Working Group
Summary Report:

WIND CHARACTERISTICS AND SMALL WECS

by

R. N. Meroney

Prepared for

Battelle, Pacific Northwest Laboratory
Richland, Washington

AMS-ERDA Workshop on
Wind Characteristics for WECS
Boston, Massachusetts
June 2, 3, and 4, 1976

June 14, 1976

CEP75-76RNM-41

HISTORY OF WECS

PART I: Wind Characteristics Research

Introduction

Past experience with large power mills indicates that perhaps the most important factor controlling success or failure of these systems is site wind characteristics. Incorrect placement of a site of only a few miles may drop performance to 1/3 of the original expectations. The difference between the power available in an annual average wind of 10 mph versus 12.5 mph is 100 percent. Once a wind system is designed to optimally operate at a lower wind speed mechanical, aerodynamic and generating efficiencies may permit only a linear improvement at higher average annual velocities (Putnam, 1948).

Recognition of wind characteristic importance has led to a series of papers and monographs on the subject. In the classical wind power books by Putnam (1948) and Golding (1955) the authors devote 45 percent of the text to wind characteristics as they influence wind machine performance.

Knowledge Prior to 1940

It is likely that early mill wrights developed time honored "rules of thumb" to guide site selection and blade construction. Unfortunately little of this appears in any written record. Smeaton (1759) reported on perhaps the first recorded experimental investigations of wind effects on solid objects. In his study of windsail characteristics he recognized that "the wind itself is too uncertain to answer the purpose: we must therefore have recourse to an artificial wind." He decided to employ a rotating arm to move his model windmill through still air in a room. Smeaton's early conclusions as maxims guided windmill utilization far over a century. One maxim still significant to this day is "the effects of the same sails at a maximum are nearly, but somewhat less than, as the cubes of the velocity of the wind."

In 1891 Professor P. La Cour of Denmark established the first laboratory devoted to wind power experimentation. His research was aimed primarily at the improvement of windmill performance in a uniform flow field. He proposed Power α (sailarca) x (wind speed)^3. Although engineers were subsequently active in designing windmills from 1900-1940 the literature does not reflect any attention to meteorological characteristics of siting nor to the turbulent environment in which the mill resides.

Nevertheless a physical understanding began to develop through this period of how the atmosphere behaves near the surface. Morgans (1931) summarized a great deal of research on the relation of ground contours, atmospheric turbulence, wind speed, wind direction. Such information subsequently guided the estimation of the influence of terrain by Putnam and Golding. The possibilities of the increased power at greater altitudes resulting from the atmospheric boundary layer led Hönnef (Golding, 1955) to propose erecting towers 1000 ft into the air.

Knowledge 1940-1950

The first serious discourse on the effects of wind resulted in the team effort associated with the Morgan, Smith-Putnam Turbine in Vermont. Special wind research programs were carried out between 1940-1945 in charge of Sverre Pettersen, Meteorologist-MIT, assisted by Karl O. Lange, MIT, with Rossby, Charles Brooks, Harvard University, and Theodore Von Karman, California Institute of Technology, in consultation. An ecological program was carried out by Robert Griggs, George Washington University.

In order to proceed with design decision to manufacture the test mill a series of assumptions were made in 1939 covering the winds behavior. The assumptions concerned

1. The free-air wind velocity at mountain-top height in Vermont.--Based on climatological data from the nearest available meteorological stations an estimate was made of gradient wind velocities. (Recall no radar was available at that time--only pilot balloon records. It was subsequently found that these balloon trajectories were actually influenced by windward effects of the Green Mountain Range. Hence a conclusion may be drawn that extrapolation of climatological data into complex terrain, or in the vicinity of complex terrain may be very locally specific.)

2. The effect of the geometry of a mountain upon the retardation or speed-up of wind flow over its summit.--It was recognized that terrain may enhance or decrease mean wind speed, direction, or turbulence. Based on potential flow theory fer uniform flow over airfoils, it was estimated a speed-up factor of at least 1.2 should exist for the site at Grandpa's Knob. Unfortunately the influence of stratification which redirected air flow around the ridge rather than over it was under-estimated. An attempt to use wind tunnels to estimate speed-up effects failed. (At that time the importance of simulating the upwind velocity profile and thermal stratification had not been recognized)

3. Prevailing wind directions in the western foothills of the Green Mountains.--Prevailing wind direction was estimated from climatological sites and a nearby mountain top station corrected for an Ekman spiral. The team subsequently found there was a dislocation in the distribution of wind directions as compared with the Ekman spiral on the windward side of mountains.

4. Influence of the structure of the wind on design.--It was assumed that if the crest resulted in an acceleration of the wind flow turbulence would decrease; however gustiness could increase in the lee of a ridge if there was separation.

It was also assumed that the net velocity integrated over a disc area of 175 feet in diameter might change at the rate of 50 percent each second, throughout an interval of 1.6 seconds. The net direction might simultaneously change at the rate of 90 degrees in 1.0 seconds.

5. Influence of the structure of the wind on estimates of output.--It was recognized that the average of the cube of the wind was greater than the cube of the average wind. They felt this factor was between 1.02 to 1.14 probably not far from 1.10.

6. Influence of atmospheric density on output.--Mean annual densities were calculated from climatological records weighted for monthly variations as corrected for altitude.

7. Influence of Estimates of Icing on Design and Site Selection.--Concern about structural failure caused by icing led to selecting a site below 2000 feet and deliberate excess strength in the blades. It was subsequently found that blade flexing removed ice rapidly before buildup was serious.

Since the above information upon which these design decisions were made were not very satisfying the extended 1940-1945 observation program was planned. Fourteen mountain tops were instrumented, at four of which vertical velocities were routinely measured. Griggs examined tree deformation and correlated it with windiness.

Some of the conclusions of this effort may be listed as follows:

1. A wind mountain range may markedly dislocate the assumed Ekman spiral in the upwind direction and cause a subsequent decrease in velocity among the windward foothills.

2. Frequency distribution curves for hours of a given wind speed displayed characteristic skewed curves which were of a Pearson Type III shape. Circle curves may be estimated when only mean velocity is known.

3. Changes in the vertical or horizontal wind velocity was found to be only 15 percent over the blade disc for Grandpa's Knob. Summits covered with trees displayed a greater variation.

4. Gust records were never evaluated.-(this data might deserve further examination since few towers of the extent of the Knob Christmas Tree have ever been taken.)

5. An estimate of long term mean velocity appeared to require a minimum of five years record. A single years response may depart from the long term average by ±26 percent i.e. power could vary by 100 percent.

At the time Putnam published his book in 1948 he concluded:

> "In sum, we believe good wind turbine sites will be found at certain points in ridges lying athwart, or nearly athwart the flow of the prevailing wind; that they are not likely to be found among upwind foothills, although they may be found on downwind shoulders; and that the deformation of the trees will serve to arrange a list of potential sites in an order of merit and will indicate whether the wind flow at a potential site is sufficiently interesting to warrant a program of anemometry."

Advise for the small scale WECS user appeared in 1946 in the Kansas State College Bulletin published by Kloeffler and Sitz (1946). Although the authors advised "whenever possible, the farmer should secure service from a transmission line," they did provide some meteorological recommendations such as

> 1) "Wind velocities below ten miles per hour are of little value for the generation of electric energy."(An explanation is provided

of how to analyze climatological data to interpret wind frequency, annual power, and calms).

2) "The usefulness of the wind for generation of electric energy depends upon the number of hours it blows per year at velocities above ten miles per hour."

3) "The number of consecutive days of calm weather and the number of periods of calm weather determine the usefulness of the wind for producing electric energy."

Ailleret (1946) spoke to the problems of variations in the wind at scales of one second, one minute, hourly, daily, monthly, and yearly as they influence and power porduction and utilization. In this case, statistical correlations were considered between wind power availability and proposed load usage over a five year period. The conclusion was that there was little correlation to the hydraulic power available at different seasons in reservoirs and rivers. He also was concerned with the lack of correlation between his climatological sites and terrain features he felt were suitable WECS sites. Finally, an anemometer was proposed which directly measured wind power available as opposed to wind speed. (In much of the early work, even through the 1950-1960 period, considerable effort was spent to develop wind power-anemometers as opposed to wind speed-anemometers. More recent investigators appear satisfied with the response and evaluation of power from standard anemometer systems).

Knowledge 1950-1960:

During the latter part of the 40's and early 50's, a number of national efforts to harness the wind were active. The Germans under Hütter, the French under Argand, the Danish under Jull, and the English with Golding built a number of 50-100 kw machines and considered the requirements of wind characteristics. A fourteen nation working group met in March 1952 and the combined proceedings of their efforts was published under the auspices of the Organization for European Economic Cooperation, Working Party No. 2 (Wind Power). Eighteen of the forty-five reports are clearly identified as wind characteristic studies. These include climatological nationwide wind surveys, wind tunnel and electrolytic tank studies of the effect of topographical relief, and description of wind measuring instrumentation.

A perusal of these articles indicates that the most serious and productive effort was that of the Electric Research Association, U.K., under the direction of E. W. Golding. Technical Paper No. 11 (1949) by E. W. Golding specifically speaks to "The Potentialities of Wind Power for Electric Generation (with special references to small-scale operation)." The report discusses the need to size mill and battery storage to avoid over loading batteries such that they are not subject to periods of over charging. (Modern circuit control methods can avoid this problem). Site selection of small mills is concluded to be limited by application since it is expected transmission losses over any distance for a small system would be uneconomical. Golding also identifies four areas for further investigation:

> 1) "Investigations would be required to determine the behavior of the wind flowing over different shapes and types of ground surfaces, of the effect of altitude upon the wind velocity over hill summits, and of the shielding effect of obstructions at various heights and distances."
>
> 2) "It is doubtful whether sufficient information already exists relating to the magnitudes and durations of gusts and of the changes in wind velocity over small areas such as those which might be swept by an aero-generator propeller."
>
> 3) "The rate of change of both velocity and direction of the wind at different heights and with different wind strength are questions which would also repay study."

4) "...it would certainly be interesting to know how far downwind a second generator should be placed to avoid interference from one already operating."

A second paper contributed by Golding (Technical Paper No. 22, 1952) reviews the progress made in the intervening three years through extensive site surveys made over hills in Ireland, Wales, and the Orkney, Hebridean and Channel Islands. Golding suggested initial tests be made of speedup effects over models in electrolytic tanks. He provides a site scale classification running from A to E based on specific annual output. At a preliminary site selection stage meteorological measurements are to be made simultaneously at a prospective site and nearby climatic stations to permit calibration and adjustment of the long term records. Finally he proposes extensive on-site measurements at a number of heights up to the hub level for the best sites. Golding found strong simularity between sites of the velocity duration curves. He suggests a one parameter family based on mean wind speed. He does warn that this family may be limited to a North Atlantic regime. Conclusions drawn from their wind survey were

1) Meteorological isovent maps were a useful guide in selection of windy sites.

2) Local sites can often be found having average wind speeds 50 to 100 percent higher than isovent values.

3) Velocity duration curves for sites physically very different were always similar in shape.

4) Coastal hills are preferred.

5) Conical hills may be as good as ridges.

6) Altitude of a hill is <u>not</u> a sufficient criterion.

7) With sufficient expertise, annual speed can be estimated by an on site visit--but not from topographical maps.

8) Good hills have bare summits.

9) Vertical wind gradient over a hill is dependent on its shape. The steeper the hill, the nearer to unity will be the wind gradient.

Despite the questions which remained at that time, the Working Group states in the OEEO (1954) document that, "There is now sufficient fundamental information available on which to base reasonably sound estimates of the wind power and annual energy available at any given site and also that the essential requirements for a suitable site have now been determined."

The group does recommend there be some standardization of meteorological measurements, of instruments, of wind speed classifications, and of methods of presenting and analyzing the results. A bibliography of wind power was proposed. It is suspected that the bibliography and glossary of terms which eventually was published as WMO Tech Note No. 4 (1954) is that mentioned.

In 1954 the UNESCO organization sponsored a Symposium on Wind and Solar Energy at New Delhi, India, Some attention was given to meteorology, however the OEEC (1954) report and Golding (1955) are more comprehensive with respect to wind characteristics.

Golding (1955) gathered together his experience with wind power analyses into a book which summarizes international experience at that time. This text is still the most comprehensive treatise available on the subject of "wind characteristics." It must be the starting place for any serious examination of wind siting problems. Concerning flow over hills, Golding agrees with Putnam that there is no specific criteria by which to make economically useful quantitative prediction of the effects of topography on wind flow. He emphasized the advantages of actual "experience" and "know how" as necessary requirements for reliable results. In Chapter 9 Golding discusses the importance of wind structure in windmill blade and control design. Questions he attempts to answer are

(a) "What rates of change of velocity are likely to occur in gusts?"
(b) "What are the probable distributions of gust velocities in relation to the area swept by the blades?"
(c) "What climatic or topographical conditions are likely to bring about gusts creating dangerously high stresses?"

Some relevant information is quoted, but Golding admits most data is not in a form suitable for the requirements of the designer of a wind power plant.

Knowledge 1960-1965:

The United Nations sponsored a Conference on New Sources of Energy Resources (1961) in Rome. Fourteen papers deal with meteorological data. Golding in a General Report (GR/6(W))identifies wind characteristics by three classes (a) long period measurements, (b) medium period measurements, and (3) short period measurements. These classes may be associated with such purposes as (a) data for probable energy output at a given site, and (b) information which guides structural design on performance of a WECS.

Perhaps the most significant new results presented at this conference was the data of Frenkiel (W/33) who described for the first time the results of his extensive measurements over hills and ridges in Israel. He concludes a 1/3.5 slope bare ridge will provide the most uniform velocity profile at hill crest.

A specific discussion session in this conference was devoted to wind measurements and the selection of wind power sites. Since their concerns are still, by and large, current a copy of the General Report by Golding and the Rapporteur's Summation are Appendix 1 of this paper.

In the same year, Golding (1961) prepared a NATO report on wind power site characteristics. The paper deals with the characteristics of the wind as a source of power and outlines methods of obtaining and analyzing wind data. Selection of favorable sites for wind power is discussed. He summarizes specific research needs for wind studies, windmill construction, and utilization. Pages 21 and 22 of that report dealing with "Possible Lines of Research" are included herein as Appendix 2. Golding concludes there is one prime need, "That is for experience in using wind-power plants under practical conditions."

The 1961 U.N. Conference in Rome requested the World Meteorological Organization to provide guidance on the effects of topography on wind speeds near the grounds. WMO Technical Note No. 63 prepared by Davidson (1964) was the dying gasp of a world wide interest in wind power. The working group was also requested to suggest experimental and/or theoretical studies required in order that more guidance could be provided in siting of WECS. This latter request has not resulted in any written document available to this author. Most of the WMO report is a review of conventional meteorology as it applies to wind machines. The section on topographical effects, however, comes to the disheartening conclusion that

> "In general, it may be concluded that it is almost impossible *a priori* to estimate the numerical value of the speedup factor if indeed such a factor exists for any particular locality."

(This conclusion is based, however, on a hodgepodge of widely varying results where no systematic effort was made to control or record hill shape, surface roughness, stratification, etc.)

Knowledge 1965-1970:

No known contributions; wind power systems essentially abandoned.

Revived Interest 1970-Present (1976):

Many windmills were built and successfully operated up to 1965, but none were cost competitive with the energy supplied by coal and oil fired steam plants and hydroelectric plants. The almost simultaneous awareness of finite energy resources and the influence of conventional energy resource impact on the environment has led to a reawakened interest in Wind-Energy Conversion Systems. Moved by early utilization predictions by W. Heronemus and the encouragement of energy conscious Congressmen like M. Gravel, a Solar Energy Panel was organized jointly by NSF and NASA which estimated 19% of the predicted annual electricity requirements by the year 2000 could be supplied by winds.

In March 1973, NSF and NASA held a workshop on WECS and prepared a set of proceedings (Savino, 1973). One paper by Nelson and Gilmore spoke to the need for a regional wind study. The proceedings includes a report from a working group on wind characteristics and siting. The committee called for

1. A search for all existing wind data and a summary prepared. (subsequently Changery (1975) prepared a guide to data compiled at the National Climatic Center.)
2. Collection of a minimum of 12 months of data at 10 and 30 meter heights at several prospective sites.
3. A detailed study of turbulence structure based on existing tower data. In addition it was suggested the literature of dynamic loading of structures be surveyed for relevant material.
4. The possibility of significant weather modifications by windmill clusters be examined.

Pages 209 to 212 of the Wind Characteristics Committee are included as Appendix 3.

Thirty individuals participated in a 3-day meeting at the National Climatic Center on July 29-31, 1974. Discussions included present data base and climatologies, data requirements, extrapolation and interpolation procedures, statistical and physical modeling, and additional research. Changery (1975) condensed the groups discussions, recommendations, and conclusions into Part 1 of his report. Part 2 summarizes that data currently available at the National Climatic Center and recommends some sources for that data not catalogued (say gust and maximum winds and turbulence data). Part 3 of this report are copies of four presentations prepared for the conference. Since the Part 1 summary is fairly concise, it is included as Appendix 4 of this report. The consensus of the individuals consulted was that extensive data collections and research already exists in many of the areas which concern WECS. The workshop recommended a survey be completed to translate this information into a form suitable for WECS design use. Since the present dat base is considered accurate only for non-mountainous areas, it is suggested that additional research efforts emphasize isolated hills and hilly and mountainous terrain. In addition, the working group recommended various tests be performed to validate the use of numerical and wind tunnel models before they are utilized in site analysis. Other statements reflected an interest in statistical techniques, gust and turbulence requirements, climate modification, and windmill sheltering effects.

In June, 1975, NSF and ERDA called together participants in current U.S. WECS program research as well as interested national and international WECS devotees to the 2nd WECS Workshop (Eldridge (1975)). Session VII included ten papers on wind characteristics. These tended to report research plans rather than results since the government funded programs were to a large extent only recently funded. Working Group E--Wind Characteristics/Site Survey, met for two evening sessions, a short report is copied as Appendix 5 herein.

It is not too surprising that the recommendations of the 1973, 1974, and 1975 Wind Characteristic Working Groups are very similar considering that many of the participants attended all sessions. Since the 1976 AMS-ERDA Workshop summarized here also retains some of the same membership, it is to be expected some consensus will appear. If there is any one conclusion which can be drawn, it is that most people consulted feel an adequate data base exists, but that it needs to be compiled, interpreted, and massaged into a form convenient for WECS users and designers. Since this same consensus has appeared four times, it would be appropriate to immediately proceed to finance this part of the WECS Wind Characteristic effort.

Part II

Working Group in Wind Characteristics for Small Systems

The group defined small WECS as those devices smaller than 100 kw. A further division based on size suggested was

a) 2-5 kw: "Sears-Roebuck" variety installations, designed for multi-purpose, multi-location installation. User may be layman, individual entrepreneur, back yard mechanic, or sophisticated industry.

b) 5-30 kw: Upper limit of off the shelf designs, these require more design sophistication but may not be rebuilt for every user.

c) 30 kw -: Sophisticated design and utilization decisions required. Probably provided by larger engineering organizations.

The discussion was further divided along the lines recommended by Golding into meteorological data types based on time scale.

a) Long term averages - data on annual, seasonal, or monthly scales.

b) Medium period measurements - data on weekly, diurnal, or hourly scales.

c) Short period measurements - data on half hour, minute, 10 second time scales.

Finally the wind characteristics effect on WECS was considered from the view of

a) The user of WECS, or

b) The designer of WECS.

SPECIFIC RECOMMENDATIONS: WC - Small Systems

LONG PERIOD DATA:

1. Climatic data already exists which can provide siting potential for annual, seasonal, and monthly variations.

2. This data should be evaluated to provide regional maps of power, wind duration statistics, and severe weather classifications to permit extrapolation or interpolotion in regions of homogeneous terrain.

3. Existing surface layer log and power laws relatable to surface roughness, and displacement heights may adjust for vertical profiles in homogeneous terrain.

4. Data management instructions (handbooks) should be prepared which would permit extension agents or consulting meteorologists to utilize NWS data tapes of maps to predict power, duration of calms, with a speciciflable reliability.

5. In more complex terrain, calibration procedures should be validated on a set of representative sites. These include

a) Use of generic description of topographical features.

b) Specification of length of local data sufficient to confirm/ or deny correlation with available climatic data resources.

c) The use of regional numerical programs pre-prepared for use by the level of expertise expected of competent extension agents.

6. What is shadow effect to be expected for windmills in the presence of different terrain features? "Wind rights."

MEDIUM DATA PERIOD:

1. In severe storm areas icing and or hail may destroy windmills or towers. An engineering study should be performed to determine whether icing or max torque produced by high winds is likely to produce tower destruction.

2. Diurnal variations in a given area are necessary for storage choices.

SHORT DATA PERIOD:

This data is more for windmill designer than windmill user. Hence, data need not be necessarily generated or interpolated to all locations.

1. 2-5 kw machines are usually designed to withstand handling, which usually overdesigns for flutter, impact, etc. One could use maximum wind gust information to set controls.

2. 5-30 kw machines are expensive enough to require consideration of span wise loading produced by severe weather. Although some data exists for frontal systems, lee waves, and thunderstorms, little coherence data may be expected. This one area may require additional data from some existing sites in severe wind areas.

3. Data developed for large machines will probably be adequate for small system design--i.e., no special small scale data.

4. It can be expected that the Rocky Flat effort should help answer

   a) How close should meteorological station be to hub to correlate with behavior?

   b) Are additional design meteorological data necessary?

   c) Is icing a real problem?

REFERENCES

1) Ailleret, P., (1946), Wind Energy: Its Value and the Choice of Site for Exploration," "Revue Générale de l'électricite'," Vol. 55, March 1946, pp. 103-108.

2) Changery, M. J., (1975), "Initial Wind Energy Data Assessment Study," Results of a Data Survey and Recommendations and Conclusions of the Data Assessment Meeting, National Climatic Center. Asheville, N. C., July 29-31, 1974, NSF-FA-N-75-020, 125 pp.

3) Dresden, D. (Chairman), (1954), "Technical Papers Presented to the Wind Power Working Party," Organization for European Economic Cooperation Committee for Productivity and Applied Research, Working Party No. 2 (Wind Power). Compiled by London Liason Office, NRC of Canada, Printed by Her Majesty's Stationary Office, London, 433 pp.

4) Eldridge, F. R., (1975), "Proceedings of the Second Workshop on Wind Energy Conversion Systems," Washington, D.C., June 9-11, 1975, NSF-RA-N-75-050 (MTR-6970), 536 pp.

5) Golding, E. W., (1961), "The Influence of Aerodynamics in Wind Power Development," NATO-AGARD Report 401, (N63-80507), 45 pp.

6) Golding, E. W., (1955), "The Generation of Electricity by Wind Power," Philosophical Library, New York, 317 pp.

7) Kloeffler, R. G. and E. L. Sitz, (1946), "Electric Energy from Winds," Kansas State College Bulletin, Vol. XXX, No. 9, September 1, 1946, 34 pp.

8) Morgans, W. R., (1931), "A Memorandum Giving a Summary of Present Knowledge of the Relation Between Ground Contours, Atmospheric Turbulence, Wind Speed and Direction," Aeronautical Research Council, Technical Report No. 1456, Great Britain, pp. 679-717, plus 28 figures.

9) Putnam, P. C., (1948), Power from the Wind, Van Nostrand Reinhold Company, New York, 224 pp.

10) Savino, J. M., ed., (1973), "Wind Energy Conversion Systems--Workshop Proceedings," NSF/RA/W-73-006, (PB231341), Washington, D.C., June 11-13, 1973, 169 pp.

11) Smeaton, J., (1759), "An Experimental Investigation Concerning the Natural Powers of Water and Wind," Phil. Trans. Roy. Soc. of London, Vol. 51, pp. 100-174.

12) UNESCO, (1956), "Symposium on Wind and Solar Energy, Proceedings of," October 1954, New Delhi, India.

13) United Nations, (1961), "Proceedings of U.N. Conference on New Sources of Energy Resource: Wind Power," Vol. 7, August 21-31, 1961, Rome, Italy.

14) World Meteorological Organization, (1954), "Energy from the Wind, Assessment of Suitable Winds and Sites," Technical Note No. 4, WMO-No. 32. TP.10.

APPENDIX 1

General Report and Rapporteur's Summation From: "Proceedings of U.N. Conference on New Sources of Energy," Rome, August 21-31, 1961 Vol. 7, pp. 3-8 and pp. 15-17.

10) Savino, J. M., ed., (1973), "Wind Energy Conversion Systems--Workshop Proceedings," NSF/RA/W-73-006, (PB231341), Washington, D.C., June 11-13, 1973, 169 pp.

11) Smeaton, J., (1759), "An Experimental Investigation Concerning the Natural Powers of Water and Wind," Phil. Trans. Roy. Soc. of London, Vol. 51, pp. 100-174.

12) UNESCO, (1956), "Symposium on Wind and Solar Energy, Proceedings of," October 1954, New Delhi, India.

13) United Nations, (1961), "Proceedings of U.N. Conference on New Sources of Energy Resource: Wind Power," Vol. 7, August 21-31, 1961, Rome, Italy.

14) World Meteorological Organization, (1954), "Energy from the Wind, Assessment of Suitable Winds and Sites," Technical Note No. 4, WMO-No. 32. TP.10.

10) Savino, J. M., ed., (1973), "Wind Energy Conversion Systems--Workshop Proceedings," NSF/RA/W-73-006, (PB231341), Washington, D.C., June 11-13, 1973, 169 pp.

11) Smeaton, J., (1759), "An Experimental Investigation Concerning the Natural Powers of Water and Wind," Phil. Trans. Roy. Soc. of London, Vol. 51, pp. 100-174.

12) UNESCO, (1956), "Symposium on Wind and Solar Energy, Proceedings of," October 1954, New Delhi, India.

13) United Nations, (1961), "Proceedings of U.N. Conference on New Sources of Energy Resource: Wind Power," Vol. 7, August 21-31, 1961, Rome, Italy.

14) World Meteorological Organization, (1954), "Energy from the Wind, Assessment of Suitable Winds and Sites," Technical Note No. 4, WMO-No. 32. TP.10.

Proceedings of U.N. Conference on New Sources of Energy, Rome, August 21-31, 1961.
Volume 7, Wind Power.

STUDIES OF WIND BEHAVIOUR AND INVESTIGATION OF SUITABLE SITES FOR WIND-DRIVEN PLANTS

Edward W. Golding *

When power is produced from conventional sources of energy—from solid, liquid or gaseous fuels, or from hydraulic energy—it is possible to predict with some certainty the performance of the driven machine because the power input is controllable and can be measured easily. With the exception of hydro-power, which frequently suffers from seasonal variations in the supply of water, it is also possible to predict what annual output of energy can be generated by a machine of given capacity. This output is governed almost entirely by the load demands: it is not limited by the availability of a source of energy for the input to the power plant.

Even for a solar power plant, the output in periods of bright sunshine can be accurately stated, while the annual output obtainable from a given piece of solar equipment, though somewhat variable, is also known within fairly narrow limits because it can be calculated from sunshine records collected by the nearest climatological station.

For wind power, the position is different. Neither the performance of a wind power plant—indicated by its efficiency as a power unit—nor its annual output of energy can easily be measured, or predicted in advance, for two reasons, both of which are subjects for discussion in this section of the Conference. The first is that the wind speed, and therefore the power input of the machine, is continually fluctuating, and the second is that the annual output of energy is influenced greatly by the precise location of the wind power installation in a given area for which, indeed, the general value of the annual mean wind speed may be known.

Variations in wind speed on time scales ranging from seconds to years are very important from different aspects of the problems involved in the design, testing and operation of wind power plants. Methods of wind measurement and the choice of instruments, suited to these time scales, must therefore receive most careful attention. Again, the influence of topography on the energy output from a windmill is so great that the selection of the site for its installation is a matter on which the economy of the whole project may depend.

It is fitting, therefore, that this section should deal with wind measurements and the selection of sites, and the fact that these two subjects are widely recognized as being of first importance is evidenced by the excellent group of papers covering the field in a well-balanced way. Thus, papers W/4, W/10, W/11, W/16 and W/19 deal with meteorological data for winds in various parts of the world and with the application of these data to wind energy calculations, while papers W/2, W/12, W/13 and W/35 discuss wind-measuring instruments and methods to be used in making wind surveys. In papers W/7, W/26, W/28 and W/33, we have valuable guidance on the principles to be followed in site selection, while paper W/14 describes methods of wind measurement associated especially with the performance of a particular wind-driven machine. Not only is the coverage of these papers wide, but the new information and ideas, some from contributors who have taken up wind power studies comparatively recently, will be refreshing to those of us who have been concerned with the subject for a lengthy period of years. Even in research work, there is a tendency to get into a rut, and one valuable function of such a conference as this is to broaden thoughts on the subject and so to encourage new methods of attacking the problems involved.

Wind measurements

Measurements to determine wind behaviour can best be classified according to the purposes which they are intended to serve. For wind power studies, as distinct from more general wind observations made by the national meteorological services, these purposes can be stated as follows:

(*a*) To provide data from which the probable energy output of a windmill of known characteristics, located at the site of the measuring station, can be predicted;

(*b*) To furnish information on the wind structure, under different weather conditions, at the site;

(*c*) To enable special studies, associated with the design and performance of wind power plant, to be made.

These three classes can be designated, according to the time scales appropriate to them, as (*a*) long-period measurements, (*b*) medium-period measurements, and (*c*) short-period measurements.

The measurements involve not only the choice of adequate instruments and their correct installation and operation, but also the subsequent analysis

* Electrical Research Association, London.

of the results obtained, to ensure that the data are presented in the form which is most useful. Let us consider the three classes individually.

Long-period measurements

The energy output of a wind-driven power unit, for any period of time T, during which the wind speed is varying – as it is always to a greater or less degree—is given by the expression

$$K \int_0^T v^3 \cdot dt$$

where v is the instantaneous wind speed and K is a factor which is a function of the efficiency of the machine, the area swept by its wind rotor and the density of the air. If the efficiency of the machine were the same for all wind speeds and, further, if a machine could be made to utilize the power in the wind over the complete range of speeds from the lowest to the highest values occurring, an integrating instrument with a driving torque proportional to (wind speed)^3 would give an accurate measurement of the total output of energy during any period of time. The French wind power specialists have used, in their surveys, an instrument of this type (as described by Argand in paper W/35), although its output is strictly proportional to v^3 only over a limited range of v. Unfortunately, it is not possible to take into account the actual, and varying, efficiency of a wind-driven generator which might be used to produce this measured energy. It must be clearly understood that such an instrument gives a measure of the energy available in the wind and not of that actually produced by a machine which must, in fact, have operating limits of wind speed, i.e., which can utilize only a part of the energy available.

This French instrument is, nevertheless, especially useful in making a comparison of the relative favourability of different sites without requiring frequent readings to be made: it can measure the total apparent energy for a long period of time. But it is important, when assessing the economy of a wind power project, to be able to determine, with some exactness, the fraction of this available energy that can be captured by a machine with specified operating characteristics. Again, it is usually necessary to subdivide the total energy into that obtainable in each month of the year or even in each day. Sometimes, indeed, it is useful to know the variations in output during a day, because any fairly regular diurnal pattern which might appear would have a bearing on the questions of utilization and energy storage. For these reasons, therefore, a measuring instrument of the "v^3" or "energy" type has limited applications: instruments which enable a more detailed examination of wind variations to be made are necessary.

The question of what types of anemometer should be chosen thus arises, and Sanuki (W/2), Tagg (W/12), Perlat (W/13) and Argand (W/35) have given helpful information on the alternative types of anemometer available and on their characteristics. One is pleased to note Sanuki's insistence on the importance of mounting anemometers correctly to avoid interference from near-by obstacles. This is a question to which, in general, insufficient attention is given by meteorologists.

The choice of instrument can be properly made only when it has been decided what is to be measured. In these long-period measurements, for the purpose of estimating the total energy which could be extracted by a windmill at a selected site, values of hourly mean wind speeds are probably the most useful. Tagg (W/12) has shown how these values, when cubed, can be used to estimate the energy output based on certain assumed operating limits of wind speed. And here, perhaps, the question of "energy pattern factor" should be briefly considered. This factor is the ratio

$$\left(\frac{\text{actual energy in the fluctuating wind}}{\text{energy calculated from the cube of the mean wind speed}}\right)$$

and it is somewhat greater than unity, because the sum of a series of cubes of numbers is greater than the cube of their mean value. It would appear, therefore, that the estimate of energy based on mean values of wind speed must err on the low side and this is, indeed, so, but it is probably wise to neglect any increase in the obtainable energy above that estimated for two main reasons: first, unless the wind-speed fluctuations, during the time over which the mean speed is measured, are wide, the energy pattern factor is not much greater than unity; and secondly, the wind-driven machine may not be able to follow these fluctuations due to the high inertia of its rotating system and to its control system which limits the power output in high wind speeds. Experience in testing such machines over a period of time has afforded no evidence that any serious under-estimation of output arises from the use of hourly mean values of wind speed in the way described by Tagg. The adoption of some period shorter than an hour might lead to a more exact estimate, but the labour involved for the analysis of the results would almost certainly not be justified.

If, then, we accept hourly mean values of wind speed, at a selected site, as the data to be obtained, the choice of suitable measuring equipment is greatly narrowed. There are several alternatives, of which the simplest is a cup anemometer, used with some form of recorder which will show the run-of-wind (in miles or kilometres) for each hour. Other instruments which may be used for the same purpose are the windmill anemometer, with a recorder, and the Dines pressure-tube anemometer. The method selected should be that which will give the most trouble-free service when installed at a remote site where little skilled maintenance is practicable, which is cheap and which does not call for an excessive amount of analysis in converting the wind records to the form required for energy estimates.

The total cost of the measuring installations for a wind survey covering an area of country is often an important consideration. Fortunately, it does not seem to be essential that hourly wind speeds should be measured at all the sites being investigated. Unless the area is very extensive, or the topography varies greatly, the wind régimes at these sites (as exemplified by their velocity-duration and power-duration curves) are sufficiently similar for the annual mean wind speed to be used as a basis for estimations. The "specific output" (in kWh per annum per kilowatt) for a site, assuming reasonable wind speed limits in the operation of a windmill located there, can be given, accurately enough for most purposes, from a knowledge of the annual mean wind speed: a curve showing the relationship between these two figures can be prepared, for any survey area, provided that full wind data (i.e. hourly mean wind speeds for a period of a year) are available, for a few sites having different annual mean wind speeds. It may, indeed, be accurate enough to accept existing curves prepared for an area with a generally similar wind régime.

This leads to considerable simplification, and cost reduction, in wind surveys: the annual mean wind speed, only, need be measured at most of the selected sites, the remainder—perhaps one fifth or one sixth of the total—being equipped with more elaborate instruments for the more detailed measurement of hourly mean speeds. Cup anemometers, measuring simply the run-of-wind, then become usable for the former purpose. Their indications being given on a simple counter, or cyclometer, they can be attended by quite unskilled local observers who can take readings at weekly, or monthly, intervals. The annual mean wind speed is obtained by dividing the total run-of-wind by the number of hours in the year. Up to the present, it has been considered that "spot" readings taken from anemometers, such as those of the cup-generator or windmill type (which indicate the instantaneous wind speed), at certain selected hours each day do not form a reliable basis for a determination of the long-period (e.g. annual) mean speed. Soliman (W/4) has shown, however, from a comparison of the results of different methods of wind measurement at eight Egyptian meteorological stations, that this is not necessarily so and that the agreement between the annual mean speed as determined from hourly mean speeds and that based on twenty-four synoptic readings is surprisingly close when the annual mean exceeds about 7 knots. Indeed, the use of only four synoptic readings might not lead to a very serious error in the annual mean value.

A wind speed value of considerable importance is the maximum which is likely to occur at a given site. Clearly, this must involve a long-term study by means of some form of recording, or registering, instrument used in conjunction with an anemometer. The latter might be a cup-type or windmill-type of instrument coupled to a small electric generator giving an output—proportional to wind speed—which can be fed into a recorder. An alternative is a Dines pressure-tube type of anemometer which has its own recording mechanism.

The designer of a windmill obviously has an interest in this maximum wind speed because of its direct bearing on the stresses which have to be withstood by the machine. The difficulty in determining the maximum lies not so much in the measuring instrument to be used—although the more sensitive the instrument the higher will be the maximum speed recorded—but in choosing the time over which records should be taken, and in deciding the probability of a dangerously high speed occurring in any specified number of years.

Two interesting new instruments, developed especially for tests associated with the Danish 200 kW aerogenerator at Gedser but erected also at several other sites, are described by Jensen (W/14). These measure, respectively, the wind energy distribution between different ranges of wind speed and the maximum velocity pressures of the wind.

Medium-period measurements

These measurements differ from those discussed above not so much in instrumentation—in fact, the same types of anemometer may be used—but in their purpose and total duration. They include measurements for the determination of the vertical and horizontal distribution of wind speed at selected sites, including simultaneous measurement of wind direction. The direction of the wind, though not usually of first importance in wind power work, has a bearing on the stability of the wind (broken ground upwind of the site may induce turbulence) and, if sufficiently persistent wind directions are found, may lead to consideration of the possibility of omitting provision for orientation of the wind power plant, thus cheapening it.

Frenkiel (W/33), in his very comprehensive study of wind flow over hill sites, has described his measurements of wind speed, direction and temperature at different heights above ground in an endeavour to obtain the fullest possible information on the effects of topography on the mean wind vertical gradient. His results, showing that, for any particular wind direction, this gradient is independent of the strength of the wind, at least within the normal operating range of a wind power plant, are very important.

Another purpose of medium-period wind measurements is the study of diurnal variations in wind speed. The prospect of there being a usable wind at any particular time of the day is important from the point of view of utilization of the power produced and of energy storage to cater for calm spells. The daily charts of the Dines pressure-tube type of anemometer, commonly used by meteorological services, gives full information on these variations, but such an instrument is expensive and is not very suitable for use at a remote site where skilled attention is not available.

Short-period measurements

Measurements of wind speed over periods of a few minutes, a few seconds, or even a fraction of a second, prove necessary in tests on the performance of wind-driven machines. They must employ instruments of sufficiently rapid response to enable gusts, which may rise very quickly and last for a very short time to be measured. This response time must, in practice, be related to the duration of gust likely to influence the machine. A high wind speed persisting for only a small fraction of a second may not contribute enough energy to have any measurable influence on the machine but, nevertheless, with only a little greater duration of the maximum gust speed, there may be effects which are important enough to measure.

These effects are of two kinds, electrical and mechanical: both the electrical power output and the stresses in the rotor blades, and other parts of the windmill structure, are affected by gusts.

In research and development work on a new type of wind-driven generator, an important series of tests are those to obtain the curve of power output for different wind speeds, and the question of how these two variables should be measured arises. Some investigators have used a wattmeter and a standard type of anemometer or, alternatively, have measured the energy output during a few minutes and the mean wind speed for the same period. The result of a number of measurements by such methods is usually a "cloud" of points, on the graph, through which some representative characteristic curve is drawn. An examination of the machine's performance in detail—which may be necessary to study the effects of small experimental changes in design—calls for quick-response instruments for measurement of both the electric power and the wind speed. The "moving-sphere" type of gust anemometer, developed by the Electrical Research Association for such a purpose, is mentioned by Tagg in his paper (W/12). By mounting the gust anemometer at the same height as the hub of the windmill rotor and locating it upwind of the machine at a distance of several rotor diameters, it has been found possible to get very good correlation between the high-speed fluctuations in wind speed and the corresponding variations in power output.

To study, by means of strain-gauges, the stresses set up in windmill blades when rotating in gusty winds, the same method of wind speed measurement has been used successfully.

Argand (W/35) describes an interesting new type of quick-response anemometer and recording equipment which can be used to measure rapid changes in both the speed and direction of the wind. No doubt this instrument will prove useful in testing the performance of a large aerogenerator. It is interesting to note that the photographic method of recording is used.

The use of meteorological data

In our consideration of the methods to be used in measuring wind, with the especial object of wind power generation in view, we must not, of course, overlook the fact that much valuable information on wind speeds and directions already exists in the records of national meteorological services. For obvious reasons, wind data obtained by these services have not been based on wind power requirements: they are related to the general wind régime for the districts surrounding the observation stations, not to particularly windy sites. Nevertheless, they are, in the main, reliable long-term records and should not be neglected merely because higher average wind speeds than those at the meteorological station can often be found at selected sites.

The papers by the World Meteorological Organization (W/11), Ramakrishnan and Venkiteshwaran (W/19), Barasoain and Fontán (W/16), Cambilargiu (W/10) and Soliman (W/4) all give valuable information on the winds in different parts of the world and relate this, as far as possible, to wind power potentialities in those areas.

How can meteorological data of this kind be put to the best advantage? One can list its uses as follows:

(*a*) As a basis for wind surveys indicating the areas where the highest wind speeds are to be found;

(*b*) As an indication of the direction of the prevailing wind—a knowledge of this is important when selecting wind power sites;

(*c*) As a measure of the constancy, or variability, of the annual mean wind speed from year to year;

(*d*) As an indication of the annual wind régime, for an area, from values of monthly mean wind speeds;

(*e*) As a measure of the diurnal variations in wind speed to be expected at different seasons of the year;

(*f*) As a guide to the maximum wind speeds, and to the durations of calm spells, which might occur.

The degree of usefulness of meteorological records naturally depends upon their detail and on the number of years for which they have been kept. Chart records of wind speed and direction, as produced, for example, by the Dines pressure-tube anemometer, will, if available for a number of years, fulfil all the uses mentioned above, while long-term records obtained even from simple cup-counter anemometers can serve purposes (*a*), (*c*) and (*d*)—and even (*e*) in the unlikely event of sufficiently frequent readings having been taken.

Much of this information is directly applicable to wind survey work because the general features of the wind régime for an area will hold also for particular sites within it. The values which, for a selected site, may differ significantly from those at the nearest meteorological station are those of annual mean wind speed, of maximum wind speed and of the durations of calm spells. But, of course, these three values are all of the highest importance in estimating the energy output of a projected windmill, in designing it to withstand high stresses set up by the wind, and in determining the dependability of the power generated or the need for energy storage.

The best procedure to be followed, therefore, is to take full account of long-term meteorological records and to supplement them by the use of measuring installations, of the kinds discussed in the papers presented, to gain full information on the wind's behaviour at the sites which appear to be most favourable for wind power.

Site selection and wind surveys

Surveys for wind power sites have as their main object the discovery of especially windy points at which wind power plants might be installed. The first considerations, in making them, are topographical. Secondary, but still important, considerations are the existence of, or the possibilities of building, access roads or tracks, and the distances of the sites from centres of habitation where the wind-generated energy could be used.

The increase of wind speed with height above level ground is a well-recognized phenomenon, so that, if the installation of windmills in a flat area, completely devoid of hills, is projected, an enhanced output from a machine of a given design and diameter of wind rotor can be achieved only by increasing the height of its supporting tower. But this must add to the capital cost of the installation and therefore to the cost of the energy produced. Whether such an increased tower height is economically justifiable must be judged by comparing this higher capital cost with the increase in output which would be achieved.

If the area in which wind power installations are to be made includes hilly country, an obvious step is to choose sites on hill summits to take advantage of their altitude above that of the surrounding level ground and so to "tap" the faster moving stream of air at this altitude. It is not, however, merely a question of choosing any hill at random. Hills on a seacoast, particularly if the prevailing wind blows from the sea, are likely to give good results but, on the other hand, hills inland, if surrounded, at a short distance, by high ground of the same order of altitude as themselves, may have disappointingly low mean wind speeds and may also be subject to frequent turbulence – induced by broken ground upwind—in the wind stream flowing over them. A really significant increase in mean wind speed, as compared with that for the surrounding low ground, can be obtained by choosing a hill with good profiles so that, acting as an aerofoil, it causes an acceleration of the wind over its summit. This means that the wind speed may, in fact, be greater than that which would be found it if were possible to measure it at the altitude of the summit but over level ground. In other words, the mean wind speed may be greater than that due to altitude alone. There is what has been called a "speed-up" effect due to the shape of the hill.

That this effect might be expected was recognized by P. C. Putnam and his co-workers on the Grandpa's Knob windmill project in the United States some twenty years ago, and such experience as it has been possible to obtain since, in the British wind surveys and those, in other countries, following similar methods, tends towards confirmation. It is, however, very difficult to prove, positively, that this speed-up effect exists at a given site and this section of the Conference is fortunate in having papers (W/26 and W/28) on this subject prepared respectively by Petterssen and Lange, both of whom were associated with the Grandpa's Knob project. These papers give valuable guidance on site selection from the theoretical and practical aspects.

Hitherto, site selection has been an art rather than a science: good hill sites have been chosen by inspection, taking into account their apparently favourable shape—with fairly steep but smooth slopes—and the nature of their surroundings. Although much has been written, during the past few decades, on the subject of wind flow over hills, very little guidance has been forthcoming on the factors influencing wind speeds over summits of hills of different shapes, so that correct selection of sites has remained very much a matter of judgement, or "inspired guessing", on the part of the wind surveyor.

As time has passed, valuable experience, and some skill, has been acquired but, even so, there have been instances of unexpected failures. Some of these have been due, almost certainly, to the fact that, although the general shape of the hill has been good, its actual summit has been too flat, so that the air stream has passed over at a height greater than that of the measuring instrument which has, therefore, been situated in a stream of slower moving air.

Accompanying the acceleration due to "speed-up effect", there is undoubtedly a reduction in the vertical wind speed gradient at the summit: the wind speed does not increase, with height above the ground, as much as it does when flowing over level country. Frenkiel, in paper W/33, describes his experimental studies of this question on both ridge-shaped and conical hills and concludes that the vertical wind gradient at the summit should be used as a quantitative measure of the favourability of the site.

The three last-mentioned papers, together with that of Ballester (W/7), who presents a very useful discussion on the theory and practice of wind surveying, have undoubtedly made an important contribution to our knowledge of the subject.

Topics for discussion

The papers presented introduce a large number of points of detail which could be discussed, but it may be more profitable to confine the discussion to the following four major subjects:

(*a*) How far can existing long-period meteorological records of wind, and the current records from meteorological stations, be used for the estimation of wind power potentialities in any region?

(*b*) What forms of measuring installations, including both the instruments themselves and their mounting above ground, should be recommended for wind surveys?

(*c*) What degree of standardization of measuring methods, and of the analysis of results, is desirable to assist in the international exchange of information on wind behaviour?

(*d*) Are we now, as a result of the papers presented (particularly W/26, W/28 and W/33), in a position to specify criteria for the selection of good wind power sites?

STUDIES OF WIND BEHAVIOUR AND INVESTIGATION OF SUITABLE SITES FOR WIND-DRIVEN PLANTS

Rapporteur's summation

Session II.B.1, on wind measurements and the selection of wind power sites, provided us, through the remarks of many contributors to the discussion, with a very comprehensive review of the present state of the art, of the accomplishments and of the deficiencies. Because the whole subject of wind measurement for power purposes is basic, as a beginning for wind developments in any area, we should try to obtain a clear statement on it as a guide to those who are considering the possibilities of this form of power. The discussion ranged over all forms of wind-measuring installations, for different purposes, and their relationship to existing wind data from the meteorological services, as well as over many points concerning the selection of favourable sites and the testing of machines. It is important now to separate these questions and to place them in their proper perspective.

In the first place, we must distinguish between the measuring methods which should be followed by those undertaking a wind survey for the first time and those which are already being followed by investigators who have had considerable experience and who have in mind the installation of large wind-driven machines, the characteristics of which must be tested under operating conditions. Both the instruments used, and the methods of installing them and analysing the results of measurements, are quite different.

For a general wind survey, with selected wind power sites, we need simple and cheap instruments, easily installed and maintained and affording only basic information on the wind régimes at the different sites to enable comparisons of their relative favourability to be made. On the other hand, when wind data is needed for the study of the performance of an installed machine of large power capacity or even — at an experimental research station — to obtain detailed information for design purposes, we need a much more elaborate installation, perhaps with a number of wind-measuring instruments placed at different heights above ground and having different response times.

As a guide on survey methods, some straightforward recommendations can certainly be made and this might be considered to be the most important object of session II.B.1. of the Conference. The most elaborate wind-measuring instruments and methods, at present, are of interest to a limited number of research workers who have already developed their own methods which can be discussed, on a semi-private basis, between the groups in the few countries concerned.

Wind survey methods

The first procedure is to choose the areas which are most likely to be windy. The long-period records from the meteorological services can be used as a guide — but only as a guide — for this purpose. Records for meteorological stations not chosen because of their especially high wind régime cannot take the place of measurements at selected sites, which may be capable of giving two or three times the annual energy which would be indicated by the meteorological station records. Those contributors who have made estimates of available wind energy in their countries, using such records, have shown their inadequacy. Although the discussion showed that synoptic records of wind speed can be useful, it is very important that, in all data from the meteorological services, both the precise method of making the measurement (including the type of instrument and method of taking the reading) and the height above ground of the instrument should be clearly stated.

If, in the areas considered, there are hills of shapes which will give unusually high winds over their summits — and information on the choice of these hills has been given in several papers — they should be selected for studies. There can be no doubt that a simple counter-type of cup anemometer should be used in the preliminary measurements. It has all the advantages of simplicity, robustness, cheapness and ease of reading to afford results which need no analysis.

If we know the annual run-of-wind at the selected sites, we know the suitability of those sites for wind power. It is pointless to attempt to install anything more elaborate than this instrument when making an initial assessment of the wind power potentialities of an area.

As for the height above ground at which the instrument should be placed, this need be no more than 3 metres if the site is on a suitably shaped hill-top without obstructions, because then the wind speed increases only very slowly with height. If the ground is flat, on the other hand, a height of 10 metres should be used. It must be remembered, however, that at 3 metres, the instrument can be read by a person standing on the ground, whereas at 10 metres it can be read only by climbing the mast.

For a second stage of a wind survey, when the wind régime at certain sites is to be measured because, as a result of measurements for a relatively short period (a few months), they have been found generally favourable, hourly mean wind speeds should be measured by a cup-contact anemometer and a chart, or tape, recorder. Analysis of the results gives the velocity-duration curve, from which annual energy estimates can be made, and indicates also diurnal variations of wind speed, as well as the duration of calm spells and the magnitudes of maximum hourly mean wind speeds.

Instruments, such as that made by the Compagnie des Compteurs de Montrouge, which measure an integrated total of wind energy within certain limits of accuracy are useful in giving a general indication of the relative windiness of sites if they are well located, in exposed positions without obstructions. They can be read at infrequent intervals, but they do not give the information which is needed for more precise estimates of annual energy obtainable, nor do they enable measurements to be made of the duration of calm spells, the diurnal variations of wind speed or maximum hourly wind speeds. These first two stages of a survey are concerned merely with wind régimes at sites.

A further stage of measurement is useful, and perhaps necessary, when it has been decided to consider a particular site in more detail in relation to a machine which might be installed there. Then, measurements of hourly mean wind speeds, or average wind speeds for shorter periods, together with wind directions, can be made at different heights above ground, particularly at that corresponding to the hub-height of the windmill to be installed. This is more important on hill-top sites than on flat ground. Measuring installations of this kind are expensive. Over level country, the rate of increase of mean wind speed with height above ground is well enough known for such measurements to be unnecessary.

The question of the height of the instrument above ground in relation to nearby obstructions can be answered by saying that such obstructions influence wind measurements in a way which cannot be stated with any precision. It is safest to measure as far as possible away from any obstructions. If measurements must be made close to, say, a group of trees or buildings, the higher the instrument above them the better. No general method of correcting for the effect of ground obstacles can be depended upon for accuracy.

One can summarize the position as follows.

(*a*) 1st-stage survey: Cup-counter anemometers should be used, mounted at 3 metres above ground on hill-tops or 10 metres above flat ground and used for a period of only a few months.

(*b*) 2nd-stage survey: Cup-contact anemometers, at the same heights as in (*a*) above, should be used with some form of simple recorder from which hourly mean wind speeds can be obtained easily.

(*c*) Wind behaviour at selected sites: Measurements of mean hourly (or shorter period) wind speeds and of wind directions can be made at various heights above ground up to at least the hub-height of the wind power machine to be installed. Such measurements are more important on hill-top sites than on level ground.

(*d*) Short-period measurements: These measurements, to determine the detailed structure of the wind, the maximum values of gust speeds and the wind distribution in both the vertical and horizontal planes, are made by means of quick-response instruments and recorders which differ with the investigator and with his purpose in making them. They are elaborate and costly and are, in the main, useful only at a wind research station where skilled staff, with full laboratory facilities, are available. Their object is to study design questions rather than the general performance of an installation.

In wind survey work, it must be borne continually in mind that, whilst the choice of good hill sites can increase the available energy by perhaps 200 or 300 per cent in relation to that obtainable on lower ground nearby, extreme accuracy is not necessary. Errors of, say, ± 5 to 10 per cent would not usually be serious and the elimination of such errors might be prohibitively costly in a widespread survey.

Site selection remains as a difficult question from the theoretical point of view, although several papers at the session gave very valuable guidance. It appears doubtful whether measurements based on such theory can, in practice, take the place of intelligent choice of sites, bearing in mind the requirements of good exposure and smoothly shaped hills with fairly steep slopes but without precipitous faces or ground obstacles.

Standardization of methods of measurement, as far as possible, is desirable for the interchange of information and the recommendations made above aim in this direction. Certainly the type of instrument used, the method of using it and of analysing the results and its height above ground should always be stated.

General requirements

Turning to more general questions, beyond the scope of session II.B.1, three points should be emphasized.

(*a*) The most important requirement in wind power development, at the present time, is to make the two participants in such developments, namely, the possible manufacturers of the plants and the potential users of these plants, much better aware of the possibilities. On the one hand, the manufacturer, busy with many good profit-earning products, is discouraged by apparent lack of demand for wind power plants, and, on the other hand, people who badly need power in the developing countries are not aware of what could be done by its use if properly organized.

(b) In many areas in non-industrialized countries, the inhabitants are unaccustomed to the use of machines as an aid to their own labour and, also, they cannot at present afford to buy elaborate and costly machines. The possibilities of introducing to such areas simple, even crude, machines, easily operated and repaired, should be studied as an urgent question. Local materials and local labour — with proper instruction — could often be used. It is much more important to introduce some kind of machine, even if it is inefficient, provided that it is cheap, than to insist on a refined and efficient, though costly, power plant.

(c) Some kind of international organization — committee, working group or association — for the continual exchange of information on wind power developments is badly needed. Much of its work could be done by correspondence, but occasional meetings should be held. A really effective, though simple, newsletter, regularly issued, could keep all interested people and organizations informed on progress and requirements.

Although, in the past, some facilities have been given for the exchange of such information (e.g. by the World Power Conference and by UNESCO through its Arid Zone Research Advisory Committee), these are quite inadequate. Wind power is a sufficiently important subject, especially for the developing countries short of power, to merit the establishment of its own means of communication. It should not have to depend upon the very limited facilities which organizations with more general interests are occasionally prepared to afford — more out of good will than of real conviction that wind power is of true significance.

APPENDIX 2

Possible Lines of Future Research Recommended by:

Golding, E. W. (1961)"The Influence of Aerodynamics in Wind Power Development"

NATO-AGARD Report 401, pp. 21-22.

6.2 Organization

The form of organization best suited to this work must vary in detail from country to country but the general outline can be sketched with some confidence. In the first place it cannot be left entirely to private enterprise. As will be understood from the previous discussion, there are three distinct aspects of successful development of wind power: the provision of a suitable machine, the choice of a good site for its installation and the planning of its utilization. Collaboration between the manufacturer of the plant, the meteorologists or others responsible for wind studies and site selection, and those concerned with the operation of the installation is therefore essential.

Each of the three sides to the question must be answered by the provision of an adequately cheap machine, giving the largest possible annual output of energy which must be fully and effectively used. Unless all three are right, the cost of the energy - which must be competitive with that from alternative sources - may be too high. If, having achieved the lowest possible construction cost, the highest output and the best plan for utilization, the energy cost is still not competitive, the straightforward conclusion must be that wind power, under the particular circumstances considered, is not practicable.

In several countries wind-power committees have been established to advise and control the work of research and development. This is sound practice provided that - and this point must be emphasized - the members of the committee are keenly interested in bringing about a successful conclusion and are prepared to assist actively in doing so. A committee which has financial control over research of this kind without sufficient knowledge of the difficulties facing the investigators, or a clear insight of the problems involved, is a handicap rather than a help.

If a thoroughly competent leader can be found for a team of workers who will tackle all aspects of the problem, calling upon manufacturing resources and those of the meteorological services, when necessary, this may be the best method. Naturally, financial control by some authority - probably Governmental - is needed, and the chief investigator must be responsible to that authority, but this should not be difficult provided the control is exercised with full understanding of the problem.

6.3 Possible Lines of Research

The lines to be followed in research and development are, of course, governed by the three main divisions of the subject, namely wind behaviour, machine construction and energy utilization. In none of these divisions have finality in investigation been reached. Nevertheless much has been done and any newly-initiated studies should take this fully into account. Failure to do so may waste much time and effort. In the suggestions which follow it is assumed that the research workers are beginning their attack on the problem: it would be pointless - and certainly presumptuous - to attempt to advise those research groups which have already made considerable progress in this field. Experience teaches, and they are already well aware of what needs to be done to further their own aims.

(a) *Wind studies.* In countries other than those (already mentioned) in which wind surveys have been made, very little is known about the behaviour of the wind from the point of view of its power potentialities. A first step in research is, therefore, to make surveys following the methods outlined in Section 3.

To these surveys, aimed at the selection of sites, may be added measurements (or analyses of existing wind data) to determine monthly and diurnal variations of wind speed, the durations of calm spells, or of periods when the wind speed is too low for power production, and the magnitude and frequency of occurrence of maximum gust speeds. The development of suitable measuring instruments and equipment for use at remote sites may sometimes be necessary.

Studies of wind behaviour in relation to topography are important. Too little is known about the precise effects of different shapes of hills upon the wind speed at various heights over their summits and of the influence of broken ground, up-wind of a site, in inducing turbulence. It has often been suggested that positions in gaps in [illegible] would be favourable sites for wind power. This may well [illegible] wind is sufficiently constant in its direction, through the [illegible] accelerated wind in the gap to counterbalance, by the increase which it causes in annual energy, the screening effect when the wind blows in other directions. Wind régimes in gaps might usefully be investigated. Another idea which has been put forward is that it would be possible, on level ground, to increase the wind speed at a given point by planting two rows of trees running in the general direction of the prevailing wind but with a diminishing distance between the rows as the site is approached. The hope is that a venturi effect would thus be achieved but little or nothing is known about the effectiveness of such a method or the details of planting and the selection of varieties of trees.

(b) *Windmill construction.* In connection with machine construction, research should be directed towards reduction of cost by the use of new materials rather than seeking for any entirely new design. Fixed-pitch blades, stalling as the wind speed increases beyond the rated wind speed, appear to offer the best solution but some work on the design of rotors with such blades remains to be done. Nor is there yet any final single solution to the problem of speed control to prevent overspeeding if the load on the machine is thrown off or if the wind speed rises to an excessive value. The possibility of devising crude, but very cheap, windmills which can be built from local materials and by only semi-skilled workers has been mentioned already and this might be a fruitful field for research. Such machines might depart from the now commonly accepted general design outlined for more sophisticated windpower plants: they might, for example, be of the vertical-axis type. Their usefulness would lie in eliminating expensive human or animal labour in simple tasks such as water lifting in under-developed dry areas. Though of low efficiency, and very limited application, they could serve as an introduction to the idea of using mechanical power from the wind and could aid agricultural development.

(c) *Utilization.* Research in this field involves social, rather than technical studies although any scheme for full utilization of the available wind energy through judiciously chosen loads must be followed by pilot installations and carefully controlled experimental operation under practical conditions. The development of load-distributing methods, of means of storing energy at low cost, and of techniques for combining wind power with that from other, supplementary, sources may also form part of the work under this heading.

APPENDIX 3

Recommendations from:

Savino, J. M. (1973) "Wind Energy Conversion Systems--Workshop Proceedings" NSF/RA/W-76-006, pp. 209-212.

REPORT OF THE COMMITTEE* ON

WIND CHARACTERISTICS AND SITING

Reliable data for wind power installations are not always readily obtainable from existing records. Wind stations have often been located at airports in order to meet the requirements of aviation.

Wind power needs are best served by choosing sites where the winds are higher than those representative of a broad area. Unfortunately, there are few wind records for such high wind speed sites. Having in mind the desirability of several established proof-of-concept units in the near future, it is recommended that three areas be chosen in which such units will be located.

On the basis of existing meteorological data, three recommended high wind areas are the Pacific Coast, the Great Plains, and the Atlantic Coast. A variety of nonmeteorological as well as meteorological criteria should be employed in pinpointing exact sites.

Relevant meteorological data are wind speed, wind direction, wind turbulence, and the variation of these within the lowest hundred meters. A priority listing of research and development requirements for an area is given below.

1. Basic wind information, existing data: A search should be made for all existing wind data for the area. These data should be assembled, their relevance assessed, and then analyzed if the data appear to be relevant and reliable. A summary of existing relevant wind information can then be prepared.

2. Basic wind information, new data: These are hourly averages of wind speed and direction at two heights, 10 meters and 30 meters, along with peak gust speeds at both heights with the frequency of occurrence of gusts in the high range specified.

A minimum of 12 months of data at each site is required, overlapping the long term record at a nearby station to determine if the winds for the 12-month period are reasonably representative of climatic normals.

Devices for recording directly the standard deviation of wind speed are commercially available and are recommended for the 30 meter height.

---

*E. Hewson, chairman; W. Barnes; D. Beattie; K. Bergey; R. Cohen; V. Nelson; R. Rotty; A. Stodhart; T. Wentink; and J. Wharton.

Standardization of units and of methods of making and analyzing measurements should be adopted.

3. Basic wind information, turbulence structure: A detailed study of turbulence structure in the lower levels should be undertaken, using existing wind data from one of the Great Plains' instrumented TV towers. Such a structure may be taken as reasonably representative, except over very rough terrain.

The extensive literature on the dynamic wind loading of structures should be examined as being highly relevant. Discussions should be held with the leading authorities in this area for the purpose of determining the extent to which recent research may be applicable to the design of equipment for generating power from the wind.

4. Weather modification: The possibility of significant weather modifications being caused by single or clustered wind turbines should be examined.

5. Public policy: The content of environmental impact statements should be set forth for the guidance of those who are to prepare and those who are to evaluate such statements. Possible legal restraints should be analyzed in detail. Sites should be selected so as to minimize both audible and visual pollution.

6. Dissemination of information: A comprehensive, annotated bibliography should be prepared, kept up to date, and widely distributed. Translations of significant results of research in other languages should be made and distributed. Some appropriate agency should be encouraged to collect and reproduce the documents that are fundamental to wind power studies. Many of these are generally unobtainable at the present time.

Explorations should be commenced with the Solar Energy Society and its Journal concerning the possibility of changing names to the Solar and Wind Energy Society and Journal. Sponsoring agencies should support such publication by authorizing substantial page charges.

7. Size of proof-of-concept units: Since ten 100-kilowatt wind turbine units appear to have substantial advantages over one 1000-kilowatt unit at this time, sites chosen for proof-of-concept units should be suitable for accommodating ten such units even if all are not installed at one time.

DISCUSSION

Q: Why do you recommend that the heights 10 and 30 meters be established as standard for measurements of hourly average wind speeds and directions, along with peak gust speeds?

A: Thirty meters was chosen as being approximately the height of the hub of a large wind turbine. For a smaller wind turbine the hub would be below 30 meters. Thus the winds at 30 meters could be taken as giving roughly those which specify anticipated wind power production and associated with gust loading on the system of rotating blades. A second set of wind measurements at 10 meters offers two primary advantages. First, since 10 meters has been adopted internationally as the height at which surface wind observations should be taken if at all possible, winds at this height at proposed wind power sites permit ready comparison with long term winds measured elsewhere. Second, wind measurements at two such heights permit meaningful vertical extrapolations of wind speed, direction, and peak gusts beyond 30 meters to provide valuable preliminary wind power design data.

Q: Why not take measurements up to 500 or 1000 feet to obtain wind information at heights which were of interest to Percy Thomas of the Federal Power Commission?

A: The group's recommendations are based on the premise that the first larger wind turbines to be built in the United States, such as the proof-of-concept units mentioned above, will have a rated capacity of 100 or perhaps 200 kilowatts. Wind measurements at 10 and 30 meters, along with the upward extrapolations that such measurements permit, are entirely adequate for the preliminary wind surveys designed to locate possible sites for wind power installations. If much larger units are contemplated, wind measurements up to 500 or 1000 feet require expensive high towers.

Q: Use a balloon.

A: A balloon will not give the required long term data. Do you mean a pilot balloon?

Q: A tethered balloon.

A1: Tethered balloons are both expensive and difficult to use, and especially so for measurements for a full year. When high winds - those of great interest for wind power - occur it would be necessary to reel in the balloon to prevent it from being blown away or driven to the ground. Attempts have been made to measure higher level winds by the use of tethered balloons but very limited success has been achieved.

A2: If we are concerned with winds at high levels above ground, measurements are not needed because synoptic data for gradient winds 2000 feet above the ground can be obtained from the pressure pattern charts.

Q: If I understand you correctly, you mentioned 10 units of 1 megawatt each. What were the size of these?

A: No. I spoke of 10 units of 100 kilowatts each for a total of 1 megawatt.

Q: Why did you choose those numbers and sizes?

A: This choice represents our group's distillation of the discussion of the previous two days. This was, in our opinion, the consensus of the workshop. We also mentioned five units of 200 kilowatts each for a total of 1 megawatt. The total capacity of a group of proof-of-concept units should be no greater than 1 megawatt in the present stage of development.

Q: What is the present status of the wind measuring network in the United States? How adequate is it?

A: For the flat areas of the Great Plains and the land to the east, the network is adequate for first rough estimates of wind power potential. Over both coastal waters and the mountainous regions the existing information is completely inadequate. For wind power estimates for such areas, we need information not on representative winds but on ones that are not representative because they are stronger than characteristic regional winds. For example, over coastal waters the wind currents and water currents are a coupled system with feedback from each component to the other, and the whole must be considered as a unit. Thus the location of maximum coastal winds may be expected to shift somewhat with the season in a manner which may become predictable as the dynamics of this coupled system is better understood through research. Similarly, research into the kinematics and dynamics of high-speed air flows in mountainous terrain will assist in locating favorable wind power sites. For certain selected areas over both coastal waters and mountainous terrain there is already sufficient wind information available to permit us to proceed with proof-of-concept experiments of the type discussed in this workshop.

APPENDIX 4

Recommendation from:

Changery, M. J. (1975) "Initial Wind Energy Data Assessment Study," NSF-RS-75-020, pp. 1-10.

Part 1

Meteorological Data Requirements and Technique Assessments

Thirty individuals participated in a 3 day meeting at the Center on July 29-31, 1974. The purpose of the meeting was to enable the meteorologist and engineer to meet and discuss meteorological problems encountered in site evaluation, data requirements and engineering design.

Topic areas included an assessment of the present data base and climatologies, data requirements, extrapolation and interpolation techniques, statistical and physical modeling, and additional research.

The participants were divided into two groups which separately discussed the topic areas. At the conclusion of a session, group chairmen presented a review of their group discussion including recommendations and conclusions to the entire group.

This summary is a condensation of their discussions, recommendations and conclusions. The first section presents the overall objective of the wind energy program in the area of wind characteristics and general conclusions of the meeting. The remaining sections discuss in more detail the topic areas mentioned.

1. General Summary and Recommendations

The objective of this portion of the wind energy program is to increase our ability to locate favorable wind sites and to validate the characteristics of those sites. The goal is to develop, over the next few years, an adequate data base and wind site prospecting techniques so that manufacturers, potential system users or consulting engineers can select sites with a minimum uncertainty as to the available power and the variation of that power over time.

The Smith-Putnam wind turbine experiment on Grandpa's Knob, Vermont, in the 1940's was halted after it experienced blade failure. Of more importance, however, was the fact that the mean wind at their site had been overestimated to such an extent that the power obtained was only 1/3rd that expected. Since wind power is a function of the cube of the speed, the estimated wind at a site must be as close as possible to the true speed or the wind turbine may not be cost competitive. It is anticipated that continuing research over the next few years might reduce this uncertainty.

The workshop concluded that extensive data collection and research in many of the areas of concern to the wind energy program has been accomplished to some degree and is available in the literature or in usable formats. The workshop recommended that a survey of the literature be undertaken to compile a document set on:

(a) Wind profiles in the boundary layer as affected by roughness, stability, terrain setting and other factors.

(b) Applicable gust and turbulence research and data, preferably 3-dimensional, in the layer from the surface to 300 feet (~100 m).

(c) Available 2 and 3-dimensional numerical modeling techniques which can be realistically modified to achieve the programs objectives. Available wind tunnel modeling techniques and results for flow over mountains and isolated hills in flat terrain.

(d) Current state of the art of remote sensing capabilities. Mention was made of satellite interrogation of self-powered instrument packages, and atmospheric infrasonic and scintillation techniques.

(e) Past and present tower data availability. In addition to the usual sources, extensive measurements may be being made by utility firms at present and prospective nuclear plant sites.

In addition, a survey should be made of research projects of groups currently working in areas of concern to the program. These groups should include universities, NASA, AEC, ERDA, NOAA and ARL, and the military services.

The workshop also recommended that, due to the interdisciplinary aspects of the wind energy program, meteorologists with experience in engineering and design criteria problems work directly with the engineering group to integrate the meteorological aspects of the problems.

2. Data Availability and Requirements

Meteorological data collected by the National Weather Service, Federal Aviation Administration, military services, merchant marine vessels and some locally operated airfields are processed and archived at the National Climatic Center. Determining the best sites for windmills and proper design for structures and rotor requires an evaluation of the available data base and climatologies. Although the primary function of the National Climatic Center (NCC) is to collect, process and disseminate meteorological and climatological data within the United States, no comprehensive listing of the data required by the wind engineering community was available. Accordingly, a survey was made of the NCC holdings of marine and land surface wind data including gustiness and extremes, upper level wind data, wind shear and persistence, turbulence, icing and tower data. These were examined for data and summaries of use in initial site selection and wind turbine design. A review of available data is included in Part 2 of this report.

The present data base is considered adequate for determination of national wind potential. Given the present network of approximately 2000 stations and additional stations for which data were collected in the past, areas of high and low wind potential can be determined. This is particularly true for the non-mountainous areas. One approach to utilizing the present data base is demonstrated by Reed (Ref. 3). In mountainous regions, data are usually available only for valley locations experiencing lower winds than nearby hilltops. Wind potential determination in these areas requires vertical and horizontal extrapolation or interpolation techniques utilizing the available data. For more detailed area and site surveys, the data base is considered marginal. The primary problem is that there are few reporting locations in hilly and mountainous regions and these are in unrepresentative sites. Detailed site surveys will require more accurate assessment of wind potential than the national survey. For design studies requiring detailed gust and turbulence data, the present data base is not adequate.

At present, data are digitized at 3 hour intervals. This is considered satisfactory for assessing prevailing direction but not the speed distributions.

The amount of power available in the wind is a function of the wind speed cubed and thus an initial assessment of wind power in a region can be obtained from available wind speed data. Hourly wind speed reporting requirements presently specify averaging the wind for a one minute interval once each hour. Studies indicate that the true average wind speed over an hour is somewhat greater than the average as now determined.

If instantaneous wind speeds are cubed over an hour and averaged, the resulting power estimates can be considerably greater than the estimate from cubing the average speed. However, a windmill is a smoothing device which will not react to speed changes lasting less than 3 to 5 seconds. Although the reported hourly wind underestimates the power, it does so by less than 10%. This estimate is based on results obtained by the Electrical Research Association in England during the 1950's.

No additional massive task of data gathering is anticipated under the wind energy program. Any additional data collection will be in support of research studies of data extrapolation and site validation techniques or for locating specific wind turbines. The sampling period for new data should include at least one month per season especially in areas of strong seasonal variability. Perhaps 80% of the data required for the objectives of the wind energy program is available at the National Climatic Center. These data need to be reduced to proper and usable form.

The following data should aid in proper site selection and optimization:

(a) Cumulative distributions of wind speed by month or season for all hours and for specified hours for determining the variation of wind over time. These distributions could be converted to power duration curves.

(b) Limits of cut-in and feathering speeds or power and frequency analyses of durations of these existing conditions.

For equipment design, detailed data as follows will be required:

(a) Distribution of direction and speed changes which can be experienced at rotor height conditionalized on the times with which the changes take place.

(b) Distribution of speed and directional shear thru the layer thicknesses of concern and this distribution also conditionalized on various time intervals.

Directional change and directional shear distribution data would not be required for vertical axis wind turbines. These detailed wind shear data may be available only from instrumented towers.

The workshop concluded that rapid directional and speed changes at rotor height may pose problems in properly reorienting the wind turbine to avoid structural damage. The changes are usually associated with fast moving strong frontal systems or with cold outflow from developing thunderstorm cells. Studies of thunderstorm outflow have been done by NSSL Oklahoma City (Ref. 4) and were also done as part of the Thunderstorm Project (Ref. 5) in the 1940's. These should be examined to determine the magnitude of the changes.

The workshop also expressed concern that vertical directional and speed shear may be significant under certain circumstances. A decoupled boundary layer with light winds below an inversion and stronger winds from possibly a different direction above could pose severe stress problems on blades rotating through these layers.

To establish the adequacy of available data, the following studies are proposed:

(a) Utilizing 10 years of hourly data for 20 representative sites, prepare bivariate (wind direction vs. speed) distributions, cumulative velocity and wind power distributions for hourly data and for 3 hourly data. This will determine the necessity of at least hourly readings.

(b) Prepare similar distributions for a 2 to 3 year period vs. a 20 year period to determine the representativeness of short term measurements.

(c) Determine wind power differences at a number of sites by cubing the average speed vs. averaging the cube of the speeds.

3. Data Extrapolation and Interpolation

Assessing the wind power potential of a location requires measurement of wind speeds. The majority of surface wind data is obtained from airport or city locations. A limited amount of data, not all of which is centrally archived, is taken at research facilities and operating locations. However, the eventual deployment of wind turbines will require an estimation of the wind not only at rotor heights but also at some horizontal distance from current reporting locations. It is impractical to collect data for extended periods for all these locations. This session discussed techniques to extrapolate and interpolate data from a reporting site to a future wind turbine site.

The basic problem is one of assessing present and future capabilities in utilizing present surface data to obtain an estimate up to 30 miles (~50 km) distant and/or up to 300 feet (~100 m) above the surface. The layer of concern is the boundary layer in which surface terrain and roughness and atmospheric thermal stratification exert a profound effect upon the wind profile both in the horizontal and vertical directions. The top of the layer or the level where the ground no longer influences the wind, is normally considered to be around 1500 to 2000 feet (~500-700 m).

The workshop concluded that available boundary layer models give an adequate estimate over flat terrain. This would include the Great Plains, Midwest and the Gulf and Atlantic coastal areas. This is for strong wind, neutral stability situations. Under stable situations, which are usually associated with light surface winds during the night, a flow separation problem may result at the top of the stable layer.

The light winds at a lower level can become decoupled from the stronger winds above because of weak turbulence intensities. The speed and directional shears under this condition could prove hazardous for a blade rotating through the layer.

Available models are marginally adequate for flat terrain with isolated hills where the hill geometry gives a known flow perturbation under neutral conditions. In mountainous terrain existing models are less satisfactory. Both the stable and unstable situations present further complications for which existing models generally adequate under neutral conditions are less suitable for describing flows. References 6-14 provide information on the fine scale structure of wind and turbulence in the boundary layer. Many additional sources may be found in the literature.

The workshop recommended that additional research efforts emphasize isolated hills and hilly and mountainous terrain.

Horizontal extrapolation of wind speed was considered more difficult than vertical extrapolation, even in flat terrain. The participants estimated that at the present state of the art under neutral conditions estimates within 25% of the actual value could be obtained for flat areas at distances up to 30 miles (~50 km). Horizontal extrapolation should be checked by using the long term climatology at a representative location in conjunction with short period measurements at a second location.

Two scales of motion are to be considered in making estimates of the extrapolated wind speeds:

(a) Those which arise from "local" thermal gradients and relief (1-100 km).

(b) Those determined by local surface roughness and thermal characteristics (<1 km).

Towers equipped with meteorological instruments have been sited in many varying types of terrain. Given the present availability of data from these towers, the group determined that good estimates of the vertical profiles over various terrain representative of most areas of the country could be obtained.

The ability of numerical and wind tunnel models to realistically simulate actual conditions is questionable. The problems of stability and proper similarity conditions in wind tunnel modeling are especially difficult to resolve. For numerical modeling a problem is posed by the thermal wind, whereby the horizontal temperature gradient changes the geostrophic wind with height.

The workshop concluded the following:

(a) The state of the art of wind profile modeling should be examined and the altitude range of validity established. Models applicable to the problems of site selection and adaptable to local conditions should then be chosen. Many existing models that have been used for airport or plant siting may be useful.

(b) Three approaches to the problem seem possible:

1. A single observation near the ground which is extrapolated upward with a deterministic function containing parameters characterizing the surface roughness, terrain setting and thermal stratification.

2. A single observation near the top of the boundary layer obtained by extrapolating from nearby, or interpolating between surrounding, rawinsonde observations. Then:

   (a) Devise a deterministic function which defines the wind profile below the observation or

   (b) Use the geostrophic drag law to calculate a stress at the ground and then come up with a log-law. This could be done under high wind neutral conditions. Under unstable conditions the problem is more complex.

3. Given two observations, one near the ground and the other near the top of the boundary layer, use interpolation procedures utilizing average vertical distributions for typical roughnesses.

These all refer to extrapolation of individual data points. It is much more difficult to extrapolate wind statistics which would require empirical studies relating wind statistics between levels. The workshop agreed that more confidence can be placed on procedures utilizing at least two data points in the vertical.

(c) The applicability of existing numerical models should be determined. Diffusion models, models of air flow over mountains and sea breeze models may all be useful. Parallel with model improvement, wind and temperature measurements should be made at specific sites to test the scheme and to enable generalization of specific site results to other similar sites. Turbulence statistics may also be important which necessitates fast response wind measurements.

(d) "Rules of thumb" should be developed relating the aerodynamics of surface features to wind power. These would be accomplished separately for terrain types where geological, vegetational, marine and man-made structures predominate. The effect on the wind of spatial density and size distribution of surface elements should also be determined. Professional judgement and experience will be important in making field surveys of possible wind turbine sites by utilizing the "rules" developed.

4. Statistical Techniques, Gust and Turbulence Requirements, Climate Modification

Statistical Techniques

Appropriate statistical evaluation of available data will be required for proper assessment of array sizes and distributions if wind turbines are extensively deployed.

Two main problems are evident in correlation across distances. The first is the case where a small network of turbines is set up with generators separated by 200 to 300 meters, to supply power to a specific locality. The turbines should be spaced such that fluctuations in wind speed through the array, and hence, the power out are smoothed. This is necessary to avoid the possibility of the power fluctuating below the level requiring a back-up source (such as a diesel generator) to constantly cut on and off. The second case is generators spread out over the area of a state or several states. Proper array spacing and distributions could change the system capacity and the storage requirements. For instance, an array could require a certain storage capability to take care of demand when the output of the array falls below a given value. The addition of a number of generators which guaranteed output always above the minimum value may be a less expensive method.

The following approaches were suggested:

(a) For various data arrays, the frequency distribution of the power output could be computed. The data could be prefiltered by operating characteristics such as cut in and rated speed to compute realistic power levels.

(b) For storage requirements, determine the return time and a frequency distribution of the return times for the array to generate a minimum amount of power once it falls below that minimum value.

(c) Eigenvector-eigenvalue or principal component analysis may be used to establish main patterns and to delineate areas which differ the greatest, thereby providing decision bases. For a given array then, this technique can be used to determine areas of diversity, or higher winds, when given sites in the array experience low wind speeds.

(d) Determine area sizes and frequency of occurrence of calm or light winds. This is similar to the EPA studies on stagnation potential but would be joint frequencies of multi-station light winds rather than a point frequency. The problem can also be approached by utilizing time autocorrelation and spatial cross correlation techniques between adjacent stations.

The considered judgement of the participants was that:

(a) Initial studies indicate average power out of a station array exceeds by at least 40% the average power out by the same number of stations if they were co-located.

(b) For local networks, assuming a 15 mph (~7 m/sec) wind and turbines 600 meters apart, the power out will be smoothed if the machines respond in 3 to 5 seconds. If they require up to a minute to respond fluctuations could result. Available spectra studies indicate considerable energy in the wind at a peak of 3 minutes. Fluctuations should be smoothed out of an array if, assuming 15 mph (~7 m/sec) wind speeds, the turbines are separated by at least 3 minutes or approximately 1.2 km.

(c) Assuming a line of turbines perpendicular to a mean flow, a spacing of at least two rotor diameters apart should ensure non-interference.

Gust and Turbulence Requirements

Atmospheric gusts and turbulence can affect a wind turbine by simply varying the output or by imposing severe and damaging stresses on the blade and structure. For the initial design of the wind turbine components, detailed analysis of gust and turbulence in different operating environments will be required.

Data applicable to this problem are available for towers in various regions of the United States. Proper evaluation of the available data is a first step in providing the required information.

The workshop concluded that:

(a) Gust factors or procedures should be developed to convert available wind speed to speeds valid for other averaging times. From this, peak and steady-state wind speeds can be determined for various averaging periods.

(b) Gust and turbulence models should be developed which are consistent with the program analysis methods to calculate dynamic loads and response. The methods may be similar to those used in the civil, aeronautical and aerospace engineering communities, so that the atmospheric gust technology used in those disciplines may be adapted to these design problems.

(c) Models should be both discrete and spectral gust models. Models should be developed such that consistency between steady-state wind profiles and turbulence be maintained as required by dynamics of the boundary layer.

(d) Models should be of sufficient detail to permit the definition of single-point and two-point, multi-time gust correlations over the surfaces of concern.

(e) The models should provide sufficient information on gust statistical distributions so that probabilistic statements can be made relative to the exceedance of gust dynamic responses and loads. They should be developed such that they permit the determination of point design environments and calculation of fatigue damage.

(f) The above should provide sufficient information to determine gust climatologies provided statistics of steady state winds exist at the point of concern. This could be accomplished on a site, regional or national basis or possibly by a design envelope approach.

Climate Modification

An array should have negligible impact on the climate. Although energy is extracted out of a thin air stream, the downward momentum flux in the atmosphere is such that no trace of the turbine should be experienced more than 10 times the rotor height downstream. This would also apply to rotor created turbulence transported downstream.

APPENDIX 5

Recommendations of Working Group E, Wind Characteristics/ Site Survey,Eldridge, F.R. (1975) "Proceedings of the Second Workshop on Wind Energy Conversion Systems," Washington, D.C., June 9-11, 1975, NSF-RA-N-75-050, pp. 487-490.

WORKING GROUP E

WIND CHARACTERISTICS/SITE SURVEY

C. G. Justus, Chairman
Georgia Institute of Technology
Atlanta, Georgia 30332

The group considered only the meteorological aspects of site surveys and did not discuss other factors such as ecological and geological interactions on site selection. The minimum types and amounts of data necessary to adequately characterize winds at a given site are summarized in Table 1. It was recognized that, in general, the complexity and expense of site surveys would depend on the size of the wind systems to be installed. Small units may not warrant any site survey (or simple techniques, developed as "fall out" of larger site survey technique research, may be employed). Site surveys for multiple unit wind systems are likely to be complex and costly (while remaining, however, a small percentage of the total project cost). Site studies should attempt to minimize possible detrimental effects of icing, corrosion, blowing sand, tornados (see, e.g., the ERDA guidelines on tornados), and thunderstorms. Detailed interactions between systems designers and site surveyors is necessary for iteration of system requirements and site survey assessment capabilities.

After appropriate research and development of techniques, site surveys may be handled commercially in a manner similar to site studies for power plants. It was suggested that the Electric Power Research Institute (EPRI) be contacted to provide inputson current costs of site surveys for fossil fired and nuclear power plants.

With regard to Federal incentives, data base, and data storage requirements, the following suggestions were made:

1. ERDA-NSF sponsored software and techniques development programs
2. General Federal research support in the area of site survey methodology
3. Eventual commercial (not Federal) handling of actual site surveys
4. Local and regional Federally funded support for wind energy promotion ("county wind agent", "wind grant colleges", etc.)
5. Establishment and maintenance of a wind energy data base
   a) Special Federal support to NCC in Asheville, or possibly handled through EPRI
   b) Tower time-series and summary and other (e.g. LO-CAT) data should be archived and documented; this might best be accomplished by an ERDA contract to collect the data and document it suitably for deposit in Asheville or other storage facilities

c) The EPA "STORET" data storage system and format was suggested as a possible data archiving method
d) EPRI should be approached to provide tower data from power companies at power plant sites
e) ERDA should require for future power plant sitings that all meteorological data be sent to the central wind energy storage facility

6. A panel should be established for working out details of site survey methodology, standardized data reduction and dissemination, and initiating the mechanics of acquiring current data for the data base. This panel should interact with other similarly established panels on systems design, for coordination between these areas.
7. Impetus should be given to meteorological instrumentation suppliers to develop low cost instrumentation system packages with digital recording or easy a/d conversion capabilities.

The importance of developing a data base from the existing field measurements (such as at power plants) cannot be over-emphasized. There are probably millions of dollars worth of directly usable (if properly reduced and documented) tower wind measurements which would be beneficial in the development of site survey methodology. It is therefore most important that recommendations 5 and 6 above be considered, since support of an effort to collect, collate, and document these existing data could return substantial benefits compared to the costs involved in trying to obtain such measurements in direct field measurement programs. Field measurement programs especially oriented toward wind energy requirements will however also be required as outlined in Table I.

WORKING GROUP PARTICIPANTS

Participants in the Wind Characteristics/Site Survey Working Group included: C. Justus, Chairman; M. Changery, A. Cole, R. Corotis, E. Davis, G. Fichtl, P. Fisher, B. Freeman, E. Gilmore, D. Grace, D. Hardy, E. Hewson, R. Krieg, S. Lee, R. Marrs, I. McLaren, R. Meroney, J. Reed, T. Torda, F. Vukovitch, T. Wentink.

DISCUSSION

TEAGUE: What price range is envisioned for a "low cost" remote site monitoring/survey system?

JUSTUS: Some numbers were discussed in the Working Group meetings. There was a suggestion that, with adequate incentives provided to manufacturers and suppliers, possibly an instrument, including a small tower, could be provided for a capital investment as low as $2,000. I think the majority were skeptical of this low a figure; but I think there was some merit to the suggestion that, as far as possible, the equipment be kept at home base. In other words, do your recording on simple recorders and use as simple as possible, but yet adequately accurate instrumentation at the potential site, and then go back and do your analysis on a shared computer at the home base. There are a number of things that could be done, we felt, to decrease the costs. $2000 may be a lower limit.

THOMAS: You mentioned vertical and horizontal placement of instruments for gust measurements. You mentioned diameter and chord placement. I do not understand what you mean by "chord placement".

JUSTUS: I was thinking that, in terms of interaction with the blades themselves, both chord-wise and span-wise fluctuations may be important in terms of dynamic interaction. Maybe this reflects my misunderstanding of what the blade designers really need. I think, in general, my comment was that we do need spacing that is on the order of the scale of the system that we are looking at, and the scales that it will interact with.

TABLE I
DATA REQUIREMENTS FOR SITE SURVEYS

Purpose, type, and amount of data and analysis needed as a minimum for adequate site survey of wind characteristics

PURPOSE	TYPE	AMOUNT
mean power output evaluation	a) general, preliminary assessment at least 8/day, 1 minute average observations	a) at least one year if at "isolated site"
	b) detailed site study: 24/day or more 1 minute averages, at least 2 vertical locations	b) a few weeks each "representative winds" season if relatable to nearby climatological (5-10 year) summary sites
	c) site surveys, with "gaps" filled in by simple boundary layer models and/or wind tunnel models	
	d) inter-site correlations to develop topographic extrapolation techniques	
storage requirement assessment	same as for mean power except continuous records at 24/day observations are preferable. Measure mean and distribution of "return time" ("lull time"). Can use summary information (velocity duration curves) for mean power, but need raw time series for storage.	5-10 years, hence must rely on climatological site data
structural response of tower and blades	turbulence structure at 2 or more vertical locations and 2 or more horizontal locations	a) several sites of different topographical type
	a) fill in "gaps" with turbulence theory (e.g., spectrum in "inertial subrange", isotropic turbulence models, etc.)	b) as long as possible in order to establish statistical criteria for structural lifetime estimates
	b) spacing of measurements approximately at size of chord and/or diameter of blades	c) special observations during perturbed (e.g. thunderstorm) conditions
	c) timing: 1 second average or 15 second average	