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INTERNATIONAL SYMPOSIUM ON WIND ENERGY SYSTEMS

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This report offers brief descriptions of the papers presented in Cambridge on 7-9 September 76. Vertical - and horizontal-axis systems were discussed both in theory and in practice. Applications ranged from "wind forms" each with hundreds of megawatt units to the use of Cretan windmills to provide water for cattle. Wing energy conversion units have been operated in several configurations and the theory of their performances is sufficiently advanced to allow design for fabrication. The trends are towards larger units for municipal → next page

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power systems and smaller units for domestic use. In the former case, the behavior of large wind turbines operating in large arrays, and the output (with and without storage) of several such arrays when geographically dispersed, has yet to be well understood. The field has reached a level of maturity characterized by such factors as economics, environmental impact, and public acceptance.

C-31-76

INTERNATIONAL SYMPOSIUM ON WIND ENERGY SYSTEMS

INTRODUCTION

The title of the Symposium aptly describes its theme. About 160 representatives from some 21 countries gathered at Cambridge University on 7-9 September to seek the answers to such questions as "What is the present state-of-the-art in wind energy and how is the field developing," and "Is there an economic case for wind power and what are the limitations in system design and site location?" Written contributions came from 9 countries, including such outposts as Tanzania and Singapore, but the US was the chief contributor with 11 of the 27 papers. Considering the 3 papers from Canada, the presentations of the North American continent in fact constituted over half the Symposium.

The written contributions were only part of the story, however, because this was one of those delightful symposia where the delegates gave as much as they got. There was considerable audience participation, and the lengthy periods allocated for discussion showed an admirable foresight on the part of the organizers, the British Hydromechanics Research Association (BHRA). There was even an "old curmudgeon" in the audience--such a frequent occurrence at BHRA symposia that I am led to wonder if they do not purposefully hire such expeditors of brisk discussion. (It was the O.C. who said, "I'm usually convinced that something could be done but nothing would be done--and right on both counts.") Appendix A is a Recipe for Successful Symposia that I have concocted after observing several BHRA successes.

In subsequent sections of this report I shall describe the main issues brought out in the several sessions. The Symposium is also mentioned in ESN 30-11:494, and the Proceedings are available from the BHRA (Cranfield, Bedford MK43 OAJ). A list of authors and titles is included as Appendix B.

TECHNICAL SESSIONS

The Symposium was organized into six sessions headed Wind Sites and Forecasting, Horizontal and Crossflow Turbines, High Speed Vertical Axis Turbines, Economics, Augmentors, and Storage. These topics are not mutually exclusive, of course, and there was considerable overlap. For instance, the subject of economics found its way into many papers and particularly the discussions (the session on economics itself contained only two papers).

A topic that emerged in the discussions as one of great interest was that of the environment (what do windmills look and sound like?), and it was unfortunate that a session could not have been devoted to this problem. Nevertheless, I see no room for improvement upon the organization of the various subjects, and will follow the Symposium arrangement.

Wind Sites and Forecasting

Like most forms of energy that originate with the sun, wind energy is found in quantities and features that vary widely in space and in time. Wind energy is kinetic energy, however, having been transformed by nature from its thermal origin. This is seen to be an advantage by most proponents of wind energy systems (WESs) since it puts them one step ahead in the process of conversion to useful work. Since wind energy has to be found before it can be exploited, "prospecting" provided the focus for the session on wind sites and forecasting.

In Sweden, the utilization of wind energy seems to be receiving very serious consideration. O. Ljungström described the Swedish government's current three-year program begun in 1975 with a budget of about $2.2 million. The program is now managed by the National Swedish Board for Energy Source Development, and is aimed at advancing the state-of-the-art, improving the data and methods available for decision-making, and proposing plans for continued R&D and eventual implementation of WESs.

The study has included the careful analysis of 10-year data for several inland and coastal sites and has led to the characterization of Wind Duration Profiles and Median Wind Data. For instance, it has been found that the fraction of time that the wind will be a specified ratio of the median can be accurately predicted by a simple logarithmic function depending upon a single parameter. The value of this parameter has been determined for various sites (coastal, near coastal, and inland). Probability functions have been determined for median winds, again depending upon site but also upon height above ground. These data have been used to develop "Wind Energy Classes" for site classification and evaluation, and have led to estimates of the "inventory" of Sweden's wind energy resources.

To convert this source information to energy output predictions, Ljungström described an analysis in which "standard" units (windmills), ranging in size from 50-110 m in rotor diameter and in power output from 1-5 MW, are considered in various arrays at the most promising locations. Preliminary results indicate that arrays of closely spaced (separation distances of 7-10 rotor diameters) units of 2-5 MW capacity are optimum from a land utilization point of view. Such a philosophy leads to the predicted feasibility of producing 10-20% of Sweden's 1990 electrical power requirement using 0.5 - 1.0% of her land area. Ljungström did not discuss in great depth the problem of storage, but it is his opinion that storable hydroelectric energy, at about 45% of the total, will allow up to 5000 MW of wind power to be directly accepted by the distribution network.

The Swedish study has even considered the aesthetic aspect of "wind farms." Ljungström showed a few artist's conceptions of these as they would appear in the Swedish countryside. The effect was not particularly repulsive to me (artist's conceptions seldom are), but the contrast between modern machinery and rural dwellings was certainly striking, and in my opinion the propellor-like horizontal-axis wind generators seemed more pleasing to the eye than did the vertical-axis egg-beater types.

Site studies and geographical arrays have also been considered by C.J. Justus (Georgia Inst. Tech.) in the simulation of wind turbine arrays for use in the New England and Middle Atlantic regions of the US. Five-year data are used from 28 sites within the study area. Justus considers the use of smaller (500-1500 kW) wind generators than those assumed by Ljungström, but his performance estimates are based on actual designs of would-be wind turbine manufacturers (Kaman, GE, and Boeing). The main goal of the study is to evaluate the extent to which the availability of power at a given level is improved by the geographical dispersal of wind power sites. Analytical expressions are developed for power output as a function of wind velocity, and these are combined with site statistics in order to obtain site outputs. Interactions between wind turbines within sites are not considered.

In contradistinction to the Swedish study, Justus finds that a 1000-kW wind turbine provides the best combination of high power level and low cut-in and rated speeds. For all units considered, reliability is considerably improved by geographical dispersal. The study also considers the effect of storage upon the performance of a given array (set of geographically dispersed sites). To give a sample set of results, 500-kW wind generators, during the month of January, would give an output of 200 kW with a reliability of 56% operating at a single site, and 65% when operating at sites within a New England coastal array. If 29 hours of energy storage were available, the reliability of the array would increase to 90% and to 95% with 37 hours of storage. Justus is of the opinion, however, that favorable coincidence of available wind power and user requirements will greatly reduce the need for storage.

G.K. Nathan and his coworkers at the University of Singapore have likewise concluded favorably with regard to wind power. They have studied the sites available in the Singapore area and found that small wind turbines of 5.4 kW capacity are economically feasible for household and irrigation use. Comparing with the $1121/kW cost of installed power in Singapore, the wind turbine unit cost of $400/kW is likely to prove competitive even after site construction and installation costs are considered.

Two papers described efforts to provide a better understanding of the behavior of winds at specific site locations. At Colorado State University, R.N. Meroney and coworkers have begun a three-year experimental program to provide a uniform body of knowledge on terrain aerodynamics. Meroney presented wind-tunnel results for the flow past triangular and sinusoidal hills. In his talk, Meroney included an interesting discussion of past studies, and his report is especially useful because of the tabulation he gives of "pros and cons" for site evaluation in hilly regions.

B.E. Freeman and J.R. Taft (Science Applications, Inc., US) have developed computer codes for the prediction of local and area wind conditions based upon data furnished by synoptic weather stations. The computer model incorporates the dynamic effects of terrain on wind channeling, blocking, and sheltering, and also includes the influence of mesoscale thermal circulations such as land-sea breezes and mountain-valley winds. The full time-dependent, three-dimensional equations of motion are utilized with diffusion terms approximated by empirical coefficients. The Dugway Proving Ground (near Salt Lake City) has been the area used to test the code and is partitioned, for this purpose, into a 23 x 23 computational mesh, with each zone measuring 5 x 5 km. The code is quite time-consuming, taking several hours to reach an equilibrium solution, and Freeman and Taft have taken extensive pains to improve computational efficiency. Although no verification is available, the calculated wind behaviors are quite "believable" and can be related to the various terrain features of the region. The capability discussed in this paper is aptly described as powerful.

Horizontal and Crossflow Turbines

Horizontal-axis turbines are by far the most common wind energy devices in use today, and are the prototypes under consideration for utilization in most large-scale wind-power plants. One probable reason for this is the relatively advanced state of propellor theory which provides a reliable point of departure for the analysis of horizontal-axis machines. Propellors and wind turbines do have fundamental differences, of course, since they accelerate and decelerate the wind, respectively. In their paper titled "Performance-Optimized Horizontal-Axis Wind Turbines," R.E. Wilson and S.N. Walker (Oregon State U.) describe the criteria appropriate for maximizing the power output at each radial station along the blades of a wind turbine rotor. Parameters are the number of blades, the tip speed ratio (tip speed/wind speed), and the lift/drag ratio of the rotor airfoil sections. The result of the calculations is the radial distribution of the product of the section chord and lift coefficient so that the specification of one of these defines the other and leads to the optimum rotor twist and chord distribution. Such specification is apparently arbitrary, and the "optimization" therefore leaves some necessity for the application of "seat-of-the-pants" aerodynamics.

The analysis of T.E. Base and L.J. Russell (U. Western Ontario), which was misplaced in the session on Wind Sites and Forecasting, is based upon the linear and angular momentum changes across the rotor annulus, as given by the Rankine-Froude momentum theory. An iteration scheme is utilized to determine the axial interference factor (which accounts for the deceleration of the axial flow) and the rotational interference factor (which leads to an induced angular velocity of the rotor). These factors depend upon rotor section shape and lift/drag characteristics, and the authors decline to present their results, presumably due to the absence of appropriate experimental data for comparison. This rather curious attitude detracts from the credibility of their analytical method which, although no optimization is attempted, appears to be potentially useful from a design point of view. Base and Russell also present a computational scheme for predicting the effect of large scale turbulence (turbulence length scale/rotor diameter ≈ 0.2) upon windmill performance.

The two papers mentioned above were the only contributions to the theory of horizontal-axis wind turbines. The remaining two papers in this session described some experiences with other kinds of turbines, only one of which had a horizontal axis. This was the so-called "cross flow turbine" discussed by M.J. Holgate (U. Durham, UK). This device resembles a paddle-wheel with curved blades, and its operation (in an unbounded freestream) does not really depend upon the orientation of its axis. The author has constructed a simple theory that is shown to be useful in determining the qualitative features of the cross flow turbine: operation at low speed ratio (peripheral speed/wind speed), low efficiencies (less than 25%) and positive starting torque. This last feature is the only apparent virtue of the device, and was verified (as were the other theoretical predictions) in laboratory tests. The authors showed a commendable measure of professionalism in their conclusion that: "In view of the low efficiencies both predicted by theory and obtained experimentally no further work, either experimental or directed towards refining the outline theory, can be justifiably recommended." (This is the most forthright public statement of negative results that I can remember having heard.)

Finally, in this session, R.E. Powe (Mississippi State U.) presented his analytical predictions for the performance of what he calls the "tracked vehicle airfoil." Powe's concept is to mount airfoil-shaped surfaces vertically on a series of carriages that are free to run along an oval track. The plane of the oval is horizontal, and its long sides are perpendicular to the prevailing wind. With a rather crude analytical model, Powe has evaluated the relative influence of several design factors such as blade height, chord, spacing, etc. In one of his most promising designs (get this) there are 3285 blades, 30.5 m/high with 6.1 m chords, mounted on 1095 carriages that role around a track whose straight sides are 7.6 km long (the semi-circular ends are 0.76 km in radius)! For a device such as this Powe predicts a factor of 1.54 in comparing the energy/time x swept area for his device with that of a "standard" windmill (132.8 as opposed to 86 kWh/month-m^2). The details of the comparison were not given and a number of questions (such as the method of power extraction) were left unanswered. One point of interest, however, is that Powe calculates his "swept area" by considering only the blades on one side of the track, although both sides apparently are assumed to extract wind energy at the same rate. The notion is certainly innovative, but it is to be hoped that a good deal more careful analysis will go into the concept before ground is broken for a system that would require space equivalent to, say, the Washington Mall.

High-Speed Vertical Axis Turbines

There are essentially two forms of vertical axis turbines currently under study for wind power extraction. The first of these, and by far the most popular, is called the "Darrieus rotor" (after G.J.M. Darrieus, author of the 1931 patent) and consists of two or more slender vertical blades with airfoil cross sections that rotate about a central vertical axle. If the blades are sufficiently flexible and are pinned to the central axle at their upper and lower extremes, they will conform to the "troposkien" curve which is the centrifugal analog to the gravitationally-induced catenary shape. The other form of vertical axis turbine which is of current interest is the "Savonius" rotor which consists of solid fins that form continuous s-shaped curves when viewed along the vertical axis. Actually, neither of these devices need have vertical axes, although this is the orientation that is most convenient--they will operate, in theory, as long as their axis is crosswind.

The vertical axis systems have several potential advantages over horizontal axis machines: they are omni-directional, requiring no yaw control to follow the wind; they do not require blade pitch control (although the fact is that pitch control, if possible, might lead to improved performance); they can be designed with most of their ancillary equipment located at a ground-level base, so that a low center of gravity is obtained and maintenance is relatively easy; their blades are held at both ends (in conventional designs) so that they do not tend to fail themselves in tension as do "propellors"; and the blades are not twisted and can be manufactured by a relatively simple extrusion process. Since however, the Darrieus rotor requires extensive lengths of unsupported blade, there are serious structural limitations on such devices; they are prone to vibration, and their application to large systems is still a matter of some debate among windmill buffs.

The National Research Council of Canada has long supported research in WESs, in particular the work of R.J. Templin and P. South who have helped bring vertical-axis technology to the point that a 200-kW prototype will soon be in operation in the Magdalen Islands in the Gulf of St. Lawrence. In their paper titled "Some Design Aspects of High-Speed Vertical Axis Wind Turbines," Templin and South give a review of their combined analytical/experimental studies that have considered optimum distribution of blade material (with respect to blade flutter), blade buckling under combined gravitational and aerodynamic load (when the rotor is stopped with a blade upwind), optimum solidity (number of blades x blade chord ÷ equatorial radius of rotor), and optimum vertical, radial, and blade-section dimensions. These latter considerations are made with cost as the independent variable. A large range of other factors are also considered.

Templin and South describe the design considerations that have led to their prototype, and they also discuss operational factors such as constant speed vs constant efficiency, and the problems associated with adding random energy from wind plants to existing power networks. Their conclusion in this latter study is that a serendipitous demand/availability obtains (in agreement with Justus) and that there may be little to be gained by the use of either long-term (seasonal) or short-term (daily) storage. Templin and South estimate the installed cost of their

200-kW unit to be $120,000. Taking into account interest rates and maintenance costs, the present value of the wind energy costs is $240,000 for 25 years of wind energy at a production rate of 600,000 kWh/yr. This gives 1.6 cents/kWh, an enormous saving over the 3.0 cents/kWh currently required on the Magdalen Islands for diesel electricity.

P.B.S. Lissaman (AeroVironment Inc., US) has developed a theory for the prediction of the performance of Darrieus and Savonius rotors. The model assumes inviscid flow, but Lissaman suggests modifications to account for viscous effects. For "low chordal ratio" devices, such as the Darrieus rotor, he applies two-dimensional airfoil theory to obtain the power coefficients as the usual (from disc actuator analysis) quadratic function of the windwise interference factor. The analysis for the high chordal ratio Savonius rotor is a good deal more complex and relates the power coefficient to the pitching moment predicted by linear theory for a semi-circular arc airfoil. Significant crosswind forces are predicted for the Savonius rotor which is a Magnus force effect due to rotation and not present in the case of low chordal ratio rotors, in the first-order theory. Lissaman has conducted much of this work in cooperation with Wilson and Walker of Oregon State U. (*loc. cit.*) and together they have obtained comparisons with experiment that appear to support the theoretical model for low chordal ratio devices. Validation of the theory for high chordal ratios awaits the availability of unambigious free wind data. This may be a long wait since there is little apparent interest in the Savonius rotor except, perhaps, as a starting device for the Darrieus type.

O. Holme (Saab-Scania, Sweden) has developed an analytical model for Darrieus rotors that is also based upon the aerodynamics of the individual blade sections. Although he does not compare his results with experimental observations, Holme's results appear to be in qualitative agreement with the analyses of others. The model is restricted in application to rotors with a large number of blades (to minimize unsteady effects) that are lightly loaded (so that linear perturbation methods may be used to determine the induced velocity from vortex sheets emanating from the blade trailing edges). A particularly interesting result is that one-half of the flow deceleration occurs within the rotor envelope (the other half occurring in the wake) so that the loading of blades on the windward side of the rotor is considerably higher than that of the leeward side.

The analysis of J.H. Strickland (Texas Tech U.) is based upon momentum balances conducted across multiple streamtubes through which elements of the Darrieus rotor pass during rotation. The scheme is similar to that of Templin and others, except the momentum conservation principle is applied to blade elements rather than treating the entire rotor within a single streamtube. Elemental contributions are summed to obtain overall power coefficients which have been compared with available experimental data. These comparisons indicated good agreement, especially at large tip-velocity ratios where the single streamtube method over-predicts the data. Distinct advantages of the method are the ability to predict local variations of interference factor in the plane of the rotor, and the capability to include the effects of non-uniform approach flows.

Several other design factors are discussed in Strickland's paper, including the influence of blade Reynolds number. On this particular point, his predictions were supported by D.J. Sharpe (Kingston Polytechnic, UK) who reported from the floor that his calculations indicated a 20% dependency in power coefficient upon blade Reynolds number (higher power coefficients for higher Reynolds numbers). Sharpe's model, like that of Strickland, is based upon multiple streamtubes.

The paper of T.E. Base and L.J. Russell, to which I have previously referred, also contains a description of an analytical model for Darrieus rotors. This is a single streamtube model that utilizes the windwise (axial) and rotational interference factors as parameters. They offer some suggestions concerning methods by which these factors may be estimated. The rather wide-ranging paper also describes wind-tunnel tests of several different configurations of vertical axis windmills; the WES program at the University of Western Ontario is apparently quite comprehensive. A noteworthy feature of these tests is the use of airfoils with rearward-facing steps in the suction surface for the enhancement of attached flow. Base and Russell see promise in this design for self-starting and high performance.

A major portion of the paper by N.V.C. Swamy (Indian Institute of Technology, Madras) and A.A. Fritzsche (Dornier System GmbH, FRG) is devoted to the calculation and approximation of catenary and troposkien shapes. Both are well approximated by a quadratic parabola, and for this shape it was found that 95% of the total torque is derived form 60% of the rotor length (the central portion). They thus propose geometries in which vertical blades are used (and not pinned to the rotor axle, at top and bottom, as in the Darrieus rotor) and claim an advantage in torque, for equivalent rotors, of about 2:1. The ground-rules of the comparison are not clear, and no detailed attention is given to the structural loading of the vertical blades, but even so it appears that this design may be preferred in low average wind-speed conditions such as are found in India (4-5 m/s).

The three remaining papers in this session were concerned with experimental results obtained from vertical-axis turbines. Or, perhaps I should say, hoped-for results, since the paper given by B.F. Blackwell (Sandia Labs., US) was more in the form of a prediction than a conclusion. Under ERDA sponsorship, Sandia has constructed a 17-m (diameter) Darrieus rotor to grace the wind-swept landscape of the New Mexico desert. The design rotational speed is 45.4 rpm with a maximum developed power of 70 kW at a wind speed of 14.3 m/s (32 mph). Because of power-train inefficiencies, 60 kW is expected at the synchronous generator. Perhaps the most intriguing aspect of the Sandia design is the blade itself which consists of an aluminum D-section for the leading edge, a paper honeycomb body, and an aluminum trailing-edge spine, with a fiberglass skin. The blade, which has a chord of 0.533 m and follows the NACA 0012 shape, is manufactured by the Kaman Aerospace Corporation.

The UK provided two examples of innovative design, largely based upon experimental developments. In the first of these, P.J. Musgrove (Reading University) has developed the "Variable Geometry Vertical Axis Windmill" (VGVAW) which consists of vertical blades such as those proposed by Swamy and Fritzsche (*loc. cit.*) and others. The uniqueness of the Musgrave machine lies in the off-center pivot point of the blades so that as rotational speed increases the upper tips of the blades tend to swing out. The extent of this swing is controlled by a spring which offsets the centrifugal force acting to spread the blades. The concept of the VGVAW was quite favorably received by the Conference delegates, and its compactness (relative to the Darrieus turbine), simplicity of construction, and self-compensating features will offer a very competitive improvement upon "standard" designs.

A.C. Baxter (U. Leicester, UK) described his frustrations in experimenting with flexible airfoil sections. His idea is to construct a blade that flexes in a manner that provides high lift coefficients at both positive and negative angles of attack. Baxter has used fabric blades which have proved unsatisfactory, mainly because of the action of centrifugal forces. He has increased the rigidity of the blade by going to a latex rubber skin. This modification has not yet yielded "useful results," and although the concept appears intriguing, Baxter appears to be having considerable difficulty in obtaining reproducible experimental evidence.

Economics

Only two papers were presented in this session--a statistic that is quite misleading since, as previously mentioned, the issue of economics or, more generally, feasibility, was in some way connected with most of the presentations. The paper by A.A. Fritzsche describes a standard accounting of the costs likely to be associated with the construction of a Darrieus-type WES. His analysis appears to have been quite detailed, although his paper includes very little quantitative information. For 4-kW WESs manufactured in lots of 50, Fritzsche estimates a cost of only DM 9800 (about $400) which is partitioned as follows: 3 rotor blades, over-speed protection and 2 Savonius starters--26%; tower and support assembly--23%; bearings--11%; and energy transmission and conversion components (gear box, clutch, and asynchronous generator)--40%. He also makes comparisons with equivalent horizontal-axis WESs and concludes that the vertical-axis devices will not be cost-competitive above a power range of about 20 kW.

The other paper in this session was contributed by B. Sørensen whose analysis is less detailed but extends beyond the unit costs considered by Fritzsche. Sørensen considers the cost of large WESs used in arrays and providing a major portion of the electrical energy handled by power distribution grids. He uses the meteorological data obtained at Risø, together with operational windmill performance data provided by the unit at Gedser, to estimate the influence of energy storage upon availability. Over a period of one year, without storage, the unit studied provides an average output of 136 W/m^2, is inoperative for 31% of the time, and delivers energy at a level above the average for 42% of the time. With a 24-h storage capability (duration that the storage system can sustain power at the average level), for example, the average power is available about 75% of the time and the duration of "over-power" is reduced to about 20%. Sørensen compares his results with data for nuclear power plants and concludes that 10 hours of storage time is sufficient to make WESs competitive as sources of mains power.

Sørensen's paper also includes a cost comparison, in terms of average cost of electricity, between wind with and without storage, fossil fuel, and nuclear energy sources. In this order, the ¢/kWh costs are: 1.3, 1.7, 2.0, and 1.8. These figures include capital, operation and maintenance, and fuel costs. His estimates are highly speculative; in fact, the changing prices of things caused Sørensen to update his figures during his presentation. Noteworthy features of these estimates are that the costs of fossil and nuclear fuel are a large portion of the total and that both these systems are severely penalized, relative to the WESs, by the efficiencies of conversion from thermal to electrical energy. The estimates appear to be conservative with respect to the cost of wind energy, e.g., the fuel costs are assumed to remain constant over the 25-year lifetime. The WESs are thus quite competitive, even within the range of uncertainty of Sørensen's data. The estimates of nuclear and fossil fuel plant electricity costs are 4-5 times greater than what they were a few years ago when WESs were rejected as alternative systems!

Augmentors

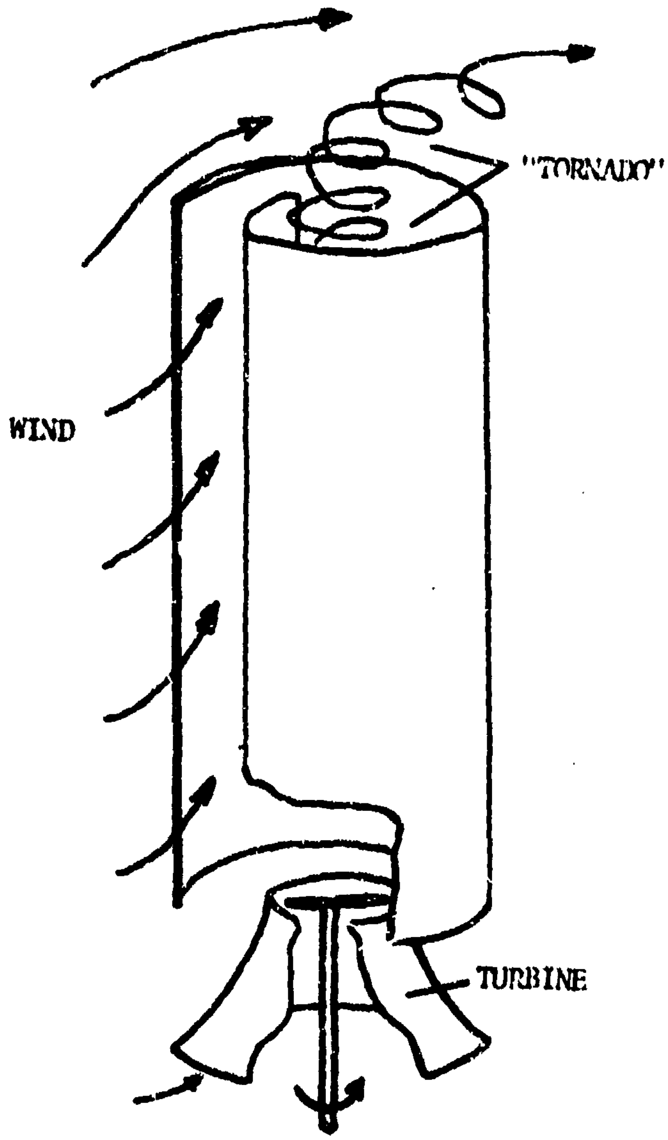
The papers in this session were devoted to various design innovations that hold promise in the concentration of the wind energy available in the vicinity of the turbine blades. Several similarities could be seen between the various concepts, particularly those involving upstream vortex generators. In all cases the cost of such augmentors was not a parameter in the analyses, although several investigators mentioned this factor as "the proof of the pudding." An upstream vortex generator for 80-m diameter horizontal-axis generator might well cost as much as the generator itself, especially when the "cost" of the preempted space is considered.

J.L. Loth described several augmentation schemes that have been evaluated at West Virginia University. The simplest of these is an obstruction which creates an accelerated flow field for use in conjunction with vertical-axis generators. With a cylindrical obstacle placed between two counter-rotating Savonius rotors, Loth has obtained power concentration ratios (R) of slightly more than 2. For horizontal-axis machines he proposes upstream vortex generators, such as wings, appropriately placed so as to increase the kinetic energy incident on the turbine. Experiments have been conducted with high-lift wings, and a small augmented horizontal-axis wind turbine has been built for future testing (it is designed for R≈3). Perhaps the most elegant innovation proposed by Loth is that of a cylindrical Darrieus rotor (one with blades that are free at the tips) with blades that are free to rotate in pitch (which determines the angle of attack), tilt outward at the bottom (so that they sweep-out a conical volume when rotating), and rotate in a plane normal to the pivot arm. These motions are induced by aerodynamic and centrifugal forces and can be regulated by appropriate placement of the blade aerodynamic center, center of gravity, and pivot arm hinge point. A stabilator is also attached to each blade which acts as a weather vane. The ensuing 3-dimensional motion is too complex to describe here (and only partially understood by this writer), but Loth claims that blades so constructed and mounted will automatically seek an optimum angle of attack throughout their rotation about the central axis, they will be self-starting, and they can be given automatic overspeed control. A 1.5-m-diameter rotor has been built, and although operating data are not provided, the paper infers that the self-starting and feathering characteristics have been verified.

P.M. Sforza (Polytechnic Institute of NY) has also experimented with vortex generation and has conducted wind-tunnel tests to determine the properties of the vortex flow fields behind highly swept delta wings. Theoretical calculations indicate an achievable power amplification of from 3 to 9, and wind-tunnel tests of subscale devices have given values on the order of 5. Tests are to continue in the field with a newly constructed prototype which consists of two small (about 1 m diameter) rotors mounted in the wake region of a flat-plate delta wing. A new wind-tunnel facility has also been built for the testing of various rotor designs.

Th. van Holten (Delft University of Technology) described his continuing studies of the effects of small lifting surfaces (tipvanes) attached to the tips of a horizontal-axis rotor. The vanes are shaped and mounted so that their pressure side is radially outward during rotation. The resulting inward force acting on the vanes is reacted by an outward force on the air which is deflected radially outward. The system of tip vanes acts like a ducted fan in that a larger amount of air flows through the turbine disc. Van Holten discusses various design parameters that influence the performance of the tipvane system. Values of R are predicted to be in the range 2-3. His theory has been partially verified by tests in which a fan with tip vanes (with no wind) is used to test the diffuser effect of the vanes. This augmentation scheme is particularly attractive from a structural point of view since the sweeping effect of the vanes produces benefits similar to those of a solid duct without the attendant massive structures.

J.T. Yen (Grumman Aerospace Corp.) proposes to duct the surface wind in such a way that a tornado-like flow is created in the downstream region of a vertical axis turbine (see sketch). He claims that the unit capacities of up to 1000 MW are rendered feasible by his concept! I was unavoidably absent from this session so that I am only able to comment upon the printed version of this work which, to say the least, is difficult to follow. Yen's analysis is apparently based upon an energy balance in which the turbine output power is equal to the total enthalpy



of the air flowing through the turbine plus that of the air entering downstream of the turbine, less the total enthalpy of the swirling flow leaving the cyclone chamber. Apparently, it is calculated that a large part of the energy that is in the wind flowing through the sides of the cylinder is somehow extracted by the turbine, even though this flow does not pass through the turbine. Huge power amplifications are obtained: Yen would have his readers believe that a 1-MW standard turbine, if placed at the foot of one of his tornado towers (which would be about 600 m high and 200 m in diameter), would then yield 100 to 1000 MW depending upon turbine power efficiency which is allowed to range from 0.3 to 0.8. The logic behind these calculations is not obvious to me, and I had difficulty understanding the many assumptions that lead to the scaling laws. These problems were aggravated by the presence of several undefined symbols including M_∞ which if allowed to tend to zero, as if it were the freestream Mach number, would yield an infinite power coefficient. My guess is that by using one value of efficiency Yen assumes that the turbine extracts power from the wind flowing into the tornado chamber behind it as efficiently as it does from the "working fluid" that actually flows through the turbine. He says that his experiments (which are not described) have yielded an augmentation factor of 6.

Storage

The issue of storage of wind generated power turns largely on economics and, for this reason, the papers in this session might well have appeared in the one on economics. In fact, there was probably enough material on economics in this Symposium to justify a separate meeting on the subject. The report of J.P. Molly indicates that the West German government has sponsored an investigation of WESs that is similar in nature to that reported by Ljungström of Sweden. Molly has conducted a survey of 25 reporting stations throughout West Germany and has coupled these statistics with the operating characteristics of horizontal-axis wind turbines with 10,000 m^2 swept areas (blade diameters: 113 m). These characteristics are extrapolated from data obtained from the 100-kW machine at Stötten.

Molly describes a variety of interesting tradeoffs. In selecting the power density level (W/m^2) of windmill units, for instance, one must consider the higher breakout torque of larger machines and the level of high winds available to drive the turbines at the increased speeds. For instance, with a mean wind velocity of 6.7 m/s 10-m above the ground, a machine rated at 100 W/m^2 will produce this power for about 40% of the year and no power 10% of the time. A wind turbine rated at 500 W/m^2 will produce at this level for only 8% of the time and will be non-productive over 23% of the year. The yearly mean power outputs for the 100 W/m^2 and 500 W/m^2 units are, respectively 70 W/m^2 and 180 W/m^2. Thus the nonlinear relationships involved are clearly illustrated. (Mother Nature, like most women, is highly nonlinear!). For the remainder of his analysis, Molly selects a 300 W/m^2 unit as his standard, giving a rated power output per turbine of 3 MW--in the same ballpark as that recommended by Ljungström.

In agreement with several other reports presented at the Symposium, Molly finds that units, or groups of units, spread apart throughout West Germany provide substantial benefits in power level reliability. With a mean velocity of 6 m/sec, for instance, the amount of time without power is reduced from about 1700 hrs/year for a single unit to 20 h/yr for 12 sites separated by a mean distance of 160 km. If the mean separation of the 12 sites is increased to 260 km, the predicted "out" period is reduced to 5 hr/yr.

Molly discusses two modes of wind power distribution: (1) without storage, in which conventional power plants are used to smooth the fluctuating output of wind plants; and (2) wind power output in conformity with demand, in which excess power is transferred to storage and deficiencies are supplied therefrom. Such systems would consist of several thousand individual units distributed over a large area with, say, 100 units at each site. The former method requires that WESs provide no more than about 15% of the total rated power output since adequate conventional power must be available to compensate nonproductive periods inherent in WESs. A combination is, of course, the best solution, and Molly investigates various ramifications of site dispersal and quantity, storage capabilities, and variations in demand. Costs are considered only in a qualitative way. Molly concludes that the fundamental difference in WESs from conventional systems, from an operational point of view, is the difficulty in predicting the times of low power output. Compound dispersed sites minimize the length of these times and storage minimizes their impact on power supplied to the user.

Som of the difficulties of the real world were brought out in the paper by G.I. Fekete who described his proposed design to supply power at a continuous level of 5000 kW to salt-mining operations in the Magdalen Islands. Using 300-kW wind turbines, Fekete found that up to 200 of them would be needed because of the predicted overall plant efficiency (about 30%) and the vagaries of the wind source. The Magdalen Islands appear to be a great place to build windmills, but I wouldn't want to live there! The annual mean wind is 9.3 m/s with an average of 10.6 m/s in December and January and "calm" periods of 7.2 m/s on the average in June and July. (There is some comfort in the fact that an annual maximum of 44.3 m/s is only likely to occur every 200 years.)

Fekete's system involves the use of hydraulic energy storage because of the near-term availability of equipment and technology for such a system. In the "storage" system, wind power is used exclusively to pump salt brine to a height of 442 m above underground cavities. This provides a 305-m head for operation of a hydroelectric plant. The "mix" system supplies wind power directly to the load when a sufficient level (5000 kW) is available and pumps water to storage during periods of excess power availability. When wind energy is insufficient, makeup power is drawn from the hydraulic reservoirs. The "mix" system appears to be superior, although this is not as obvious as it seems since the economics involved are storage intensive--storage cavern cost is $1.3 million per day's storage capacity while wind generators are priced at $0.35 million per unit. Fekete treats various "worst" cases (during the month of June), and in the end he recommends a mix system using about 85 wind generators with 9 caverns having a usable capacity of 0.2 x 10^6 m^3 and giving 11 days of storage capability. A land area of 22 km^2 is required with a capital cost of about $75 million and an energy cost on the order of 20¢/kWh.

There is a valuable lesson to be learned from Fekete's analysis, which he claims is within an uncertainty range of 20%: if 85 wind turbines rated at 300 kW apiece are used to generate power in a relatively favorable wind environment, an optimistic estimate is that 5,000 kW (not 25,500!) of continuous power will be available to the load. The inefficiency and high cost of hydraulic storage is, of course, a major factor in these estimates. For instance, if the brine were pumped from the same level as the hydroelectric generators, instead of from caverns 137 m below, an efficiency of 305/442 = 0.69 would be eliminated. Other efficiencies peculiar to hydroelectric storage are those of the pumps (70%) and hydroelectric generators (80%).

M.E. Parkes (U. of Newcastle upon Tyne, UK) and F.J.M van de Laak (Tanzania) provide a fresh and somewhat startling insight into the energy facts of life in developing countries. Tanzania has an area of 340,000 square miles, a population of 12 million people and about the same amount of livestock. About 95% of the population are involved in agriculture which contributes only about 50% of the gross domestic product. The difficulty of access to reliable water supply is seen to be a significant contribution to this relative inefficiency of the agricultural sector. It is argued that low-technology wind energy, with storage, may be a viable alternative to the use of diesel engines to power water pumps. Parkes and van de Laak give information on the Tanzania situation that, however fascinating, is not repeated here except for the following quote concerning irrigation for the small landholder. "It must be stressed that engineering is not the fundamental difficulty underlying irrigation practise in the less developed countries. The problem is to define the social context of such developments. The size of smallholding can only be established by asking: what area is the small holder capable of farming efficiently, what does he want to farm, what is he accustomed to farming and what area should he farm in the interests of the community? Factors which may not be readily appreciated are that there is a relatively large increase in labour requirements for irrigated as opposed to rain-fed farming and that wide differences in labour requirement among crops make crop choice the largest single determinant of farm size. Level of mechanization is a further complicating factor."

The authors conclude that windmills are feasible for rural water supply of small units of population if large (larger than needed for diesel systems) storage systems are available and if local manufacture is possible. Feasibility for irrigation is marginal because of socio-economic factors, but there is promise in the use of single units for providing water for livestock.

The final paper of the Symposium served to establish a lower bound on the power levels of current interest to WES enthusiasts. In contrast to the 5 MW wind turbine units under consideration for use in large scale power systems, P. Hirst and D.H. Rees (UK) described a 100-W device for use with low-power electronic equipment such as communications repeaters and navigational aids. The main feature of their design is an electromechanical control circuit which provides a load on the wind rotor that is tailored to provide near-optimum efficiency over a wide range of wind speeds. The basic wind turbine design is assumed to be that of the vertical axis type, and continuous power output is made available through the use of lead-acid storage batteries.

Discussion Forum

The Discussion Forum served to underline the "soft" sciences, such as economics, safety, and environment which appear to present the most critical problems in predicting the future of WESs. The Forum was "kicked-off" by short summaries given by leading figures in the wind energy programs of three countries.

J. Allen (Atomic Energy Research Establishment at Harwell, UK) emphasized the "go" status of the technology and the "hold" status of socio-economic aspects of wind energy. The western regions of the British Isles are well suited to wind power, and Allen believes that prototype wind machines are operating sufficiently close to specifications as to warrant technological confidence. He emphasized that even though fuel prices are presently inflated, the current cost of capital is also high--to an extent that economics will not now overcome bureaucratic inertia. In addition, it is not now known whether WESs are sufficiently reliable (they must have a useful life of at least 25 years), and much has yet to be understood concerning their environmental impact.

Representing the US Energy Research and Development Agency (ERDA), L.V. Divone described the position that wind energy occupies among other ERDA programs of alternate energy: tides, ocean thermals, and direct solar. Divone pointed with justifiable pride to the rather exceptional speed with which WES technology has progressed under ERDA sponsorship: from research to development in 3 years! The ERDA Mod I horizontal axis wind turbine is 61 m in diameter with a power output of 1.5 MW (about 500 W/m^2) at a wind speed of 19 mph. Divone again emphasized the problem of energy cost vs. energy value. Many factors come into play, such as the time of day, but the main issue is "what is the cost of the form of energy that is saved when wind power is activated?"

From the point of view of The Netherlands, G.G. Piepers emphasized the environment--acceptance of WESs in any significant amount would require a revolution in urban planning. He also ventured the opinion that the switching and distribution problem, when wind energy is used to augment existing electrical networks, is a problem whose magnitude has been greatly underestimated.

The Discussion Forum featured animated exchanges between and among the delegates and speakers. A prevalent emotion was the fear of bureaucratic paralysis because of uncertainties that, in the end, would be resolved only by decisive action. The mood (I thought) was generally that wind energy has been shown to be cost effective with a level of certainty that is easily sufficient to justify further and larger programs. Issues such as noise, safety, reliability, and aesthetic appeal are matters that must be resolved along with, but not before, the installation and operation of future-generation systems.

SUMMARY

The comments in the previous section serve as a partial summary: wind energy is feasible to a first approximation, analytical tools are at hand to predict cost and performance, and near-optimum units and arrays can be designed. The field is at that level of maturity where hard management decisions must dictate either a growing or static future.

The field of wind energy engineering is fraught with potential research and exploratory engineering research projects. These include optimal design, the study of flows associated with wind turbine units operating in arrays, a variety of augmentation schemes (many of which have been described herein), the development of small and compact units (such as for household power), hybrid devices (using wind energy in combination with other solar forms), and continued analysis of the structural, mechanical, electrical, and aerodynamic behavior of wind turbine units and arrays.

In my opinion, the Symposium was intensely interesting and of great benefit to those who could attend. The results cited in the several papers were occasionally tentative, and even far out, but there was plenty of hard evidence, technically and economically, that the wind is a viable energy resource.

APP A

Recipe for St ssful Symposia

1. Select limited topical areas, e.g. "Wind Power"--not "Alternate Energy Sources." This tends to create a delegation which is limited in size and truly interested in the meeting subject.

2. Plan well ahead. Get announcements out well in advance. These should include a provisional program (with titles and authors), a clear description of the venue, accommodations, and special events, and a breakdown of fees that does not require an intrepretation by a CPA.

3. Require fully prepared papers from the authors, and distribute them to the registrants at least two weeks prior to the meeting.

4. Plan the program content to allow for a good balance between theory and practice.

5. Don't have too many papers--perhaps 2 or 3 per session with 3 or 4 sessions per day with breaks in between.

6. Allow ample time for discussion--a minimum of half the time alloted to presentations. Use an "old curmudgeon" if you can find one. (Emeritus faculty are often available for this duty.)

7. Select keynote speakers and session chairmen who are familiar with broad aspects of the technical subject, such as national programs and priorities, historical developments, and future goals.

8. Have the meeting in an attractive academic environment that is convenient to public transportation and accommodations.

9. Have a limited number of high-quality "special-events" (tours, banquets, etc.). Include their cost in the registration fee. Treat these events as part of the program. Do not have a myriad of alternatives that confuse and divide the delegation.

10. Have a few professionals out front at the Conference. A "professional" is defined as someone who is intimately familar with the planned program and events, tries to learn the delegates' names, and can exhibit an air of being in control even if all else is in utter disarray. (This generally excludes scientists, engineers, and educators.)

APPENDIX B

Titles and Authors: International Symposium on Wind Energy Systems Cambridge University 7-9 September, 1976

WIND SITES AND FORECASTING

Large scale wind energy conversion system (WECS) design and installation as affected by site wind energy characteristics, grouping arrangement and social acceptance.
O. Ljungström, National Swedish Board for Energy Source Development (NE), Sweden.

The potential for power production by large dispersed arrays of wind turbines.
C.G. Justus, Georgia Institute of Technology, USA.

A study on the use of windmills in Singapore.
G.K. Nathan, G.P.D. Rajasooria, K.C. Tan and T.L. Tan, University of Singapore, Singapore.

Wind tunnel simulation of the influence of two dimensional ridges on wind speed and turbulence.
R.N. Meroney, V.A. Sandborn, R. Bouwmeester and M. Rider, Colorado State University, USA.

Mathematical modelling of topographic effects on wind energy systems.
B.E. Freeman and J.R. Taft, Science Applications, USA.

Computer aided aerogenerator analysis and performance.
T.E. Base and L.J. Russell, The University of Western Ontario, Canada.

HORIZONTAL AND CROSSFLOW TURBINES

Performance--optimized horizontal-axis wind turbines.
R.E. Wilson and S.N. Walker, Oregon State University, USA.

A cross flow wind turbine.
M.J. Holgate, University of Durham, UK.

A wind energy conversion system based on the tracked vehicle airfoil concept.
R.E. Powe, Mississippi State University, USA.

HIGH SPEED VERTICAL AXIS TURBINES

Status of the ERDA/Sandia 17-metre Darrieus turbine design.
B.F. Blackwell, Sandia Laboratories, USA.

Some design aspects of high-speed vertical-axis wind turbines.
R.J. Templin and P. South, National Research Council, Canada.

General performance theory for crosswind axis turbines.
P.B.S. Lissaman, AeroVironment, Inc., USA.

A performance prediction model for the Darrieus turbine.
J.M. Strickland, Texas Technical University, USA.

A contribution to the aerodynamic theory of the vertical-axis wind turbine.
O. Holme, Saab-Scania AB (Aerospace Division), Sweden.

Aerodynamic studies on vertical-axis wind turbines.
N.V.C. Swamy, Indian Institute of Technology, India, and A.A. Fritzsche, Dornier System GmbH, German Federal Republic.

The variable geometry vertical axis windmill.
P.J. Musgrove, Reading University, UK.

A low cost windmill rotor.
A.C. Baxter, University of Leicester, UK.

ECONOMICS

Economics of a vertical-axis wind turbine.
A.A. Fritzsche, Dornier System GmbH, German Federal Republic.

Direct and indirect economics of wind energy systems relative to fuel based systems.
B. Sørensen, University of Copenhagen, Denmark.

AUGMENTORS

Vortex augmentors for wind energy conversion.
P.M. Sforza, Polytechnic Institute of New York, USA.

WVU wind energy concentrators.
J.L. Loth, West Virginia University, USA.

Windmills with diffuser effect induced by small tipvanes.
Th. van Holten, Delft University of Technology, The Netherlands.

Tornado-type wind energy systems: Basic consideration.
J.T. Yen, Grumman Aerospace Corporation, USA.

STORAGE

Balancing power supply from wind energy converting systems.
J.P. Molly, Deutsche Forschungs-und Versuchsanstalt fur Luft-und Raumfahrt e.v. (DFVLR), German Federal Republic.

A self-contained 5,000 kw capacity wind energy conversion system with storage.
G.I. Fekete, McGill University, Canada.

Windpower installations for water pumping in developing countries.
M.E. Parkes, University of Newcastle-upon Tyne, UK, and F.J.M. van de Laak, Shiryanga Regional Water Development Authority, Tanzania.

The regulation, storage and conversion of wind produced electrical energy at the level of a few hundred watts.
P. Hirst, Marinair (Radar) Ltd., UK, and D.H. Rees, Saffron Electronics, UK.