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SITES FOR WIND-POWER INSTALLATIONS

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INTRODUCTION

The objective of this research is to increase technical capacity to locate favorable wind system sites, reduce uncertainty in the prediction or validation of the characteristics of sites, and thus assist in the sizing and performance prediction of wind systems. The research will include evaluation of low speed aerodynamics over terrain and boundary flow conditions over ridges and in valley exits to mountain barriers by means of modeling and analytic techniques.

The Fluid Dynamics and Diffusion Laboratory at Colorado State University has unique experience and the largest set of facilities in the United States for purposes of modeling of the atmospheric surface layer. The staff have completed over ten studies in recent years of flow over hills and mountainous terrain. Details of a number of these studies have been compared with field measurements with good agreement. Neutral, stable, and unstable stratification conditions were examined; velocities, turbulence, and wind directions were measured.

Past experience with large power mills indicates that perhaps the single most important factor controlling success or failure of these systems is site selection! Incorrect placement of a site by only a few miles may drop performance to 1/5 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 operate optimally at a lower wind speed, mechanical, aerodynamic and generating efficiencies may permit only a linear improvement at higher average annual velocities (20).

Recognition of site selection importance has prompted a series of monographs on this subject. Unfortunately there is only a limited amount of suitable field information from which the authors could draw conclusions. Indeed, because of the very variability of the atmosphere and the presence of many factors which exist simultaneously it is difficult to isolate the independent influence of topography profile, surface roughness or stability. In the 1940's and early 1950's laboratory studies in aeronautical wind tunnels were also completed; unfortunately the investigators found to their dismay little resemblance between the field and wind tunnel results. Successful modeling of atmospheric phenomena in a wind tunnel has only been accomplished in the last fifteen years.

The thin surface layers developed in the short aeronautical tunnels failed to reproduce even the gross character of wind profile, stratification, turbulence intensity and spectra required. In addition, early attempts to produce thicker shear layers with grids produced flows which were not spatially stationary. The Meteorological Wind Tunnel at Colorado State University is capable of simulating these effects together and can produce a working shear layer of several feet in depth.

Certain advantages of benefits of laboratory simulation may be realized when similarity conditions are partially or actually satisfied between field and model. These are:

(1) The problem may be studied in the three space dimensions.

(2) A certain latitude is available for controlling the essential variables in the problem.

(3) The inherent possibility for defining and locating particular problems which might exist on proposed weather sensitive field projects.

(4) Determination of the location of sites for meteorological instruments and towers, wind power generators, etc., in the actual field for the purpose of obtaining representative observations pertinent to a particular project.

(5) Obtaining relevant data that may be used in guiding field programs toward their proposed goals.

(6) The reduction in time and expense of extensive field programs or studies.

REVIEW OF PRESENT UNDERSTANDING OF WIND-POWER SITE SELECTION

In what appears to be the most recent statement concerning the art of wind power site selection the World Meteorological Committee led by Ben Davidson (1964) remark that

> "...the question of the variation of wind and of exchange coefficient with height above the surface layer is not at this stage in a very satisfactory state.... Still less satisfactory is the theory of wind flow in the neighborhood of obstacles. Here the conclusions of potential flow theory may be drastically modified by buoyancy forces, irregularities in slope of the obstacles and the small-scale roughness aspects of both the up and downwind slopes."

Since it is desirable to be able to analyze potential site locations quickly it is unfortunate that the quantitative effect of these important variables is not known. Nevertheless, there do exist a few field measurement programs over terrain features carried out to estimate wind power potential (10,20,7,2,13). These results are to a large degree site specific and do not cover a wide enough range of terrain types to allow more than a very limited and qualitative generalization to other situations. The combination of hill features, roughnesses, upstream topographies and stabilities studied to date even appear to lead to a set of contradictory conclusions (6).

One can nevertheless divide the influence of the atmospheric motion on wind power into four areas.

(1) Variation of wind speed over uniform terrain,

(2) Local wind circulations,

(3) Flow over slight or moderate relief and

(4) Flow over high mountains.

Each of these areas has received attention from past investigators. Indeed a wealth of information exists on category (1), the understanding of which has recently been summarized in an AMS monograph (12). However if there is an abrupt change in roughness and heating for even flat terrain major changes can occur as considered under category (2), local wind circulations.

Local wind circulations may be driven by inhomogeneities in roughness, temperature, or pressure. A good deal has been learned recently in the laboratory about these situations. If a wind power site is placed near a sea shore for example, the influence of the sea breeze may be significant. Similar effects may exist near an urban heat island. Saddle points, passes, or gaps offer possibilities for enhanced winds especially if they are open to a prevailing wind direction. Such local effects can greatly enhance energy potential yet they do not usually show up in national wind survey results.

Flow over slight or moderate relief may result in enhanced wind speeds due to wind "overshoot" or "speed up." Frenkiel (1962) and Golding (1952 and 1956) published results over four hill summits. Davidson concludes that is "almost impossible <u>a priori</u> to estimate the numerical value of the speed up factor if indeed such a factor exists for any particular locality." It would indeed be unfortunate if the wind-energy program abandons this area with so little actual information--the energy advantages to prediction to within even 25 percent are immense. A number of laboratory investigations of this type are already available, although the data has not been analyzed in terms of siting wind-power systems. Plate and Lin (1965) and Plate and Sheih (1965) report measurements of neutral shear flow over triangular and sinusoidal ridges. Plate et al. (1969) measure turbulence downwind of a sinusoidal ridge. Beebe and Cermak (1971) have measured flow fields over a wavy boundary where the ridges have various amplitudes and wave lengths. Current research at CSU is examining stratified shear flow over hemispherically shaped hills. Stratification has a strong effect on flow over and around hills. The intensity of an inversion may influence both wind velocity and direction (20,7). If inversions are frequent, a site on the hillside rather than on the hilltop may lead to larger annual average velocities.

Wind flow over high mountain ridges yields potential wind power sites. It is true that such sites often produce very high winds of large gustiness--yet future designs for power mills may permit use of this extremely energetic wind. Stratified flow over mountain ridges may lead to lee waves or helm winds (23). Scorer (1952) has studied high winds in mountain gaps. Mountain ranges can lead to regions of underspeed as well as overspeed; thus the exact site is critical. Mountain range effects cannot be studied, however, without adequate simulation of stratification (or "compressibility" as described by Putnam). Golding (1955) recognized the importance of model tests. He mentions his own attempts to model flow fields by means of an electrolytic tank. He acknowledges the limitations of such efforts but realizes that more information is needed and the model studies could "at least indicate the relative merits of widely different shapes of hills and hill groups." As noted by Smith (1974) with respect to flow over building complexes:

> "It should also be remembered that this particular problem does not need to be solved and re-solved at every site in the country. It is true that an idealized series of tests could not be expected to represent very complicated structures and terrain, but in many localities models developed to fit simple shapes would be a satisfactory guide."

Other studies in wind tunnels have been completed for various terrains and urban topography (1,4,11,14,8,23,16,15). A great deal has been learned concerning modeling terrain influences since the early wind power siting effort. Despite the variety of specific studies no effort has been made to systematically understand the separate and/or combined influence of terrain aspect ratio, insolation, roughness, and stratification.

PROPOSED RESEARCH

The previous remarks summarize briefly the current status of understanding for siting of wind-power installations. The need for a well organized experimental and analytic study is apparent. A systematic research program, primarily experimental in nature, is under way which will provide, over a three year period, a unified body of knowledge on windmill siting aerodynamics. The acquisition of the knowledge is planned to minimize the experimental work yet permit reaching all objectives. The research will produce information of immediate use in wind-power site selection, architectural planning, wind loading on buildings, and environmental control.

Objectives of this research are specifically:

(1) To determine local flow phenomena over topography--boundary layer displacement, separation, reattachment--as affected by hill or ridge profile, upwind surface roughness, insolation, and stratification.

(2) To develop knowledge of integral wind effects on topography which will lead to criteria in terms of upwind topography type and placement for the prediction of effect on speedup and gustiness.

(3) To establish how the local flow environment such as gustiness and mean wind speeds are affected through the combined action of the individual effects listed above.

(4) To relate the new knowledge gained through laboratory measurements and through analysis to real meteorological events and to provide a "handbook" of site selection methods for wind-power purposes.

A wide range of natural wind characteristics can be simulated by means of the unique meteorological and environmental wind tunnels of the Fluid Dynamics and Diffusion Laboratory which are being used for the proposed research. Characteristics of major concern are magnitudes and spatial distribution of mean velocity, turbulence scales and turbulence spectra of winds approaching the wind power site. Verification that natural wind characteristics are simulated to a high degree of approximation by the long-test-section type wind tunnel has been reported by Cermak et al. (1966).

The detailed structure of boundary layers formed in the long-test-section are varied by changing roughness characteristics of the lower boundary (floor), introduction of vorticity and turbulence at the test section by means of vortex generators and grids, introduction of large scale lateral motions by moving deflector vanes and introduction of hill-like surface irregularities. For all of the major topographics studied in long-test-section wind tunnels, the wind characteristics inherent in flow over a plane rough boundary with roughness-element size scaled according to the geometric scale have been used.

Topographical features for which the wind effects will be studied in detail include a wide range of potential configurations. Two basic profile shapes, triangular and sinusoidal, will be used for the ridge section and isolated hill. The influence of gaps and notches or converging valley systems will be studied separately. Variations in geometry for this study are summarized in the following list.

(1) Single hill and ridge cross sections

    (a) triangles--slopes 1:2, 1:3, 1:5, 1:6

    (b) sinusoidal--(similar average values)

(2) Same hills with roughness added

(3) Same hills with insolation (heated sides)

(4) Ridge sections with canyons or notches--depth ~1/4, 1/3, 1/2 height

(5) Converging valley ridges--four angles

(6) Pairs of conical hills-separation distance to height ratio: 1, 2, 5, 10

(7) Field validation model (to be selected: (perhaps from Golding, Putnam, or Frenkiel sites)

Other geometries may be included as the research indicates the occurrence of significant flow behavior at intermediate values of the geometrical parameters.

This investigation on wind effects is composed of a large number of combinations of the variables describing wind characteristics and topography geometry. A consolidated tabulation of the primary experimental configurations is presented in an effort to provide a good perspective in Table I.

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TABLE I
CONSOLIDATED TABULATION OF PRIMARY EXPERIMENTAL CONFIGURATIONS

WIND CHARACTERISTICS*					TOPOGRAPHY					
h	h/H	h/L	Temperature**	Turbulence	H/L	Shape		Surface		H/a
						Dimensions	Profile	Heated	Roughness	
Smooth	--	--	Neutral & Stable	Natural Boundary Layer	1/2, 1/3 1/5, 1/6	Hill Ridges Notches Valleys	Triangular & Sinusoidal	Cold & Hot	Smooth & Rough	1/12-1/24
0.1"	1/60	1/120-1/360	"	"	"	"	"	"	"	"
0.5"	1/12	1/24-1/72	Neutral	"	"	Hill Ridges	"	Cold	Rough	"
1.0"	1/6	1.12-1/36	"	"	"	"	"	"	"	"
2.0"	1/3	1/6-1/18	"	"	"	"	"	"	"	"

Symbols: h = height of roughness element; H = height of topography; L = lateral dimension of topography;

a = minimum dimension of cross section.

* Wind speed can vary from 2-100 ft/sec, and topography can be rotated to give continuous variation of direction

** Two stable stratifications

Assume H = 6", a = 6' or 12' for this table.