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WIND TURBINE SITING: A SUMMARY OF THE STATE OF THE ART

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ABSTRACT

The process of siting large wind turbines may be divided into two broad steps: site selection, and site evaluation. Site selection is the process of locating windy sites where wind energy development shows promise of economic viability. Site evaluation is the process of determining in detail for a given site the economic potential of the site. This paper emphasizes the state of the art in the first aspect of siting, site selection. Several techniques for assessing the wind resource have been explored or developed in the Federal Wind Energy Program. Local topography and meteorology will determine which of the techniques should be used in locating potential sites. None of the techniques can do the job alone, none are foolproof, and all require considerable knowledge and experience to apply correctly. Therefore, efficient siting requires a strategy which is founded on broad-based application of several techniques without relying solely on one narrow field of expertise.

TECHNIQUES FOR RESOURCE EVALUATION

The main meteorological problem in siting is the variability of the wind resource. The variation in magnitude of the wind from one place to another makes site selection difficult. The variation of wind with time at a particular location complicates site evaluation. Wind characteristics such as average wind speed, turbulence intensity, and seasonal and diurnal variations can be significantly different over seemingly short distances. This means that there is only limited value in direct application of existing wind data collected at historical stations--stations that were probably established without wind energy applications in mind, such as airports or thermal power plants.

Since the wind resource variability is so great and the cost of onsite measurements can be large, there is great interest in techniques for

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estimating the wind energy potential of an area or site without having to initiate wind measurements everywhere. Numerous techniques for doing this exist or have been proposed. These techniques can be applied over large land areas to identify smaller high wind potential areas or they can be used to estimate wind behavior at a particular site. Among these techniques are:

- analysis of existing and supplementary wind data
- topographic indicators
- biological indicators
- geographical indicators
- social/cultural indicators
- numerical modeling
- physical modeling.

A brief description of these is given below. Further detail and references to original sources are found in [1]. Following these descriptions, example guidelines on their application in a siting program are given.

Existing and Supplementary Wind Data Analysis

Since the atmosphere obeys physical laws governing conservation of mass, momentum and energy, some knowledge of the state of the atmosphere at one or more points presumably should allow statements to be made about the state of the atmosphere at other points. The topographical indicator techniques and numerical and physical modeling techniques may be applied to make these statements. Basic input to each technique is some kind of analysis or summary of patterns of the meteorology at selected points throughout the territory being analyzed.

The elements to be characterized as a pattern depend upon the subsequent use of and references to these patterns. A reference to "prevailing northwest winds at the site" may be as close as one gets to recognizing a pattern at a very flat site. More formal recognition of patterns may be required if numerical models will be used. Whether or not air temperature is an element to be considered in the pattern recognition process is also dictated by the choice of analysis methods. For one type of numerical model discussed later, the fact that the valley winds can be cold does not matter. However, this might be a highly significant point to other kinds of models or to the meteorologist using topographical indicators.

When data from a single station are being analyzed, the common products used to characterize the wind behavior are frequency distributions of different wind behaviors of interest and averages. Innumerable displays of statistics could be used to characterize a measurement location. Table 1 provides some indication of the utility of several different single or joint frequency distributions.

TABLE 1. TYPICAL FREQUENCY DISTRIBUTION PRODUCTS AND THEIR POTENTIAL APPLICATIONS

Dimensions of Frequency Distribution	Usefulness of Characterization of Wind Behavior or Analysis of Wind Potential
Wind Speed	Estimating energy production.
Wind Direction	Assessing local or regional effects of topography
Wind Speed - Wind Direction	Determining principal directions of wind power. Necessary for cluster design.
Wind Speed - Time of Day	Determining diurnal load match. Caution is required, however, for vertical extrapolation of diurnal behavior.
Wind Speed - Month of Year	Determine seasonal load match.
Wind Direction - Time of Day - Month of Year	Assessing local or regional thermally driven wind systems, such as sea breeze or mountain-valley winds.
Duration of Wind Speed Persistence in Specified Speed Interval - Month of Year	Assessing probability of continuously available wind power. Determining partitioning of available wind energy between large-scale migrating storms and regional or local thermally driven wind systems. Determining optimum times for scheduled wind turbine maintenance.

More involved approaches are required to recognize wind behavior patterns using several meteorological stations instead of just one. The approaches range from highly subjective to completely automated objective derivation of categories of meteorological behavior.

One approach to use when analyzing data for a region is to establish a synoptic climatology. A synoptic climatology regards patterns of weather (winds, clouds, precipitation, etc.) as functions of the static surface pressure distribution [2]. Basic pressure pattern types are recognized using subjective or objective analysis of a long history of weather maps (which are contour plots of the atmospheric pressure field). Then, at every time in the record and for every location, a pattern type can be assigned. Following that, wind behavior at measurement sites is statistically analyzed as a function of pattern type, or wind behavior as a function of pattern type is estimated between stations by application of numerical models or topographical indicators for each type. With the statistics on the frequency of occurrence of each type determined from the assignment procedure, weighted average wind behaviors can be established at points of interest. Examples of this approach to preliminary resource assessments using subjectively derived pressure patterns or types are described in [3,4].

One objective procedure for pattern recognition is known as principal components analysis (PCA), also sometimes referred to as eigenvector or empirical orthogonal function analysis. PCA applications to wind energy problems have concentrated on patterns among wind vectors measured throughout a region prior to application of numerical models [5,6,1]. Consider wind speed and direction measurements made hourly at 10 locations for a year. The PCA technique (following the procedures of [5] would mathematically determine 10 patterns, or eigenvectors. All 8760 hourly patterns could be described as variously weighted combinations of the 10 eigenvectors. A strength of the PCA analysis is that all 8760 hourly patterns could be approximately described using weighted combinations of just a few of the eigenvectors, with the remainder of the eigenvectors needed only to describe some small residual variance in the data set unexplained by the primary eigenvectors. It is frequently possible to assign some physical meaning to these primary eigenvector wind patterns, although this is not necessarily true since the eigenvectors are artifacts of an abstract mathematical procedure.

Once the eigenvectors and their weighting factors (known as the principal components) are determined, they may be used to generate approximate statistics of wind behavior at sites throughout the area. Days for which the behavior of the eigenvector weighting factors are similar can be identified. From each group of similar days, a typical day can be selected. Numerical models [5] or other techniques are then used to interpolate winds between measurement locations. Then, knowing roughly the frequency of occurrence of these typical days identified by PCA, one could generate statistics of wind behavior at any desired location. Alternatively, Endlich et al. [6] exploit the properties of a linear numerical model. That is, if the input data may be represented by 70% of eigenvector A, 25% of eigenvector B (and some residual variance), the solution can be represented by 70% of the solution for eigenvector A plus 25% of the solution for B. Since only a few eigenvectors can describe most of the input data set, the numerical model need be run only a few times. Weighted combinations of these solutions yield statistics (for as long a period as the data set) at any point in the region (Figure 1).

After analyzing wind patterns and applying other techniques to pick out likely high wind resource sites, one may wish to instrument those sites. Then there arises the problem of interpreting the climatological significance of the relatively short-term data. A basic first question to ask of a year's data at a candidate site is how representative of a long-term (e.g., 30 yr) mean is the measured annual mean, since annual energy production from a wind turbine will be roughly proportional to the annual mean wind speed. This question has been studied extensively [7,8,9] with roughly the same result based on analysis of numerous National Weather Service sites and across the United States and in Hawaii and Alaska. As a national average, there are regional variations [7] the climatic mean wind speed will be within $\pm 10\%$ of a single annual mean wind speed observation 90% of the time.

Attempts to adjust the climatic wind speed estimate using a season or year of site measurements and a comparison with nearby climatic data

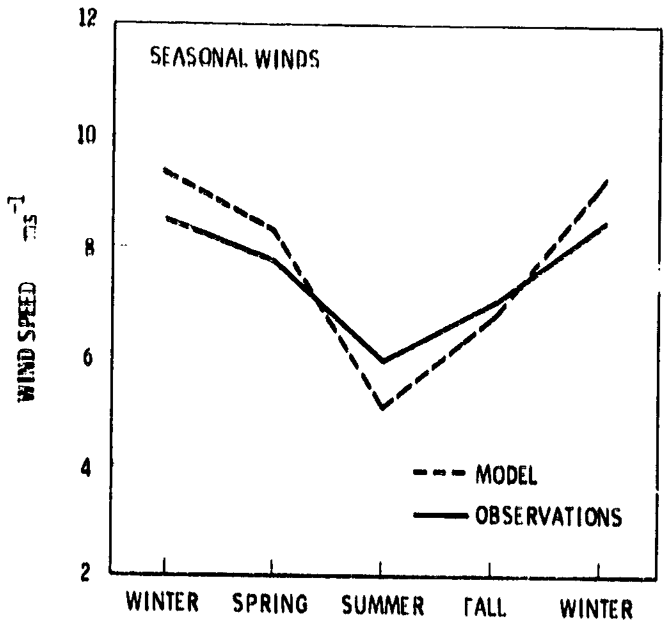

FIGURE 1. COMPARISON OF OBSERVED AND PREDICTED SEASONAL MEA[illegible] [illegible] SPEEDS FOR MT. TOM, MASSACHUSETTS. PREDICTIO[illegible] [illegible]ASED ON AN EIGENVECTOR ANALYSIS PROCEDUR[illegible] [illegible]ED [illegible] A MASS CONSISTENT MODEL [6].

have been made [1,7,8,10]. The simplest approach is to determine the ratio of the mean wind speeds simultaneously measured at the site and the climatic station and multiply the ratio by the climatic wind speed measured at the climatic station. This essentially assumes that monthly or seasonal mean wind speeds are perfectly and linearly correlated (a correlation coefficient of $r = 1.0$)[(a)] at all locations with an area. Typical correlation of monthly mean speeds between sites within 100 km of each other in fairly simple terrain is $r \approx 0.4-0.5$; for annual means $r \approx 0.3-0.5$ [7]. Corotis [8] suggests an adjustment that incorporates the correlation explicitly. However, ample evidence exists to show that adjustment of annual or monthly mean wind speeds does not yield significant and reliable improvement in estimates of the climatic means [1,7,8]. Furthermore the correlation of annual and monthly means between sites is a very sensitive quantity, because the interannual standard deviations are small [1,8].

Topographical Indicators

Historically, wind machines have been sited by applying topographical indicators, which are empirical guidelines describing the general

(a) The square of the correlation coefficient, r^2, is a measure of the fraction of the variance about the mean value that is attributable to the relationship of two quantitites. Thus, if the correlation between monthly means at two sites is $r = 0.5$, only 25% of the variance about the climatic mean at each site may be attributed to a correlation between monthly means at the two sites.

effects of terrain or surface obstacles on the wind. Recently, topographical indicators were used extensively in the DOE regional resource assessments. Topographical guidelines are based on a physical understanding of how topography affects flow and on experience gained through observation. An understanding of these guidelines is also invaluable in interpreting the results of numerical and physical modeling studies and measurements.

A number of topographical features are recognized as indicators of high wind energy potential. One group includes gaps, passes, and gorges in areas of frequent strong pressure gradients. These strong pressure gradients occur when large temperature gradients form across a mountain barrier. For example, coastal mountains separate a nearly uniform temperature marine air mass from continental air masses. The inland air can become hot in summer or daytime, or cold in winter or at night, thereby causing seasonal and diurnal fluctuations in the pressure gradient across passes. Pressure gradients also form across mountain ranges when strong winds, as from a storm, blow up against the mountain barrier. If the flow has insufficient kinetic energy to cross the potential energy barrier that the mountains represent, the gaps, passes, and gorges are the relief points for the winds driven by the storm.

Long valleys extending parallel to prevailing wind directions are often good wind energy regions also. The wind stream is channelled by the valley walls. At narrow points along a broad valley, mass conservation causes winds to accelerate through the constriction. In the opposite way the river of air spreads out and slows down where the valley widens.

Summits of ridges and mountains usually provide enhanced wind resource areas. Over small-scale hills and ridges (less than 300 m high), the air accelerates over the crest. This is also due to mass conservation; a stream of air is vertically compressed as it flows over the hill and so must move faster in the constricted region. This is not necessarily so for the flow over large-scale mountains. The winds at summit elevation of a high mountain may actually slow down near the summit because of the drag that the mountain exerts on the flow. However, mountains and ridges are still usually good resource areas because they are like tall towers that intercept the flow at higher levels where winds are usually stronger.

Some features that indicate low wind energy potential are basins and valleys that are perpendicular to the prevailing wind. These features can be low wind areas because the flow spreads out over them, opposite to the effect of flow acceleration over ridges, or because they collect cold, heavy air that stagnates at potential energy minima.

Proper use of topographical indicators requires an experienced boundary layer meteorologist because the issue of when and how to use them, and how far to trust them, are complex. Consider the complexity of flow over a small isolated hill. Wind speeds at a given height above the terrain surface usually are higher over the summit of a hill than over surrounding lowlands. One experiment reported by Bradley [11], designed to collect a data set for testing of numerical and analytical models of flow over hills, consisted of detailed measurements from a tower atop a 170-m hill and from another tower on the flat plain upwind of the hill. Reasonably good comparisons between model predictions (based on the upwind tower measurements) and the summit measurements were obtained for a very restricted set of atmospheric conditions. The first restriction was that the atmospheric stability was nearly neutral, which means that the vertical temperature structure is such that buoyancy forces on warm or cool parcels of air do not contribute to generation (unstable conditions) or suppression (stable conditions) of turbulence, and hence do not contribute to mixing of mean wind speeds from different levels. The second restriction was that the height of the planetary boundary layer (PBL) was at least 500 m above the plain. The top of the PBL is often made visible by the temperature inversion that forms a "lid" that traps smog beneath it. Oftentimes the wind speed increases as air flows through the constriction formed by the temperature inversion and the hill, but due to the complicated response of the atmosphere this may not always be so. Bradley states, "Several occurrences of the distortion of [wind] profiles by the low-level inversion have been observed but were not consistent, sometimes resulting in strongly accelerated flow at the upper levels on the tower, and at other times strong retardation."

The example illustrates that even in the most simple of cases, topographical indicators provide only qualitative information. Generic flow guidelines have been developed from theory, from numerical and physical simulations of flow over model terrain, and from actual measurements of flow around full-scale features. Succinct generalizations drawn from these studies are useful; however, reliance upon them must be tempered. Topographical indicators should therefore be used as guidelines to:

- understand flow-terrain interactions
- indicate where to look for, or when to use, other indicators
- indicate where to make measurements
- interpret measurements already made.

Biological Indicators

The study of tree deformation indicates that trees are a useful tool for determining prevailing wind direction, identifying areas where severe wind and/or ice loads may occur, and for estimating mean annual wind speed. Estimates of mean annual wind speed based on wind-deformed trees, although subject to some uncertainty, are simple, quick, inexpensive and usable for identifying locations where more detailed wind measurements are justified, and as a guide for preliminary ranking of sites in terms of wind power potential.

The degree of permanent tree deformation has been calibrated against the annual mean wind speed for numerous genera of trees [12]. This was accomplished by measurement of the annual mean wind speed near several trees of each genus and determining a linear relationship between the value of various indices of tree deformation and the measured mean wind speed. Several indices of tree deformation were explored. The Griggs-

Putnam index for conifers and the Barsch index for deciduous trees subjectively categorize the degree of deformation into eight classes. The deformation ratio measures various angles of tree crown asymmetry and trunk deflection. The compression ratio measures asymmetry in the tree ring growth in the trunk.

The Griggs-Putnam Index or the Barsch Index, in general, provide the best estimates of mean annual wind speed. The mean wind speeds and the 95% confidence limits as a function index value were determined for many genera of trees [12] and also reported in [1]. However, it is best to interpret tree deformation in a local region as a relative indicator of wind speed. The data used in [12] represent trees and wind measurements that span much of the U.S., but calibrations can vary locally [13]. In addition [13] found that deformation of California Oaks could not adequately discriminate between the intermediate wind speed indices, and suggested this may be due to the effects of local winter ice loading on the trees.

In mountainous areas, winds are complex and the sparse wind data available provide little information on wind direction. By observing flagged trees, the branches of which grow away from the prevailing wind direction, the direction of flagging can be determined and marked on a topographic map. In this way, the mean flow pattern in a local area can be noted.

Trees can also be used as indicators of destructive forces of severe wind and icing, which may present problems for wind turbines, their support structures, and the power transmission lines from the turbines [4,12]. Broken branches, wind throw (leaning trees) and blow-down are all evidence of severe winds. Trees with broken branches or tops and a lack of bark on the upwind side can indicate severe winds or wind-driven ice.

Geomorphological Indicators

When winds interact with and alter the earth's surface, the geomorphological features that result are called eolian landforms. Especially in arid regions where vegetation is sparse, winds can erode the surface, transport sand and dust, and deposit sediment. The erosional and depositional eolian landforms and the characteristics of the transported sediments are indicators of the history of the winds that caused these landforms.

Geomorphological interpretative techniques can be applied for three purposes:

- to indicate that a relatively good wind resource exists where eolian landforms are present
- to determine crude estimates of mean wind speeds from observed sand dune migration rates, sand size particle distributions, and sand ripple formation [1,14]
- to indicate prevailing wind directions.

The principal difficulty with estimating wind speeds using these techniques is that substantial prior knowledge of the wind climatology is required. For example, how much of the total dune migration is cancelled by winds of opposite directions, or how frequently are winds strong enough to cause the sands of a certain size to move? If these answers are in hand prior to eolian feature analysis, why carry out the analysis?

Information gained from the use of geomorphological indicators is sometimes helpful in forming an integrated picture of the wind regime in a data-sparse area. However, the effort expended should be compared with the great uncertainty of the technique. Aerial photographs may be obtained during the early stages of the siting process for purposes other than for examining eolian landforms. If eolian indicators are found in the photographs, interpret the photographs as quickly as possible and use geomorphological indicator techniques only as part of site visits that include other activities, e.g., setting out anemometers or inspecting terrain feasibility. In this way, information can be added to the data base of the site without undue delay and expense.

Social and Cultural Indicators

Human cultural and behavioral responses to the climatic wind resource provide indications of the wind resource characteristics, just as geomorphology and ecology are partially determined by the wind. A sharp observer exploring a candidate resource area should actively look for and evaluate clues provided by social and cultural indicators of wind. Some examples are:

- location of grazing land versus crop land
- evidence of past use of wind power
- roadway signs
- evidence of past use of wind power
- roadway signs
- wind damage to power lines, buildings, billboards, etc.
- location of snow fences.

Long-time residents of an area, especially those that work outdoors and cover a large territory (such as utility linemen), can sometimes provide useful information. However, people tend to overestimate average wind speeds because they remember specific discrete wind events rather than average conditions. Even so, a person may be able to say with considerable confidence that region X has more wind than region Y. If region Y is near an existing anemometer, then some useful information may be available to incorporate into the evaluation.

Numerical Modeling

A numerical model consists of a set of equations that are assumed to adequately represent the process being studied and a procedure for solving these equations. Unfortunately there is no general solution to the equations that describe these processes. A common approach is to enlist the assistance of computers to numerically achieve a solution to the fundamental equations, also known as primitive equations. Even numerically derived solutions of the primitive equations are extremely difficult and costly to obtain, so other approaches seek to simplify the problem by starting with a set of simpler equations, e.g., a set that only considers conservation of mass.

The advantage of numerical modeling as a tool for siting is that numerical models provide an objective method for estimating the effects of terrain on airflow and for interpolating wind data from locations where there are observations to locations where there are none. The primary disadvantage associated with the use of numerical models is the uncertainty in their accuracy, which is due to lack of verification. There have not been enough experiments in which model simulations have been compared with good field measurements. This will remain the case for a long time, since there are not very many good data sets for experiments of this type. The expense of gathering good verification data is large. The only alternative is good judgment. The person analyzing model results should accept or reject them on the basis of how well he feels the model simulates the important physical processes controlling the flow.

A primitive equation model available at the University of Virginia was tested with wind turbine siting applications in mind [15]. Figure 2 compares model predictions of wind power density (units of 100 W/m^2) with measurements obtained primarily from a research aircraft that flew a rectangular pattern over the Delmarva Peninsula. The general pattern of the wind power field (inland minimum, coastal gradient, offshore maximum) is reproduced by the model, but the model missed on details of the magnitudes.

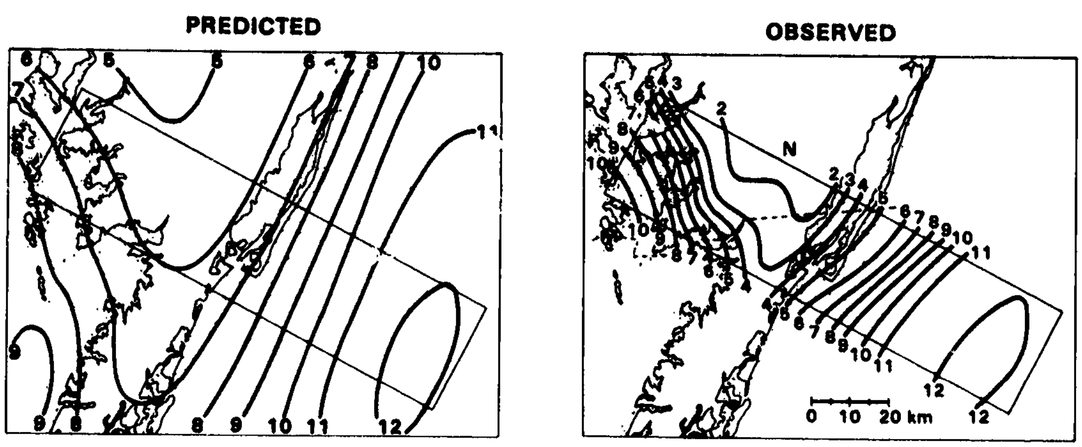

FIGURE 2. AREAL DISTRIBUTION OF PREDICTED AND OBSERVED WIND POWER DENSITY (100 W/m^2) AT 170 m ABOVE THE SURFACE OVER THE DELMARVA PENINSULA. PREDICTIONS MADE BY THE UNIVERSITY OF VIRGINIA MESOSCALE MODEL INITIALIZED FOR 30 JAN 80, 0828 EST.

In an analysis of the skill of the model [15], it was argued that prediction errors must be partitioned into those due to inadequacies of the model and inadequacies of the initial data used to start and carry out a simulation. It was argued that the skill of choosing initial data was lower than the skill of the model. In the same study, the model predictions showed no skill at all in the South Texas Coast area. That was attributed to the diurnal variations of the large-scale pressure field caused by the gently sloping topography in the south central United States. Those variations were not incorporated into the initial and boundary conditions. That study concludes: "We conclude that for coastlines with little topography, the mesoscale model usefully predicts the magnitude and location of the centers of maximum and minimum wind power. For coastal areas with considerable topography, a more complete initialization of the model is required." In fact, whether or not primitive equation models can operate successfully for wind energy assessments in areas of significant topography is still a matter that is under research scrutiny.

A simpler class of models that attempts to satisfy many of the physical laws of a complex primitive equation model but at a small fraction of the cost is conceivable. Most of these would be generally referred to as two-dimensional models. One type of two-dimensional model simulates air flow in a vertical plane by specifying that terms in the equations dealing with variations perpendicular to the simulated plane are non-existent. For example, flow from the ocean over a coastal ridge might be simulated with such a model. Often times this type of two-dimensional model is developed as a subset of a larger three-dimensional primitive equation model and used for initial tests prior to a full-scale three-dimensional model run. Other two-dimensional models solve equations describing flow in some suitably defined layer near the ground, usually the planetary boundary layer, which may be several hundred meters to a few kilometers thick. Layer-averaged primitive equation models [16,17] require surface and lateral boundary conditions similar to more elaborate models, but a number of questionable assumptions must be made about conditions at the top of the layer. The same is true for layer-averaged models that solve simplified equations derived from the primitive equations [18]. How the upper boundary is modeled will have a significant impact on the resulting near-surface windfield for reasons related to processes discussed previously under topographical indicators. Although these models should be able to mimic certain effects where differences in surface temperature, surface roughness, and elevation are present, there has not been much verification effort. Consequently their reliability and accuracy related to wind energy applications is still poorly known.

The simplest models that have been used for wind energy applications are known as objective analysis or mass-consistent models [1,5,6,19,20]. These models use input data and some initialization scheme to generate a wind vector at each point in a three-dimensional grid. This initial windfield is then adjusted with successive iterations until the windfield satisfies the physical constraint imposed on the solution, namely, the conservation of mass. Mathematically, the minimum adjustment possible is made so the flow is as near the initial guess as mass consistency allows. The quality of the initial guess windfield is obviously critical. Other conditions in the model determine how the adjustments are achieved. The lower boundary condition requires the surface winds to be parallel to the terrain slope. A model parameter controls how much adjustment takes place in the vertical dimension rather than horizontally, thereby controlling how much air blows over a ridge and how much goes around. The height of the top of the modeled region can be varied (tuned) to control the amount of speedup realized over mountain summits [6].

Objective analysis models have received the most attention for verification studies for wind energy applications [1]. The general results are usually quite reasonable. A modeling study of Oahu [21], for example, showed some reduction of wind speed upwind of the steep windward ridge, maximum winds along the ridgetops, and light winds in the lee of the mountains. Of course, those general predictions are just what one would expect from application of topographical indicators.

Table 2 provides a perspective on numerical model accuracy and relates it to accuracy achievable through use of topographical indicators. The table shows, for example, an Oahu simulation using a high data density input [21]; that of the four windiest sites predicted with the model, only one was actually observed to be in the four windiest sites. However, five of the top seven (and nine of the top ten) sites predicted were actually observed in the top seven (and top ten) most windy sites. The table indicates that there is a 20% chance that the result could have been obtained through a random selection of any four of the sites. However, there is just a very small chance that random selection of seven of the 20 sites would result in at least five of the observed top seven sites being selected. These results suggest that the model should be used as an indicator of high wind resource *areas* from which several sites may be selected for further consideration or instrumentation, but that the model should not be relied on to pinpoint the absolute best *site*.

The results in Table 2 from modeling the Nevada Test Site [22] differ somewhat from the Oahu results. Three of the top four sites were selected by the model but only five of the top ten. This occurred because the best sites were on well-exposed high ground, easily discriminated by the model, whereas the remainder of the sites did not span a very large range of mean wind speeds.

Table 2 also shows results from a ranking of the 20 Oahu and the 20 Nevada sites where a meteorologist experienced in the use of topographical indicators and unfamiliar with the model verification studies, determined a rank. Evidently, a qualified meteorologist can compete fairly well with the mass consistent models.

A model's accuracy should also be judged in terms of the use of its output. A first investigator might claim the seasonal trends shown in Figure 1 are well captured by the model. A second might say that the error of nearly 1 m/s in the mean in every season but Fall represents a significant error in the prediction of site energy production. And a third might counter the second by questioning the accuracy with which energy production estimates can be made and by pointing out that the

TABLE 2. NUMBER OF SITES OBSERVED IN TOP X SITES THAT WERE PREDICTED TO BE IN TOP X SITES

The value in parentheses is the chance that the tabulated result could be achieved by random selection

Case and Prediction Method	Top X Sites of 20		
	X=4	X=7	X=10
Oahu, NOABL[(a)], 6 stations plus rawinsonde input [21]	1 (20%)	5 (<1%)	9 (<1%)
Oahu, NOABL, rawinsonde input [21]	1 (20%)	5 (<1%)	8 (<1%)
Nevada, NOABL, 6 stations plus rawinsonde input [22]	3 (<1%)	4 (1%)	5 (2%)
Oahu, topographical indicators[(b)]	3 (<1%)	6 (<1%)	8 (<1%)
Nevada, topographical indicators[(b)]	2 (3%)	3 (3%)	6 (1%)

(a) NOABL is the name of a mass consistent objective analysis model [20]
(b) The rank was determined independently using topographical indicators by a recognized expert.

importance of the errors may vary seasonally as the fuel mix of the utility varies seasonally.

Physical Modeling

Physical modeling involves placing a scaled model of an object into a wind tunnel, water tunnel (also known as a flume), or a towing tank in order to determine how the object interacts with a fluid flowing over it. If the modeling study is constrained to consider only those problems that can be properly posed in a flow facility, physical modeling can yield results more accurate than numerical models. Physical modeling of atmospheric flows does require large, specialized facilities, however.

The theoretical foundation of physical modeling is the principle of similarity. The principal states that if certain constraints are met, flow over a dimensionally similar model will be identical to flow over the full-size object--as long as boundary conditions are also the same. The constraints can be found by analyzing the equations that describe fluid flow.

The equations describing air flow in a wind tunnel are identical to the equations describing flow over full-scale terrain (and the same as the primitive equations discussed under numerical modeling). What differs between wind tunnel and full-scale flows is the relative importance of various terms in the equations of motion. The importance of various terms in the equations of motion is related to the relative values among a group of dimensionless numbers. The Reynolds number, Re, describes the ratio of accelerations in the flow to viscous forces (actually, force per unit mass, hence units of acceleration). At high Reynolds numbers typical of atmospheric flows, the value of Re characterizes certain properties of the turbulence structure of the flow. The Rossby number, Ro, relates the accelerations in the flow to the effects (Coriolis force) due to the earth's rotation. The Rossby number is small, meaning rotation is an important aspect of the flow, if large (1000 km) sections of terrain are being studied. The ratio of accelerations to buoyancy forces is expressed in the Froude number, Fr. Atmospheric stability, which depends on the vertical variation of wind and temperature, is reflected in the Froude number. Atmospheric stability controls detailed characteristics of the turbulence structure, which in turn feeds back to affect the wind structure, so the Froude number is an important descriptor of the flow.

Analysis of the equations of motion shows that the key requirements for modeling atmospheric flow for wind energy purposes are a region smaller than a few tens of kilometers, a large Reynolds number, a Froude number identical to the actual flow, and identical initial and boundary conditions [1]. Strict similarity is impossible to achieve for all flows. For example, maintaining Reynolds number similarity within full-scale and laboratory flows may make it impossible to maintain Froude number similarity. How satisfactorily a physical model satisfies these requirements is largely a function of stability. The similarity constraints are met most easily for slightly to moderately unstable flows when local terrain relief is small compared to the depth of the boundary layer. Under these conditions, flow in the boundary layer should be fairly homogeneous and the wind profiles simple with little turning of the wind vector with height. This situation results in fairly simple boundary conditions and the atmospheric flow can probably be represented by a neutral stability boundary layer in a wind or water tunnel.

APPLICATION OF THE SITING TECHNIQUES

The siting techniques discussed above are applied differently, or not at all, at various points in the siting process depending on the particular problem at hand. Currently, a siting methodology is under development[a] that encompasses all siting issues, not just the meteorological aspects of siting. Four stages of siting are identified:

I Identification and Ranking of Candidate Resource Areas
II Selecting Potential Candidate Sites
III Selecting Candidate Sites
IV Selecting Preferred Sites.

(a) Electric Power Research Institute project RP-1520, Developing a Wind Turbine Siting Methodology for the Utility Industry.

The following is a description of how a meteorologist might undertake the second stage, which is most like what one might call wind prospecting. Further guidance for this and other stages may be found in [1] and the forthcoming EPRI report.

Stage II seeks to identify Potential Candidate Sites (PCS) within the identified Candidate Resource Areas (CRA). The usable siting techniques in an approximate order of cost effectiveness are:

- evaluated existing data
- topographical indicators
- biological indicators
- social and cultural indicators
- numerical modeling
- geomorphological indicators.

The meteorologist should begin by determining the meteorological patterns that dominate winds in the CRA. Especially important are the wind directions. Then, topographical maps would be consulted. When the wind patterns are interpreted with the topographical indicators, the meteorologist should be able to identify the best likely wind zones. Looking more closely at the topography within each zone, the meteorologist could even begin to make a tentative list of locations from which the list of Potential Candidate Sites may later emerge.

The most cost-effective thing to do at that time is to have the meteorologist go to the CRA, drive through it and examine it for biological, social/cultural, or geomorphological indicators. Special, though not exclusive, attention should be paid to the sites on the tentative list of locations developed prior to going out in the field. During this drive through the CRA, the meteorologist will clearly be somewhat confined to stay near roads (road qualities and bridge load limits should be considered for possible future construction access) and possibly transmission lines. On this drive through the CRA, the meteorologist may formulate a recommendation on the necessity of performing off-road prospecting trips, aerial surveys, or application of numerical modeling studies.

If the topography is hilly or mountainous and the meteorologist sees no consistent evidence from biological or geomorphological indicators, the use of numerical models should be considered. Physical modeling is not appropriate because of the large terrain areas involved. The mass-consistent models are probably the easiest to apply. However, since mass-consistent models tend to predict just what one would predict through application of topographical indicators, the time and expense of a field program just to obtain data to drive a model must be carefully weighed against the anticipated results. It is probably more prudent to first run the model with available data. The sensitivity of the model predictions to variations or adjustments to the input data should be determined. If little sensitivity is found, one could accept the indications of the high wind areas and go examine those areas for supporting evidence (such as deformed vegetation). If a great deal of sensitivity is found, supporting field measurements should be considered. But the reason for the sensitivity should also be considered.

The model may not be handling the specific simulation well, in which case its predictions will be suspect. Or, the sensitivity may be due to real physical interaction between winds and terrain. In that case, the sensitivity should raise the question of whether or not there might be troublesome high variability of the wind resource in that area.

The primitive equation models theoretically should perform better in the flatter coastal candidate resource areas where surface temperature and roughness variations are significant. Recall, however, from the discussion on numerical modeling above, that a sophisticated primitive equation model failed to demonstrate skill in its predictions on the south Texas coast due to the fact that subtle diurnal changes in the large-scale atmospheric pressure field were not incorporated into the input conditions. That kind of failure to obtain proper input could easily occur in the actual application of models by utility subcontractors. The evidence of failure wouldn't appear until after verifying site measurements were made. Again, the best use of the models is probably in sensitivity testing.

SUMMARY

There are wind resource evaluation problems to solve at all stages of the siting process. The problems stem primarily from the spatial variability of the wind resource, which makes site selection difficult, and from the temporal variability of the resource, which makes the estimation of long-term wind statistics difficult. Numerous techniques for solving these problems have been studied, and are summarized in this paper.

The current capabilities and limitations of each technique are fairly well-known. As a result, some techniques are applicable only to certain problems. Efficient solution of the meteorological siting problems at each stage of the siting process requires a strategy for applying the techniques. The strategy should be governed by applying techniques together or in sequence at each stage. This is done in a way that the first techniques(s) applied produce the most information toward satisfying the objectives of each stage for a given increment of cost. A suggested guideline for one stage is given. The actual strategy used for any specific siting problem will require fine tuning by the boundary layer meteorologist overseeing the wind resource evaluation efforts.

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