JOUSTING WITH THE WIND - A GENERAL REVIEW OF THE WIND ENERGY PROBLEM

by

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ABSTRACT

The windmill, that familiar if not always reliable workhouse of rural mankind, seems headed back into the whirl again. Visions of wind-driven power sources have tantalised mankind for centuries. The history of wind generated electricity will be surveyed, together with various ingenious devices to produce electric power from the wind. Meteorological constraints on wind generated electricity will be summarised. The U.S. Meteorological programme as it relates to wind energy research over the next few years will be discussed.

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1.0 INTRODUCTION

In 1891 the Danish State established a windmill experimental station at Askov under the direction of Professor Poul la Cour. Professor la Cour was the first to undertake systematic investigations of electrical generation of power from windmills. His research was the first since that of John Smeaton (1759) to examine the aerodynamic performance of windmill blades and to establish guidelines for hardware construction. La Cour, who was popularly known as "the man who could turn rain and wind into light and power", may justifiably be considered the father of current desire to produce significant amounts of electrical power from large windmills.

2.0 WIND MACHINES

Investigations since 1895 would appear to suggest that almost anything erected in a moving air stream will move and can potentially generate some power. A taxonomy recently prepared by Eldridge (1975) includes over thirty concepts or combinations of concepts to extract power from the wind.

During the 1920s a number of inventors examined the possibilities of lift augmented by the Magnus effect. Flettner (1926) applied his ideas to ship propulsion and a complicated "rotor-windmill". Von Karman, however, critiqued the idea as not efficient as conventional propeller blades and the idea was abandoned. Tracked vehicles driven by lift generating Flettner rotors 90 feet high and 28 feet in diameter were considered by Madaras in the early 1930s. This project was subsequently abandoned.

For sites such as the Rhöne Valley where the wind is predominantly uni-directional, J.B. Morel proposed removing power from the wind by means of vertical "Venetian blinds" consisting of hinged slats, of aerofoil sections carried between two endless belts running over wheels at top and bottom. A Morel "Barrage" windmill producing 100 kW was constructed in the late 1940s.

Other elegant ideas, yet unbuilt, include Hewson's (1975) wing-aerogenerator which sucks air up through turbines inserted in support columns of a stationary porous airfoil. Minardi's (1975) electrofluid-dynamic wind generator has no moving parts at all. It utilizes the wind to carry charged aerosol particles across arrays of high voltage annodes and cathodes. (So on to other ideas yet to be conceived.)

More practical but less amusing or diverting are the series of large machines constructed to produce power in the range from 100 to 1250 kilowatts. Table 1 provides a sketch of the characteristics of twelve such machines. These devices have been run in a variety of operating conditions ranging from supplementing a 20 MW peat burning plant to complementing diesel-power utility networks. One may conclude that it is thus technically feasible to extract power from the wind. Most of these machines were/or are reasonably efficient (i.e., they approach Betz efficiencies under ideal conditions if mechanical losses are discounted). Roadblocks to successful initiation of a wind-power electrical system thus appear to be inertia of users, institutional resistance and public acceptance. Coty and Vaughn (1977) contend an initial order of 40 2-MW units by federal power agencies is enough to start the production cycle. Nonetheless, the final satisfaction with windmills once commissioned may lie more with the competent evaluation of meteorological characteristics of a given site than the design of the hardware.

3.0 WIND CHARACTERISTICS RESEARCH

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.

3.1 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 recognised 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 for 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 (sailarea) 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) summarised 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.

3.2 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 behaviour. 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 recognised that terrain may enhance or decrease mean wind speed, direction, or turbulence. Based on potential flow theory for 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 recognised.)

3. Prevailing wind directions in the western foothills of the Green Mountains --
Prevailing wind direction was estimated from climato-logical 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 recognised 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 was 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. Such curves may be estimated when only mean velocity is known.

3. Changes in the vertical or horizontal wind velocity were 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 year's record. A single year's 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."

Advice 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 analyse 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 production and utilisation. 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.)

3.3 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 Juul, and the English with Golding, built a number of 50-1000 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 were 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 stora 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 behaviour 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 speed-up 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 ter 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 similarity 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 surveys 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 analysing 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 organisation 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 summarises 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 emphasised 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.

3.4 KNOWLEDGE 1960-1965:

The United Nations sponsored a Conference on New Sources of Energy Resources (1961) in Rome. Fourteen papers dealt 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 hill 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.

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 analysing wind data. Selection of favourable sites for wind power is discussed. He summarises specific research needs for wind studies, windmill construction, and utilisation. 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 Meterological Organisation to provide guidance on the effects of topography on wind speeds near the ground. 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.)

3.5 KNOWLEGE 1965-1970:

No known contributions; wind power systems essentially abandoned.

3.6 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 utilisation predictions by W. Heronemus and the encouragement of energy conscious Congressmen like M. Gravel, a Solar Energy Panel was organised 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 Centre.)

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.

Thirty individuals participated in a 3-day meeting at the National Climatic Centre on July 29-31, 1974. Discussions included present data base and climatologies, data requirements, extrapolation and interpolation procedures, statistical and physical modelling, and additional research. Changery (1975) condensed the groups discussions, recommendations, and conclusions into Part 1 of his report. Part 2 summarises that data currently available at the National Climatic Centre 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. 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 data base is considered accurate only for non-mountainous areas, it is suggested that additional research efforts emphasise 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 utilised 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.

In June 1976, ERDA, together with the American Meteorological Society co-sponsored a Workshop specifically on Wind Characteristics for WECS. This Conference brainstormed the utilisation of meterological information during the design, siting, and operation of various size windmills and windmill systems. Elderkin, Armsdale, and Tennyson (1976) have summarised the consensus noted and the research projected. An extended report also exists which includes detailed conclusions of the workshop

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 also retained some of the same membership, it was to be expected some consensus appeared. 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.

4.0 <u>UNITED STATES WIND ENERGY PROGRAM</u>:

The United States has embarked on a highly accelerated program to examine the potential of a number of alternative energy technologies, including WECS. The effort is consolidated under the Wind Energy Branch of the Solar Energy Division, ERDA. This effort is directed by Dr Lou Divone;

however, to provide administrative support, research planning and technical guidance, the total program has been divided into sub-tasks assigned to various Government agencies as follows:

Horizontal Axis WECS Development - NASA, Cleveland, Ohio.

Vertical Axis WECS Development - ERDA, Sandia Laboratories-Albequerque, New Mexico.

Rural and Agricultural Applications, ARS, Belsville, Maryland.

Meteorological Characteristics - ERDA, Battelle - Pacific N.W. Laboratories, Richland, Washington.

Small Windmill Hardware Testing and Development - ERDA, Rockwell International, Rocky Flats, Denver, Colorado

The current thrust of research in the Meteorological area is directed toward:

Wind characteristics and large system design - this includes wind as it influences windmill 1) structural strength, 2) structural fatigue, 3) wind turbine performance, and 4) turbine control system design.

Wind characteristics and large system application - this includes siting of large numbers of turbines over a wide geographical area in an optimum manner and operating a large system in the presence of a spatially variable wind field.

Wind characteristics and small WECS - the production of siting handbooks and thus satisfactory utilisation of meteorological information by the small WECS user is the concern of this area.

Currently funded projects include site selection methodologies, siting handbooks, stochastic characteristics of the wind in view of windmill performance, and network response of WECS to spatial or temporal variation over large geographic regions.

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LARGE WIND GENERATOR PROJECTS, 100 kW+

Country/Place	Years of Operation	Nominal Capacity (kW)	Rotor Diameter (m)	Tower Height	Number of Blades	Weight (kg)	RPM	Rated Wind Speed (m/s)	Cut in Speed (m/s)	Feather speed (m/s)	Remarks
USSR, Balaclava	1931 - ?	100	30.5	30.5	3	--	30	11	-	-	
USA, Vermont	1941-1945	1250	53	35.5	2	238,000	28	13.4	-	-	Blade failure
Switzerland, Grenoble	1947-1950	100	~11	~11	Multi	-	-	-	-	-	Unidirectional Morrel Barrage
UK, St. Albans	1952	100	24.4	30	2	36,000	95	14.8	8	29	Technical Failure Hollow Blades
UK, Orkney	1955	100	15	24	3	12,712	130	15.6	10.3	26.8	Operational problem
UK, Isle of Man	1958	100	15	11	3	6,500		18.3	7.6	31.3	
Denmark, Gedser	1957-1968	200	24	25	3	-	30	15	5	-	
France, Nogent Le Roi	1958-1963	800	31	30.5	3	195,000	47	16.1	7	56	
France, St. Remy des Landes	1960's	130	21	20	3	29,000	56	12.5	-	-	
"	1960's	1000	35	30	3	87,000	-	16.5	-	-	Mechanical Failure
Germany, Stötten	1957-1966	100	35	24.4	2	-	42	8	3	-	
USA, Ohio	1975 -	100	38	30.5	2		40	8	4	27	Mod-0
Canada, Magdalen Islands	1977 -	200	24	37	2	-	-	-	6.3	-	Vertical axis, Darrieus type