quads of energy per year, but would represent only one-quarter of the maximum potential market. To fulfull this need, a peak annual production of about 6,000 1- to 2-MW capacity units at a capital cost of about $800/kW was projected. These projections are considerably higher than earlier DOE estimates for wind energy [3]. As a result, wind energy dominated the solar technologies in the electric utility sector with an expected installed capacity of from 40 to 60 GW by 2000, and delivered energy ranging from 1.7 to 3.0 x 10^{11} kWh/yr. Differences in projected delivered energy depend on the different federal policies and incentives assumed.

Wind and Solar Energy

The President's Council on Environmental Quality summarized recent technical and economic progress [4] leading to perhaps the most optimistic official evaluation to date of future solar energy applications. That study concluded that with a serious effort to conserve energy, solar technologies might meet one-quarter of our national energy needs by the year 2000. To meet that goal, a wide variety of solar approaches would be required. A total of 20 to 30 quads of displaced fuel per year was estimated by 2000, with wind energy as one of the largest single solar energy sources. It was concluded that the rate at which wind energy can be introduced into the economy will depend heavily on the results of current research programs and on subsequent commercialization efforts. Increased emphasis on smaller scale applications was recommended, under the assumption that smaller systems can be deployed and tested within much shorter times and may, due to manufacturing mass production economies, be the most cost-effective in the long run. An aggressive program to deploy solar technologies in developing countries and thus promote a large enough world market to justify mass production was recommended. Wind energy systems can meet many of the needs of these countries. Relatively small systems can provide energy at dispersed sites without the expense and delay of extensive transmission networks. Simplicity of design can lead to rapid manufacturing of decentralized equipment. While present wind energy equipment cannot compete well with the relatively low electric power rates of 3¢-6¢/kWh in the United States, it is much more competitive abroad. Competitive prices in the developing countries are as high as 45¢/kWh for central power grids, and rural areas may pay as much as $1/kWh for diesel generator electric power.

Social Benefits

A third major review of the federal solar program was recently completed [5] for DOE by SRI International. Many factors, in addition to the number of projected quads of energy delivered in future years, were addressed. The social benefits considered were energy contributions, environmental value, indigenous energy value, conservation of fossil fuels, potential for major technical advances, compatibility with present energy systems, and export market value. The comparative merits of seven major solar technologies were addressed but not evaluated relative to nonsolar options. Each solar technology was ranked in terms of its expected overall benefit to society in future years. In the near term (1985), the three solar technologies of greatest benefit to society are solar heating, biomass, and wind energy. In the intermediate term (2000), the two of the greatest value are solar heating and wind. In the long term (2020), the solar technology of greatest benefit to society was wind energy, which was ranked significantly higher than all competing solar technologies. The results of the ranking process are shown in Table I. In addition, it was also indicated that both wind energy and photovoltaics might produce even greater social benefits under increased research emphasis. These results were meant to provide general guidance to DOE in the formulation of solar energy research, development, and deployment decisions.

Economic Factors

The range of uncertainty in future costs of wind turbines was believed to be smaller than for other solar-electric options. This is because the technology of towers, blades, transmissions and controls are relatively familiar and considerable experience exists in manufacturing of small commercial units. Cost estimates for large wind energy devices can be determined for horizontal- and vertical-axis machines with power ranges of 0.2 MW to 1.5 MW. Most estimates in dollars per kilowatt are based on conceptual designs projected to 100 unit production costs. Present values range from about $500 to $1400 /kW. Current costs for small wind turbines are available for commercial units which range in size from a few to about 50 kW. Costs vary considerably, but a number of units are available at prices of $2000 to $3000 /kW.

The study concluded that horizontal-axis wind turbines may well be economically practical today. The economics of wind energy depend heavily on the mean wind velocity. Although it was concluded that large wind turbines in areas of high mean wind speeds may produce electricity at a cost competitive with electricity from fuel oil today, the most likely candidates for near-term economical generation of electricity included machines of all scales--15 kW, 200 kW, and 1.5 MW. The other important application of wind energy identified was in agricultural water pumping. Small wind turbines have a long and successful history of use for this purpose.

Wind Resource and Limitations

In examining wind utilization, three issues were considered: the wind resource; the wind machines; and integration of the resource, the machine, and the application. In considering the resource, it is useful to note that the sunniest areas of the southwestern United States have a mean insolation of less than 300 W/m^2. Many United States sites have mean wind fluxes of more than 500 W/m^2 (measured in the vertical plane). Some sites, where speeds are enhanced by topography, have very high mean energy fluxes of 1,000 W/m^2 or more. Furthermore, the potential wind resource is enormous. Very large amounts of wind power have been estimated in other studies based upon the mean kinetic energy of the atmosphere. Not all of this energy, however, is available in a practical sense. When a reasonable energy extraction rate and other limiting factors are assumed, a power extraction of about 2.5 TW can be estimated for the United States [6], based on only those areas with the highest wind speeds.

In the evaluation of social benefits, the technical limit of each technology was evaluated rather than a projected market penetration. All technical limits were expressed in quads of energy, fossil fuel equivalent. The largest technical limit, 29 quads, was estimated for wind energy. Although significant technical difficulties were recognized, the technical limit was chosen to represent the maximum contribution expected under favorable circumstances. The maximum potential use of wind energy in the United States is not easy to determine because the wind resource is so large and matching it to suitable applications is so important. Nevertheless, several independent studies [1, 2, 7] have all indicated market saturation limits in the range of 20 to 30 quads for wind energy.

Recommended Program

Because the wind can be used in so many applications, the energy resource is so large, and many applications have near-term economic promise, additional effort to develop this technology was an obvious policy issue. Recommendations for an expanded program [5] included the following: (1) simultaneous development of several different megawatt-scale wind turbines tailored to a wide variety of different sites; (2) accelerated demonstration or experimental programs involving field use of equipment in conjunction with utilities; (3) operational tests of prototype multiunit "wind farms"; (4) continued development of unusual or innovative concepts and designs; (5) additional effort to inventory potential wind sites including the specific requirements of potential users; and (6) providing assistance to industry in equipment design and material selection.

TABLE I
SOLAR TECHNOLOGIES RANKED BY TOTAL BENEFITS[1]

1985		2000		2020	
System	Ranking	System	Ranking	System	Ranking
SHACOB	79	SHACOB	86	Wind	90
Biomass	68	Wind	78	SHACOB	73
Wind	67	Biomass	49	Photovoltaics	65
Photovoltaics	21	Photovoltaics	36	Biomass	48
Thermal Power	12	OTEC	17	OTEC	40
Process Heat	10	Thermal Power	16	Thermal Power	35
OTEC	1	Process Heat	11	Process Heat	21

Each technology could receive a maximum of 100 points, and the ranking gives a relative figure of merit for comparison of one technology with another. In 1985 wind and biomass have an almost equal ranking and are rated well above all technlogies except solar heating. By 2000 wind is only slightly less beneficial than solar heating, and by 2020 it is a clear first choice among all solar technologies. Wind energy conversion devices thus produce high social benefits in all time periods. Important expected benefits include the large potential energy contribution, conservation of oil and gas, and near-term economic competitiveness with alternative energy sources.

[1]As determined in A Comparative Evaluation of Solar Alternatives: Implications for Federal RD&D, Volumes I and II, SRI International, prepared under contract for the Solar Working Group, U.S. Department of Energy, January 1978.

II. WIND ENERGY IN THE WESTERN UNITED STATES

Locations with the highest wind energy densities commonly occur in mountainous or coastal regions. Therefore, many sites in the western United States may be favorable locations for early deployment of wind energy collection systems. Additional areas of high wind energy also exist on the western plains somewhat east of the Rocky Mountains. The siting and wind resource assessment techniques useful over much of the Midwest are not appropriate for the western parts of the nation. Mountainous regions experience complex flow variations, and rugged coastal areas are also affected by the land/sea influence on large-scale weather systems. These complex atmospheric flows require detailed measurement and modeling efforts for optimum siting and energy conversion.

National Resource Assessments

Several studies of the wind energy potential nationwide have been conducted [2, 7, 8, 9]. The conclusions of these studies were similar but not quantitatively identical. In all cases, the greatest uncertainty about the resource existed in the mountainous regions. Available data for these areas are less representative of the true wind energy potential than data for other parts of the nation. The wind power available on mountain peaks and in valley areas depends as much on the shape and alignment of the local terrain and on large-scale regional weather patterns as it does on the height of the mountains. Wind speeds are sometimes greatest on mountain peaks, and in other cases are strongest in gaps between mountains [10]. Only mean wind speed summaries are readily available for many stations, and attempts to estimate the wind energy potential from such records have been shown to underestimate by over 50% the wind energy at some windy sites in the Pacific Northwest [11]. Several areas of possible error or uncertainty in wind power estimates have been noted [9], including atmospheric density variations, year-to-year changes in mean annual wind speed, sheltered or nonrepresentative instrument exposures, vertical extrapolation (which is most difficult in complex terrain), and the interpolation of wind data to intervening locations (which also is difficult in hilly or mountainous areas). Consequently, considerable uncertainty exists with regard to the wind potential in the western region. Nevertheless, reasonable estimates of wind power over exposed areas (e.g., hilltops or open shoreline sites) indicate that large wind power densities are to be expected across the western United States. Energy densities of from 400 to 500 W/m^2 occur in Wyoming, and values of from 300 to 400 W/m^2 are common over the mountainous parts of New Mexico, Colorado, Montana, Idaho, and the coastal areas of California, Washington, and Oregon. The evidence of a high wind energy potential in this region underscores the need for a more refined resource assessment effort in this part of the country. Another interesting feature of wind power in the western United States is that the seasonal maximum occurs in the winter. The wind, therefore, correlates with seasonal heating demands and may also supplement hydroelectric power at the time when minimum water flow is available.

Wind-Hydroelectric Power

Several studies have considered the combination of wind power with hydroelectric power in the West [12, 13]. These studies have included both pumped storage and the substitution of wind energy for water usage in hydroelectric generation. In work conducted for the Corps of Engineers [12], the wind power potential in the Pacific Northwest was studied by evaluating six good wind energy sites in conjunction with the hydroelectric storage and generating capacity of the area. The wind measurement stations used were well exposed in windy areas and generally indicated much more available power than that indicated by nearby National Weather Service stations. Wind data from specific sites were analyzed to determine wind variability and the required amounts of hydroelectric storage for smoothing wind fluctuations. One way to reduce fluctuations in wind-generated power is to combine the power generated at diverse locations. Fluctuations in regional wind-generated power can be further smoothed by storing excess energy in existing hydroelectric reservoirs or at possible future pumped storage sites. By considering the wind data and representative pumped storage sites in the area, it was estimated that a typical storage site could provide about two days of storage for the output of approximately 350 wind turbines with rotor diameters of 40 meters. It was not assumed that the wind generators would be located at these hydroelectric sites, but rather at locations having the largest wind power densities.

Estimated Installed Capacity

Wind data were analyzed for hourly, daily, and monthly variations. A much higher diurnal variation was found in summer than in winter. The six-month period from February through July indicated a much higher power potential than the other months of the year. It was concluded that wind power alone is not reliable on a daily basis, but that it may be used very effectively to supplement hydroelectric power in the Pacific Northwest. If wind electric generation was established at each of the sites studied and suitable energy storage provided, then roughly 176 wind generators of 1.8 MW capacity each could be located at each wind farm. A total of about 900 such wind generators would produce an average of about 3.3×10^9 kWh annually. Energy policy studies for the Northwest concluded that the total installed capacity of wind generators over the next two decades would be limited by the logistics of manufacturing and installing large numbers of wind turbines, available hydroelectric energy storage, and the actual selection of sites. Based on these considerations, it was concluded that 500 to 2,000 MW capacity could be in operation by the year 2000. In order to achieve that objective, it was recommended that a few wind generators be installed in the near future in the Pacific Northwest in order to gain operational experience at prospective sites for wind energy development.

Wind Power and Water Resources

The combination of wind energy with hydroelectric power was considered for other parts of the West by the Bureau of Reclamation. A study of the estimated performance, cost, and marketing aspects of a large wind power system integrated with an existing hydroelectric network was completed [13] for a high wind region in southern Wyoming. This study also concluded that large wind turbine generators could be effectively and economically integrated with the federal hydroelectric system.

In the study, it was assumed that approximately 100 MW of installed capacity would be integrated with the existing hydroelectric system within the Colorado River Storage Project, which would serve as an energy storage system. Generation at hydroelectric facilities would be reduced by an amount equal to the wind turbine generation, thus storing water for later use in power generation or increased agricultural use. The wind site considered was Medicine Bow, Wyoming, where the annual average wind power is approximately 500 W/m^2. The available wind power at Medicine Bow is considerably higher in winter than in summer. This makes the integration of wind power and hydroelectric power easier because spring runoff from snowmelt in the Rocky Mountains provides more water for hydropower in the summer. Wind power is greatest in the winter when the least water is available for power generation. In addition, diurnal wind speeds in the area tend to reach a maximum in midday, corresponding to the period of peak daily power demand. Due to the high wind power potential at this site, a wind turbine designed for 1.5 MW could be provided with a 2 MW generator (at an increased capital cost of approximately 5%) and thus increase annual energy production by approximately 17%.

Integrating wind generators with energy storage permits redistribution of wind energy to meet either base load or daily peaking demands. Wind generators themselves supply energy but contribute little effective base load generating capacity. A hydroelectric facility supplies firm base load generation capacity. If only existing hydroelectric projects are used for back-up power, there is little or no increase in regional generating capacity. However, during periods of wind turbine operation, displaced hydroelectric capacity is available for other uses such as reserve capacity, emergency assistance, and short-term power sales. The several advantages of using hydroelectric storage include the following: a considerable amount of energy can be stored; no new technology is required; existing storage is available for immediate use by wind generator networks; and additional pumped storage could become available in the future. Thus it is probable that existing hydroelectric reservoirs can provide one of the most convenient and economical storage systems presently available for large amounts of wind energy. The combined system taps the energy in the earth's solar-hydrologic cycle (wind, rain, and sea) and has the potential to make wind power more convenient and economically attractive than as a fuel-saver only.

III. SERI AND THE REGIONAL SOLAR CENTERS

As its primary mission, SERI is to function as the DOE lead institution with regard to solar research, development, and demonstration activities nationwide. The Institute has been given the principal responsibility for management and performance of assigned solar research programs. It provides planning support to the Assistant Secretary for Energy Technology in the development of national solar energy policies and research plans and has the major role in international solar technology programs. SERI is also responsible for maintaining a capability in market analysis and in assessing institutional barriers to solar technology on the national and international level. In keeping with these national responsibilities, SERI will assist DOE in coordinating the national solar research, development, and demonstration program and could participate in certain programs carried out for DOE by the Regional Solar Centers and the states.

In carrying out their primary mission, the Regional Solar Centers are responsible, within their respective areas, as the lead DOE institutions for regional commercialization of solar technologies and for energy conservation integral to solar applications. Assignments to carry out these missions are through the Assistant Secretary for Conservation and Solar Applications. In addition, the Regional Solar Centers may undertake solar development projects which complement and support the national DOE program.

The establishment of a network of regional solar centers was based upon a decision by DOE that the most effective way to encourage widespread use of solar energy would be through a regionally diversified effort. Regional programs, to be effective, must be consistent with the requirements of the national solar effort. Both SERI and the regional solar centers are performers, along with many other laboratories, private organizations, and universities, in the national solar program. Within these guidelines, programs at SERI and the regional centers will encompass educational activities and distribution of consumer protection information, technology transfer programs, economic studies, and the identification of appropriate solar incentives. The regional centers have an important role in assisting states in their efforts to implement solar standards and incentives, to provide technical training for solar products, and to develop educational programs. Other additional important activities will certainly be undertaken also. The institutional framework in which wind energy will develop has not yet fully emerged. That framework includes the entire complex of public policy, product distribution and marketing, consumer attitudes, public information, lending practices, and other factors. It is very likely that regional considerations will have a strong influence on the evolution of many elements which constitute that institutional framework.

Regional Differences and Energy Needs

Different climatic conditions in different regions obviously affect the availability of various solar enery forms. Each region also has its own energy requirements and nonsolar energy sources. The relative value of wind energy in meeting local energy needs and in competing with alternative solar or nonsolar sources will be different for each region. This will be very important in influencing the rate at which specific markets for wind energy applications develop in different parts of the country. Thus, the local energy sources, energy demands, and energy economics will influence the commercial development of wind energy and can lead to dramatic regional differences in its rate of utilization. Several areas of analysis and development are most appropriately considered on a regional basis. One is the establishment of economic incentives through the selection of the most effective policies for each part of the nation. Local and regional land use policy can create either barriers or incentives for wind energy utilization, and local building codes must also be considered. Electric utility regulation as it impacts commercial development of wind energy is also important. This issue includes rate structures and regulatory jurisdiction as well as an active involvement of the utilities in the development and promotion of wind energy as a viable technology. Public information and technology transfer need to be oriented to the requirements of local businesses and communities. Assistance at the regional level should be provided to private enterprise in the transfer of wind technology from the research and demonstration stage to commercial products and services. The service industry to distribute, site, and maintain wind energy systems obviously must be built at the local level. A well organized regional involvement will contribute significantly to these objectives.

SERI Wind Program

It is useful at this point to give a brief statement of the SERI program in Wind Energy Utilization. Both the technical and nontechnical aspects of wind energy are treated in the SERI program. There are several primary objectives of the effort. They are: to improve the wind energy resource data base, to determine the economic and environmental requirements for significant market penetration, to identify appropriate governmental policies and incentives that will promote such market penetration, to define the requirements of dispersed wind energy systems in small utility and nonutility applications, and to stimulate the development of innovative wind energy conversion devices. The program is divided into four major tasks which are:

(1) Wind Resource Data Improvement; (2) Market, Social, and Environmental Analysis; (3) Dispersed Applications and Systems Analysis; and (4) Innovative Wind Systems Program Management for DOE. The Wind Resource Data Improvment task involves field measurements, data analysis, and atmospheric modeling activities which address the specific siting and operational requirements of accelerated wind energy utilization. This activity is strongly concerned with meeting the data needs of a rapidly growing wind energy industry. The objective of the Market, Social, and Environmental Analysis task is to develop the information needed to design government incentives and to plan information dissemination efforts that will accelerate utilization of wind energy, especially in nonutility applications or with small utilities. This task will complement ongoing work by selecting several promising applications for detailed market, social, and environmental analyses. The Dispersed Applications and Systems Analysis task addresses near-term applications of wind energy in integrating units with small utilities, matching of equipment in nonelectric usage with industry or agriculture, and performance and cost analyses of electric and nonelectric wind energy conversion devices. The objective of the Innovative Wind Systems Program is to support research that may lead to technological breakthroughs or other improvements which result in more cost-effective wind energy devices for various applications. Management of this program involves issuing solicitations for research proposals and continual review of subcontracted research with respect to the objectives of the DOE national wind program.

Related SERI Activities

Accomplishment of tasks within SERI will be achieved by using the results of both the operational divisions of SERI and results from work contracted to organizations outside SERI in direct support of internal task objectives. A related major activity of SERI is the development of a comprehensive collection of solar energy information. This will provide a unique and valuable resource to the wind energy community. SERI has been assigned responsibility by the Congress for development and operation of a Solar Energy Information Data Bank. It will provide a centralized and comprehensive system to furnish technical and nontechnical information to local agencies, states, and other groups. It will also support a national library and computer system to provide models, data, and library services to researchers across the country. SERI is also active in international wind energy programs with Saudi Arabia, Spain, and the International Energy Agency. In addition, the Institute will also have a major involvement in the support of conceptual research within the academic community.

State, Regional, and National Efforts

What are some specific areas of possible interaction with the western region in wind energy development? The western region has a large wind energy resource. Much of the area is mountainous and requires special siting techniques for optimum use of wind energy. Large-scale hydroelectric facilities are broadly distributed with over half of the national capacity located in the Pacific Coast region. Studies of the integration of wind energy conversion devices with hydroelectric systems for storage and water conservation have been mentioned above. Cooperative programs within the region to evaluate the wind-hydroelectric potential are a possible area of activity. SERI can take an active role in working with other federal departments and agencies in such activities. State programs to test wind turbines under local conditions are another area of possible future interaction. The advantages to the national program would be in developing standarized methods for site documentation and in developing performance information on a variety of turbine designs and sizes in different parts of the country. Wind power could be an attractive alternative for small-scale rural electricity users. Problems encountered in siting or in equipment design to meet an important regional application might be referenced to the SERI research program. Applications of wind energy in water pumping are another area of regional interest. Water is an extremely valuable resource in the West. Demands for irrigation in the West might be met by wind energy in many locations. Nonagricultural water pumping may also use wind energy. These applications include pipelines, aquaducts, municipal water systems, and water treatment facilities. The match between the local wind resource, available wind turbine hardware, and pumping requirements would require study. The wind may also be combined with low-head hydroelectric power throughout the West. Low-head water power is one option in providing energy storage. A first step would be correlating the wind resource in the West with potential low-head water resources and testing available wind and hydroelectric hardware to determine its suitability and economic value in supplying energy. In all these activities the Regional Solar Centers, state, and local governments can be an effective force in resolving regulatory and land use problems.

IV. WHAT IS NEEDED

Additional work in three areas is needed to promote the accelerated use of wind energy. There is a need for greater operational experience with wind turbines and much more performance data for actual machines of different types in various applications and environments. A growing involvement of the private sector and a flexible approach to the design and development of hardware are also important. Additional meteorological data specific to wind energy are needed, as well as further work in developing and testing siting methods. Further comments on these three areas are given below.

Performance Evaluations

In the area of performance data and operational experience, it is important to begin a comparative evaluation of different hardware designs at the same site. Ideally, several sites across the nation with significantly different climatologies would be used in these experiments. Comparative testing of vertical-axis and horizontal-axis wind turbines at the same location is important. Several designs of each major type should be tested together. Such plans should include full instrumentation to measure both the wind environment and equipment stresses and power ouput. Accelerated test procedures could be considered and compared with actual field experience. Public viewing at the test sites can also increase awareness and interest in wind energy.

Intermediate sized machines with rotor diameters of approximately 40 meters and power outputs of from 100 to 500 kW are well suited to comparative testing. The unit cost of such wind turbines is far less than that of the largest units that may ultimately be used for utility power generation. The collection of operational and performance data should proceed in parallel with a research program to solve siting and engineering problems as they occur, and to develop and test operational strategies for either individual machines or "wind farms." This activity would also provide valuable information on equipment reliability and possible environmental or safety problems. To be most effective, the performance data and operational experience must be freely and rapidly exchanged with equipment manufacturers and future wind energy clients in the private sector.

Applications

Wind energy is unique among the solar forms in that it can directly provide mechanical power in the range of from 1 to 1000 kW or more per unit. A wide variety of applications for wind energy exist. It is well suited for remote power at windy sites, for irrigation; for telecommunications power; for water aeration; small industrial applications, and recreational sites; for crop drying and fertilizer production; and in space heating, either directly or by powering a heat pump. Such applications are in addition to large-scale utility power delivery and distributed electric power generation in conjunction with a utility grid. Future equipment designs should be tailored to their application and the wind resource at their intended site. Different physical environments imply different materials problems. The ocean or coastal environment, for example, obviously presents different problems than does a desert site. Ideally the site-specific wind characteristics, wind turbine hardware, intended application, and load all should be included in an engineering design optimization for a given site. This can be approached in practice through the phased development of turbines and relatively minor design refinements to maximize delivered energy.

Hardware Development

A growing involvement of the private sector in wind energy is already becoming apparent. For all the reasons stated above, a flexible approach in equipment design is important in the development of future commercial products. One way to promote this objective is public sponsorship of a large number of designs in parallel at the small, intermediate, and large unit power levels. It is important that the "front end" risk and cost be removed in the early stages of development. As an example, American machines are now designed and built with non-metric unit parts. Standard international (S.I.) manufacturing techniques could be used in building prototype machines in the expectation that a substantial international market for wind energy products will exist. Subsequent industrial conversion to S.I. could thus be avoided in developing these completely new products. Early and significant involvement of the ultimate user, whether it is a utility company, an industrial client, or an agricultural center, is important. An expanded national effort will be required, however, to support several different designs at the 1 to 2 MW size for utility power. The program might also use a large number of intermediate sized machines (approximately 100 kW) in a developmental and testing effort. Machines up to 200 kW in power output can be used both in clusters and as single units. Intermediate sized machines can provide valuable information to manufacturers interested in serving both utility and nonelectric applications. Moreover, the risk of failure is reduced by performing experiments at the smaller sizes, and the lead time required is similarly reduced. Finally, attention will have to be given to building a service industry to distribute, install, and maintain wind turbines.

Meteorological Data

There are presently far less meteorological data collected specifically for wind energy development than there are for other purposes. A strong need exists for an improvement in data collection procedures to support wind energy. Seasonal and diurnal changes in the wind are important, as is the variation of the wind speed with height above ground, especially for the largest machines now planned. A standard approach to data collection and analysis would benefit the industry. This can be supported by a specialized data network for wind energy resource assessment. Many more measurements at remote or presently uninstrumented sites are needed. Modern automated measurement systems can and should be employed. A national data collection network implemented today can provide the long-term data needed ten years from today when large-scale wind energy utilization will occur.

Siting and Resource Utilization

Many approaches to equipment siting exist, but few have been broadly used. Specialized wind resource studies for different regional energy needs are critical. Measurement of many "nonstandard" meteorological parameters will be needed to document the suitability of each site and to provide data to optimally match machines to site applications. Presently available siting methods need to be tested and evaluated by applying them to a wide variety of applications in different geographic settings. Important wind characteristics include the low frequency variability of the average wind on an hourly, monthly, and yearly basis, as well as the sequence and duration of wind calms. Peak gusts and directional shear are important to determine structural requirements. Additional studies on wind turbine wakes are needed as a part of the siting problem to determine optimum machine spacing for local wind characteristics. Much more information is needed to determine vertical wind profiles as a function of atmospheric stability, surface roughness conditions, and surrounding terrain. Improved wind forecasts are important for either utility operations or to predict energy displaced by decentralized wind energy devices. Better forecasting methods are needed to estimate speeds 24 hours or less in advance. A wind speed decrease will require supplemental power generation, and a large speed increase (such as that accompanying a storm) may require protective action.

Improvement of present wind data calls for the review and evaluation of the data requirements necessary for industrial wind energy development. Wind tunnel models, analytical methods to interpolate wind data, numerical computer models, and field measurements all can be expected to contribute in siting and resource assessment studies. Present wind energy data acquisition procedures should be examined and improved methods developed through research and technology transfer activities. Standard methods of data collection and analysis can provide specific wind resource data for future needs.

Problem Areas

Certain problem areas need to be recognized. The economic value of wind energy cannot be simply determined. Wind turbines cannot be readily compared to other devices in terms of dollars per kilowatt of rated capacity. Present methods of indicating machine size are not ideal. For wind turbines, the rotor diameter required for annual energy delivered at a particular site is the primary factor of interest. Therefore, both rotor size and site resource characteristics should be used in comparing wind energy with alternative energy options.

The value of wind energy needs to be judged by the value of the energy it replaces. Energy costs in utility applications are not the same as in other applications. Utility power costs also vary greatly from one part of the nation to another and even more dramatically in other parts of the world. Present estimates indicate that wind energy can soon be economically competitive in many electric and nonelectric applications. Therefore, the achievement of predetermined cost goals is probably less important in the near term than the development, siting, testing, and evaluation of many different turbine designs.

Finally, we should consider what products need to be developed first. Although machines will surely be located in low wind speed areas, the known high wind speed regions within the United States offer a very large energy potential and substantial product market. Indeed, the resource in high wind speed areas alone greatly exceeds all projected saturation levels for wind utilization. Products tailored to the best resource areas thus can be expected to have the greatest opportunity to succeed both technically and economically in the next decade.

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