Siting Guidelines for Utility Application of Wind Turbines

EPRI

EPRI AP-2795
Project 1520-1
Final Report
January 1983

Keywords:

Wind Turbines
Wind Power
Generation Planning
Power Generation
Site Selection
Site Evaluation

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Richland, Washington

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EPRI-AP--2795

DE83 007428

Siting Guidelines for Utility Application of Wind Turbines

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Research Project 1520-1

Final Report, January 1983

Prepared by

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ABSTRACT

This report describes utility-oriented guidelines for identifying viable sites for wind turbines. The report also discusses topics and procedures that are important in carrying out a wind turbine siting program. These topics include:

- a description of the Department of Energy wind resource atlases
- procedures for predicting wind turbine performance at potential sites
- methods for analyzing wind turbine economics
- procedures for estimating installation and maintenance costs
- methods for analyzing the distribution of wind resources over an area
- instrumentation for documenting wind behavior at potential sites.

The procedure described in the report is applicable to small and large utilities. Although the procedure was developed as a site-selection tool, it can also be used by a utility who wishes to estimate the potential for wind turbine penetration into its future generation mix.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

Electric utility industry activities in wind power have increased significantly in recent years due to encouraging results that have emanated from various federal and privately funded research programs. A considerable amount of utility activity has been directed toward the identification of sites that are suitable for future wind power generation stations. RP1520-1 was aimed at developing guidelines that individual utilities can use as a general approach to systematizing their siting efforts. The guidelines are not intended to be a rigid procedure that is optimal for every case but rather a framework which individual utilities can adapt to fit their own specific circumstances. The guidelines were developed by the contractor, Battelle, Pacific Northwest Laboratories, with the support of three utility subcontractors: Consumers Power Company (Michigan), Long Island Lighting Company (New York), and Molokai Electric Company (Hawaii).

PROJECT OBJECTIVE

The primary objective of RP1520-1 was to develop guidelines for electric utilities to employ in siting wind power generation stations. The guidelines were to be sufficiently flexible that they could be readily adapted to the specific needs of a wide variety of electric utilities.

PROJECT RESULTS

The siting guidelines are organized in four sequential stages:

- Identification and ranking of candidate resource areas (those with good winds)
- Selection of potential candidate sites (sites that appear suitable in terms of wind resource, engineering, and public acceptance)
- Selection of candidate sites (those having the lowest estimated cost of development and best prospects for development)
- Selection of preferred sites by detailed economic analysis

Each stage is subdivided into more detailed steps.

The siting guidelines can be used to site individual wind turbines or clusters of wind turbines. Application of the guidelines is not restricted to any specific wind turbine size range. The guidelines have been structured to aid in screening out unattractive sites by considering fundamental siting issues such as land availability and land accessibility. Extensive use of existing records of weather and climatology also aids in the site selection process. Construction of expensive meteorological towers and initiation of costly wind measurement programs are thus deferred until a small number of preferred sites have been identified. Most of the siting issues for wind power generation stations are identical to the issues traditionally encountered by the utility industry in siting other equipment.

A trial application of the siting guidelines was performed by the utility subcontractors. This trial application produced experience that was used to refine steps in the siting guidelines and to estimate time and resource requirements for conducting a siting program of the type described in the guidelines. This report contains a complete description of the refined siting guidelines. Another report documenting the trial application in the form of examples is in preparation and will subsequently be available from EPRI.

This report also contains a general discussion of information relevant to siting wind power generation stations. Extensive literature citations guide the reader in locating relevant existing information sources. The siting guidelines can be used for a straightforward site selection process, and they can be used to provide an initial estimate of wind power penetration potential for a utility system by determining the number and size of suitable sites to which the utility has access.

Frank R. Goodman, Jr., Project Manager
Advanced Power Systems Division

ACKNOWLEDGMENTS

This report is the product of a collaborative effort between Battelle, Pacific Northwest Laboratories and three utility subcontractors: Consumers Power Company, Long Island Lighting Company, and Molokai Electric Ltd. The principal investigator wishes to acknowledge the substantial assistance of Thomas R. Hiester of Battelle, Robert Gerzetich of Consumers Power, Bruce E. Humenik of Long Island Lighting, and John N. Urauchi of Molokai Electric in developing the guideline siting procedures given in this report. In addition to their help in developing the guidelines, Mr. Hiester contributed Appendices F and G, Mr. Humenik wrote Appendix C, and Mr. Gerzetich provided Appendix D.

The authors of this report wish to thank Dr. Frank R. Goodman of the Electric Power Research Institute for his interest in and support of this project. Dr. Goodman played an active role as program manager. His criticism and advice was greatly appreciated. The authors also wish to acknowledge the important contributions of the utility review panel for RP 1520 to the successful completion of this project. Our meetings with the review panel provided a lively forum for the discussion and refinement of our ideas. The panel's inputs were always positive and always appreciated by us.

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SUMMARY

Guidelines for siting wind turbines were developed. The work was performed by Battelle, Pacific Northwest Laboratories with the assistance of three utility subcontractors: Consumers Power Company, Long Island Lighting Company and Molokai Electric, Ltd. The guidelines are presented in the form of a step-by-step procedure for identifying viable wind turbine sites within a large or a small study area. This guideline procedure represents a framework that can be adapted to meet the specific needs of any utility.

Development of the guidelines followed the philosophy that

- procedures for siting wind turbines should be similar to procedures used for siting conventional power plants
- economic viability should be considered as early in the selection process as practicable
- a wind turbine siting procedure should concentrate on rapid identification of the best potential sites in a study area
- existing information on wind resources should be used to the fullest extent possible
- extensive wind data measurements should be confined to the most promising wind turbine sites.

The guideline procedure is divided into four stages. In the first stage, a study area is screened for Candidate Resource Areas that appear to have sufficiently high wind resources to contain a number of economically viable wind turbine sites. In the second stage, each Candidate Resource Area is screened for Potential Candidate Sites. The Potential Candidate Sites are windy locations where the installation of a number of wind turbine generators appears to be practical from engineering and public acceptance viewpoints. In the third stage, the Potential Candidate Sites are examined through onsite inspection. Rough estimates of site-specific development costs are made, and the likelihood that the site will be economically viable is reexamined. The most viable sites are designated Candidate Sites. In the fourth stage, each Candidate Site is subjected to rigorous economic analysis and ranked according to economic viability. This stage of the siting process requires high-quality estimates of site development costs and accurate estimates of wind turbine energy production.

The latter requirement will call for detailed measurements of wind behavior at each Candidate Site.

In applying the guidelines, the utilities found that the first two stages could be completed in a few months. The time required to complete the third stage depended upon the number and the location of the sites visited. Nevertheless, the third stage can probably be completed in a few weeks. Completion of the fourth stage depends upon the time required to obtain a suitable wind data base at each site. Obtaining this data base could require from one to five years of measurement--depending on the accuracy required by the utility.

In developing and applying these guidelines, the authors found that enough is known about wind turbines and the factors that constrain their siting to design a thoroughly professional and defensible siting procedure. However, information on several siting issues is still incomplete. This lack of information makes the siting of wind turbines a less rigorous procedure than the siting of conventional power plants. The major issues limiting rigorous application of these siting guidelines are the lack of experience on wind turbine installation costs, operation and maintenance costs, service life and performance characteristics--all of which stem from the current precommercial nature of wind turbine technology.

Section 1

INTRODUCTION

DEFINITION OF THE PROBLEM

In most respects, wind turbine siting presents the same problems to a utility as the siting of other facilities. However, the siting of wind turbines differs from the siting of other generation facilities in one fundamental way: it is impossible to determine net energy generation, the temporal characteristics of this generation or even the approximate cost of energy for a given wind turbine until the site is known. Wind behavior at a site governs the performance of a wind turbine; thus, the economic viability of a particular wind turbine installation at a particular site cannot be predicted without accurate knowledge of this behavior. Given this fact, the magnitude and temporal behavior of the wind at a potential site becomes a principal factor in site selection.

Although a suitable wind resource is the indispensable attribute of any wind turbine site, it is not the only factor that must be considered in wind turbine siting. Wind turbines located at a viable site must have the following attributes:

- positive economic value to the owner
- acceptable impact on the local environment
- no adverse impacts on the utility's operations
- compatibility with pertinent land use or regulatory constraints
- design compatibility with local meteorological extremes
- public acceptance.

A successful site-selection procedure must be capable of rapidly identifying land with high wind resources. Then, it must efficiently screen this land for those portions that appear to offer the other attributes of a viable site. The objective is to focus most of the effort and resources on those parcels that show true potential.

The chief obstacle to rapid identification and evaluation of potential wind turbine sites is poor knowledge of the wind resource. Existing wind resource information cannot be used to determine wind behavior at the vast majority of potential wind

turbine sites - at least with the accuracy needed to establish a site's economic viability. The reasons for this conclusion are ones of logistics and fundamental physics. Wind data are rarely collected at places that would prove to be good wind turbine sites nor are they collected at heights above the ground that are relevant to large wind turbines. The physics governing the behavior of the wind are sufficiently complex that wind magnitude, direction and temporal behavior can change drastically in short distances. Consequently, available wind information is frequently unrepresentative of potential sites that could exist in the surrounding area.

The siting problem, therefore, can be summarized as follows: The viability of a potential wind turbine site is governed by a number of factors. These factors control the site's economic potential, its environmental impact and its public acceptability. One of the chief factors controlling a site's economic potential is the magnitude and temporal behavior of the wind resource. Wind behavior near the surface of the earth, however, is very complicated and it can change rapidly in both the horizontal and vertical directions. Techniques for extrapolating existing data to points of interest have limited accuracy; moreover, the existing wind data may not have the desired time resolution. Given the spatial variability of the wind resource and the limited capabilities of existing extrapolation techniques, it is impractical, except in very simple terrain, to design a wind measurement network that could characterize the wind resource at every location over a large area. Consequently, customized wind measurements will be required at most sites before their economic viability can be determined. Wind measurements take time to plan and to implement. They can also be costly. The most practical solution to the problem of wind turbine siting is to use existing wind resource information to identify potential areas where the wind resource might be large enough to be economically viable. Within the viable areas, locations that can be developed as practical wind turbine sites are identified. Wind measurements are then restricted to those sites.

OBJECTIVE OF THIS REPORT

This report presents guidelines for siting utility-scale wind turbine generators in terms of a step-by-step siting procedure. The procedure, especially its first two stages, can also be used as a gross resource assessment tool - a method for determining the size of the contribution wind energy could make to a utility's future generation needs. The procedure follows the approach outlined in the preceding paragraphs. The procedure concentrates on using existing wind resource information to locate potentially viable wind turbine sites. The procedure assumes that the economic viability (or near-viability) of a wind turbine development must be demonstrated before installation of the wind turbines can begin. Determining the economic potential of

a wind turbine installation requires fairly detailed knowledge of wind behavior at the site, and in most situations obtaining this knowledge requires a special measurement program. Because wind measurement programs are expensive and time-consuming, wind measurements are delayed to as late in the siting process as possible. All other site-selection factors (environmental impact, institutional constraints, etc.) should be reviewed before a wind measurement program is begun at a possible site. Wind measurements should only be made at locations that could ultimately be developed into a practical wind turbine site.

There are essentially two ways a utility can approach the problem of siting wind turbines. The first way is to identify a number of potential sites at the onset of the process. These sites might be places where the utility owns land or has collected wind data for some reason. No matter what the reason for selection, these sites would be ones where the installation of wind turbines would be convenient to the utility. Once the potential sites are identified, the selection process becomes one of determining the economic viability of each site and of assuring that the most viable sites have no serious environmental or public acceptance problems. This type of approach might be applied by a utility siting its first wind turbine, when the major purpose of siting the turbine is to obtain some experience in wind turbine operation, or by a utility knowing the exact location of a site with excellent wind resource. It is also the approach that might be followed by a utility whose choice of sites is severely restricted by operational or institutional (such as zoning) constraints.

A second way of approaching the siting problem is to set aside all preconceptions of where potential sites may be located and look for sites over a wide area. This approach might identify some of the sites that would have been selected by the first approach, but it should identify additional sites as well. The second approach to siting might be followed by a utility with no advance idea of where viable wind turbine sites might be located, or it might be followed by a utility wishing to build up a site bank. The approach might also be followed by a utility looking for sites with more attractive economics than those it would select for reasons of convenience.

Wind turbine siting is not the type of problem that is amenable to a "cookbook" solution. Each siting situation is different and could call for modifications to the approach outlined in this report or emphasis on different aspects of the approach. Accordingly, the siting procedure presented in this report is meant to be a guide, not a prescribed methodology. The procedure gives a step-by-step solution to the generic problem of a utility wishing to find viable wind turbine sites in a large

area. The procedure follows the second approach to site selection; it is an approach that could be called "site prospecting." The procedure presents a logical approach that can be modified to meet the needs of a particular application. In describing the siting process, the authors strove to provide sufficient detail to enable the reader to understand the issues involved in site selection, the procedures needed to address these issues, and the type of expertise a utility will need to employ in solving the problem. With an understanding of the general siting process, the reader will be in a better position to solve his own siting problem.

ORGANIZATION OF THIS REPORT

The major purpose of this report is to present a generic procedure that utilities can use as a guide in developing their own procedures for siting wind turbines. Before describing this procedure, the major issues involved in wind turbine siting are discussed in Section 2. Sections 3 through 7 describe the siting procedure. These sections contain not only a step-by-step description of the procedure, but also examples of its application. Section 8 presents the conclusions of this study and identifies those aspects of wind turbine siting that require additional research.

Following the main body of the report are appendices that discuss several important aspects of the wind turbine siting problem. The wind resource atlases* are a significant source of wind resource information and fill an important role in the siting procedure described in this report. These atlases are described in Appendix A. A critical link in the decision-making process of wind turbine siting is the procedure used to convert information on the wind resource to estimates of the amount of electricity a given wind turbine will produce at a site. The methods that are currently used to provide these estimates, along with a discussion of their probable accuracy, is given in Appendix B. Appendix C reviews procedures that are currently used to determine the economic viability of a wind turbine installation, while Appendix D discusses procedures for estimating the costs of developing a wind turbine site. Appendix E provides some generic cost information on wind turbine systems. This information is taken from the EPRI Technical Assessments Guide (1). Information on procedures for evaluating wind resources is given in Appendix F, while Appendix G covers wind instrumentation and describes instrumentation systems that could be used at various stages of the siting process.

*The wind resource atlases, developed under the sponsorship of the U.S. Department of Energy (DOE), illustrate estimates of annual average wind power across the United States.

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Section 2

A REVIEW OF SITING ISSUES

Finding a viable wind turbine site involves more than just identifying a windy location. A good wind turbine site must be economically viable (a function of site development costs as well as the magnitude of the wind resource), compatible with environmental and institutional constraints, compatible with wind turbine design specifications for meteorological extremes, and publicly acceptable. The effects of wind turbines on utility system dynamics are also a concern.

In this section, the important issues in wind turbine site selection are reviewed. The review is not meant to give exhaustive coverage of each issue. Instead, the nature of each issue is described and its importance is assessed. Whenever possible, the reader is referred to publications that discuss the issue in more detail.

ECONOMIC VALUE

The major purpose of a wind turbine generator is to reduce the costs of producing electricity; therefore, economic viability will be the primary attribute of an acceptable wind turbine site. Because of the unpredictability of the wind, wind turbines will probably be used as fuel savers. Thus the value of wind-generated electricity will depend on how this energy matches the load. Since energy production costs can vary both with time of day and with season, judging the economic viability of a wind turbine site will require information on the magnitude and temporal behavior of the wind for a typical year. Judging economic value also requires procedures for converting wind data into estimates of wind turbine output and for determining how this output interacts with the load and affects energy production costs.

The economic value of a particular wind turbine installation is obviously affected by the behavior of the wind at the site. However, another factor - installation costs - is also a primary concern. The costs currently projected for mass-produced wind turbine equipment indicate that wind-generated electricity will be competitive with only a portion of a utility's generating mix. For example, there are few utilities for which wind-generated electricity will be cheaper than base load generation. Since one cannot control the behavior of the wind, there are strong incentives for holding down installation costs in order to increase the size of the cost window

in which wind-generated electricity can effectively compete. Given the need to control installation (or site development) costs, wind turbine sites that have low land and construction costs, are located near existing roads and power lines, and require few modifications to the existing utility system will be favored.

In the past few years a good deal of work has been done on the problem of determining economic value for wind turbine generators. Unfortunately, one of the most common methods for determining the relative economic values of competing power generation systems, levelized busbar cost of energy (1), is not a very good indicator of economic value for wind turbine generators. The cost of energy can be a useful parameter in the early stages of site selection (see Sections 4 and 6). However, the problem with cost of energy as an indicator of economic value is that it gives no indication of the production cost savings realized by a wind turbine installation. Two different wind turbine installations with the same levelized cost of energy could deliver significantly different production cost savings depending on the temporal behavior of their output. Accurate determination of the economic value of a wind turbine installation requires a production cost model that accounts for the temporal behavior of wind turbine output. Several such models have been developed (2-5). In addition, economic evaluation of wind turbine installations is discussed in more detail in Appendix C.

ENVIRONMENTAL IMPACTS

In general, the environmental impacts of wind turbines are minimal; however, there are a few and in certain situations they could be significant enough to eliminate a particular location from consideration as a wind turbine site. The principal environmental issues that have been identified as possible areas of concern are:

- visual impact
- effects on birds
- noise
- electromagnetic interference (EMI)
- effects on local microclimate and ecology.

Each of these issues is discussed in more detail below.

Visual Impact

Large wind turbines are very large structures. They will be sited in open, remote areas and will be visible for miles. Because of their very nature, they cannot be screened from view. Consequently, the visual impact of wind turbines is an important siting factor.

Visual impact is obviously a very subjective thing. A person's visual reaction to a wind turbine is as much a product of his cultural, social and economic point of view as of the aesthetic merits of the installation. Visual impact is also a function of visual context. For example, Figures 2-1 and 2-2 are photographs of the DOE/NASA MOD-2 wind turbine cluster near Goldendale, Washington. Figure 2-1 shows the installation from a distance of about five miles, and Figure 2-2 depicts a portion of the installation from about 1500 m (1 mile). Although the MOD-2 is a very large piece of machinery (hub height 60 m (200 ft) above the surface, rotor diameter 91 m (300 ft)), both figures show that it is nearly lost in the vastness of the western landscape.

In summary, the visual impact of a wind turbine installation depends on how well it appears to blend with its surroundings. Sites where large man-made objects do not seem to "fit" (e.g., a wild scenic seashore) are best avoided. Visual impact can be evaluated by examining public reaction to previous installations and by polling public reaction to the proposed installation (supported by artist's depictions of how the installation will look). However, one should be careful of attaching too much significance to the public's reactions to the first few wind turbine installations. These reactions will be strongly affected by the novelty of wind energy. Public attitudes could change as the technology becomes more familiar.

Effects on Birds

One of the principal environmental concerns about large wind turbine installations has been the danger they might present to birds, particularly nocturnal migrants. The most thorough investigation of the environmental impacts of wind turbines was conducted by Rogers et al. (6). The study was conducted at the DOE/NASA MOD-0 wind turbine installation at Plum Brook, Ohio, and covered a total of 28 nights during the peak fall and spring migration dates of 1976 and 1977.

In spite of the limited nature of the study (the turbine was rotating only 10% of the time), Rogers and her colleagues believe that there was sufficient evidence to conclude: "....it appears that the WTG at NASA-Plum Brook is not consistently lethal to a significant number of low-level, night-migrating birds, even on nights favoring high migration traffic rates combined with low cloud ceiling and fog" (p. 101). Rogers also states that the danger wind turbines would present to birds was small compared to the hazard presented by tall radio or television transmission towers with their myriad of guy wires. However, Rogers et al. include several qualifications to their conclusions. First of all, they emphasize that their conclusions only apply to wind turbines of the same physical size as the MOD-0 and to sites similar to Plum

Figure 2-1. View of DOE/NASA MOD-2 Wind Turbine Near Goldendale, Washington. View is from a distance of about 8 km (5 mi). The MOD-2 is a 2500-kW, 2-bladed machine. Rotor diameter is 91 m (300 ft); the center of the wind turbine's rotor disk is about 60 m (200 ft) above the ground.

Figure 2-2. View of DOE/NASA MOD-2 Wind Turbines From a Distance of About 1500 m (1 mi)

Brook. A taller wind turbine or a wind turbine located in a place where night-migrating birds fly closer to the ground could pose a larger danger. Another point is that the hazard a large structure poses to night-flying birds is greatly affected by the way the structure is lighted. Strobe lights are thought to be less attracting or disorienting to birds than the traditional red beacons.

In summary, it appears that large wind turbines pose no greater danger to birds than other similar-sized structures. Even so, it would be wise to avoid siting wind turbines in places where large numbers of night-migrating birds might pass close to the ground. It would also be wise to avoid sites that are near places where birds congregate.

Noise

Another area of public concern about wind turbines is noise. Most of the audible sound associated with wind turbines is caused by the flow over the blade surfaces and by the wakes shed from these blades. The intensity of this sound (the acoustic power level) depends on the blade tip speed and the aerodynamic loading of the blades. An additional source of noise is pulsed, low-frequency sound associated with the passage of a blade by the tower support structure. This source of noise is a function of turbine orientation (upwind or downwind) and tower design.

A preliminary study of the audible noise characteristics of horizontal-axis wind turbines has been made by Keast and Potter (7). The study was based on standard theories of aerodynamically generated sound and on a few preliminary noise measurements from the MOD-0 wind turbine at Plum Brook. Based on the theory developed in the study, noise regulations of the states of Minnesota and Illinois and a U.S. Environmental Protection Agency (EPA) guideline for avoiding noise complaints from the public, the following "acceptability distances" were computed for the following three horizontal-axis wind turbines built for DOE:

- MOD-0A - 170 to 550 m (500 to 1800 ft)
- MOD-1 - 370 to 1800 m (1200 to 6000 ft)
- MOD-2 - 400 to 1200 m (1300 to 4000 ft).

The acceptability distances were the distances downwind of the turbines beyond which the Minnesota, Illinois, and EPA regulations are all satisfied. Keast and Potter emphasize that these distances should be considered both preliminary and conservative since, at the time of the report, the theory on which they are based had not been fully tested. The guidelines given by Keast and Potter do seem to agree with the

subjective impressions of persons who have heard the turbines. According to personal accounts received by the authors, the noise generated by large horizontal-axis wind turbines during startup, shutdown and normal operation is neither loud nor annoying. In fact, it is not particularly louder than the natural noise of the wind itself. Objective measurements of the acoustic power of sound generated by the DOE wind turbines have been made and should be reported in the near future.* These measurements should provide a more definitive test of the procedures and conclusions of Keast and Potter.

The only public complaints about noise from large wind turbines have come from one installation - the MOD-1 at Boone, North Carolina (8). These complaints were due to an infrasonic component of the MOD-1 noise spectrum rattling a small number of nearby houses. Problems with infrasonics have not been reported at any other large wind turbine sites, and recent measurements of the MOD-2 noise spectrum indicate that infrasonics should not be a problem with that turbine.* It appears that the MOD-1 noise problems were a unique product of certain MOD-1 design characteristics and certain features of the site (8).**

Electromagnetic Interference

Interference with electromagnetic waves (EMI) is another potential environmental impact of wind turbines that has received wide publicity. The problem is caused by reflection of the electromagnetic waves from the rotating blades of the turbine. This causes multi-path interference. Most studies of wind turbine EMI have concentrated on television interference (9). Wind turbines might also affect radio navigation systems or microwave transmission, but there has been little research in this area.

The TV interference problem can be solved by connecting affected sets to a cable TV system (assuming that the receiving antenna of the cable system is unaffected by the wind turbine). In some cases, however, the cable TV solution may not be practical.

*Personal communication, Neil B. Kelley, Solar Energy Research Institute, Golden, Colorado.

**There have been a small number of complaints about noise from smaller turbines that have been largely traceable to gear box noise. These complaints could be a factor if people perceive noise from "turbines" to be a problem. The public may not differentiate small from large and may in fact perceive bigger turbines to represent a bigger noise problem. Utilities may thus want to be aware that noise can be an issue (even though objectively it doesn't represent a problem for large turbines) and be prepared to discuss it with the local community.

Thus there have been some studies on overcoming television EMI by means of highly directional receiving antennas (8). The results of these studies are not yet available.

Predicting the exact nature of a potential EMI problem is not simple, for EMI depends on the type of signals involved and shape of surrounding terrain. Guidelines are available for identifying sites with the potential for TV interference (9). Similar guidelines are not available for other signals.

Effects on Microclimate and Ecology

Another area of environmental concern is the impact a wind turbine could have on the microclimate and ecology of a site. There are several ways in which the local microclimate and ecology would be affected by a wind turbine installation. One source of change would be modification of the land and ground cover during the construction phase of a wind turbine project. Another source of change would be the increased noise and activity that would occur through normal operation of the installation. A third source of change would be the effect of the wind turbines on local wind patterns. Gauging the environmental impact of the first two effects presents little problem since they are similar to impacts from other conventional projects. However, the effects a wind turbine installation has on the wind are unique.

By changing the air flow over the site, wind turbines could affect local rainfall patterns, snow cover and surface evaporation rate. However, the changes that a wind turbine exerts on the wind are small except very near the turbine structure. It is hard to see how such changes could result in significant impacts on local microclimate, especially when compared with the natural variability of meteorological phenomena. Rogers et al. (6) have conducted the most thorough investigation to date of the microclimatic impact of wind turbines. Rogers et al. examined the effects of the MOD-0 at Plum Brook on the horizontal variation in incident precipitation, incident solar radiation, horizontal and vertical distributions of air and surface temperature, wind velocity and atmospheric carbon dioxide concentrations. All effects were negligible compared with normal atmospheric variability.

INSTITUTIONAL ISSUES

As a "new" technology in a research and development phase, wind turbines have not been the specific subject of much litigation or regulatory legislation. However, some institutional and legal constraints on wind turbine siting do exist, and they are important. The Solar Energy Research Institute (SERI) has published a general, annotated bibliography of various publications and court cases pertaining to the

legal and institutional issues arising from the use of wind or solar energy (10). In addition, a group at George Washington University has examined the specific legal and institutional constraints on wind energy development (11). These constraints include: general regulations and restrictions on land use, safety codes, Federal Aviation Administration height standards, Federal Communication Commission Regulations, and the question of access to the wind or "wind rights". Each of these issues is discussed in more detail below.

General Regulations and Restrictions on Land Use

Regulations, statutes and policies that could affect the use of land as a wind turbine site include:

- power plant siting statutes
- zoning regulations
- noise pollution control statutes
- coastal, navigable waters, and wetland protection statutes
- environmental policy statutes
- historic preservation statutes
- water pollution control statutes and limitations on fugitive dust emissions (during the construction phase)
- wildlife and plant protection statutes
- regulations and statutes governing use of federal lands.

Since wind turbines have not entered routine commercial service, there are few formal siting regulations that apply. This situation may change as more units are installed. Already, one state (Oregon) has established formal procedures for licensing the construction and operation of wind turbine clusters. In the meantime, the only formal regulations applying to wind turbine siting and installation are the applicable zoning laws, land use constraints and pertinent general statutes and regulations listed above. Different regulations and statutes will apply to different sites, and each utility is assumed to be familiar with those that would apply in a given case. It is also assumed that each utility has developed procedures for dealing with these issues, as they are frequently encountered in the siting of more conventional facilities.

Safety Considerations

The safety aspects of constructing and operating a wind turbine can be divided into those aspects affecting the safety of the personnel working on the site and those aspects affecting the safety of the general public.* The most unusual safety consideration is the remote possibility that a workman or perhaps one of the general public would be struck by debris thrown from a wind turbine blade. This probability may require a safety exclusion zone to be established around each wind turbine in order to protect the general public. The size of the zone would vary with each wind turbine design, but it would probably be on the order of several hundred feet for large, horizontal-axis machines. Activities that would allow members of the general public to spend extended periods of time within the exclusion zone would probably be prohibited. On the other hand, activities that would allow members of the public to be in the exclusion zone for short periods might be acceptable.

Federal Aviation Administration Height Standards

The Federal Aviation Administration (FAA) requires that all objects exceeding a height of 200 feet be marked and lighted in accordance with applicable standards (14). Regulations also require anyone planning to construct an object that would require marking and lighting to give adequate notice to the FAA of the object's location and size. Marking of the object (alternating orange and white bands for tower-like structures) is required for daytime visibility, while lights (placed at various specified levels) are required for nighttime visibility. There are exceptions to these general rules, however. Near airports, objects below 200 feet in height may have to be marked and lighted, the orange and white marking bands can be eliminated if the object is equipped with high intensity strobes, and the marking and lighting specifications can be modified upon recommendation of the appropriate FAA regional office.

Most large wind turbines, particularly horizontal axis turbines, will require some variance from standard FAA marking and lighting specifications. For example, FAA lighting standards require the top level of lights to be installed on the highest point of the structure. For a horizontal-axis wind turbine, this would be the blade tip. Lighting blade tips, however, is not very practical. At the MOD-2 site at Goodnoe Hills, Washington, the requirement for lighting the highest point of the structure was apparently satisfied for all three turbines by placing the beacon light

*A review of the safety aspects of wind turbines is given by James (12) and Eggwertz et al. (13).

on top of a centrally located, 350-ft meteorological tower. Likewise, the requirement for marking was modified to include only a portion of the wind turbine blades (see Figure 2-3). The variances that the FAA would allow at a given installation, however, would be determined on an individual basis.

The FAA lighting requirement presents a classic case of conflicting requirements. Adequate marking and lighting are needed to assure that the wind turbine will not be a hazard to aircraft. However, making the wind turbine too conspicuous may adversely affect public acceptance of the installation. The hazard a turbine might present to birds could also be increased if the turbine were lighted in a way that caused the birds to become disoriented. Reaching a satisfactory solution to the marking and lighting question will obviously require some negotiation between the utility and the FAA.

Federal Communication Commission Regulations

Since large wind turbines can be a source of interference with electromagnetic waves, wind turbines could be considered an "incidental radiation device" capable of causing "harmful interference" (see (11)). Federal Communication Commission regulations mandate that incidental radiation devices be operated so that they cause no harmful interference. This would appear to mean that if operation of wind turbines were found to interfere with radio frequency communications, the turbine owner would be required to remedy the problem.

Wind Rights

A parcel of land is chosen as a wind turbine site primarily because it enjoys a strong, reliable wind resource. Once the turbine is installed, the owners of a wind turbine installation will not want any development upwind of the turbine that could block the free flow of air to the site or reduce the magnitude of the wind resource. If the turbine is sited on a ridge or hilltop or if the turbine is located right on the shore of a large body of water, this concern could be irrelevant, but for turbines sited on relatively flat terrain, it could be an important problem.

A utility should not assume that once wind turbines have been installed on a site, owners of land upwind will be restricted from interfering with the air flow. According to Mayo et al. (11), courts in the United States have held on numerous occasions that a land owner has no rights to a free and unimpeded flow of air or sunlight. In fact, courts have held that a land owner has the right to develop his property (subject to zoning restrictions) even when this development was alleged to cause economic harm to a neighbor by blocking his access to sunlight (Fontainebleau Hotel

Figure 2-3. View of DOE/NASA MOD-2 Wind Turbine Near Goldendale, Washington, Showing FAA-Approved Marking

Corporation versus Forty-five Twenty-five, Inc., 114 So. 2d 357 (Fla. 1959) as cited in (10)) or when the construction of a wall blocking the flow of air and light to a neighbor's property might have been done for spite (Cohen vs. Perrino, 355 Pa. 455, 50 A. 2d 348 as cited in (10)).

Wind rights can only be assured by having legally binding restrictions on upwind development. For large wind turbines this could require restrictions on a considerable amount of land. Studies of flow over obstacles such as buildings and shelterbelts (rows of trees) have shown the downstream flow to be disturbed for distances up to ten times the height of the obstacle (15,16). Moreover, if one wanted to ensure that there would never be any radical change in surface roughness that could reduce the strength of the flow over a site (such as the upwind land changing from grasslands to a tree farm), restrictions on upwind development might be required for distances even greater than ten times the mean height of the roughness elements (such as trees). In order to cover all possibilities, restrictions on future land development could be required for distances up to ten times the maximum height of the wind turbine in all significant energy-producing wind directions.

There are three ways a utility could obtain wind rights protection. One way would be to purchase or lease the required land, another way would be to obtain a "negative easement" on the required land (11), and the third way would be to obtain protection through zoning restrictions or statutory limitations on upwind land use. The first two solutions could be expensive, especially if only a few wind turbines were to be located at the site. According to Mayo et al. (11), obtaining a negative easement that would restrict future development of upwind land could be as expensive as outright purchase. If protection of wind rights were deemed necessary, the third alternative appears to be attractive - assuming these restrictions could be obtained in a timely manner. Protection of wind rights through zoning or legislation would not be absolute, however. Laws and zoning regulations can be changed.

Another way of dealing with the wind rights issue is to ignore it. During the site selection process one could opt for land where significant changes in existing land use would be unlikely over the life span of the wind turbines. This may even be a characteristic of a good wind turbine site. After all, land that is consistently exposed to high winds is usually of poor quality and affords a miserable habitat for plants and animals.

METEOROLOGICAL HAZARDS

In selecting sites for wind turbines, some consideration should be given to conditions that, for lack of a better word, will be termed "hazards". Some of these phenomena could indeed be hazards threatening the structural integrity of the wind turbines; other phenomena represent no catastrophic threat but could affect maintenance costs, ease of operation or service life of the equipment.

Icing

Icing can affect wind turbine operations in several ways. First of all, severe ice buildup affects both the static and wind loads on structures. Hence, wind turbine systems, transmission lines and any ancillary meteorological equipment must be designed to handle these loads. Icing could also affect the operation of wind turbines; they may have to be shut down if ice begins to build up on the blades in order to prevent debris from being thrown from the blades or excessive loads from building on the blade systems. In addition, icing of anemometers could shut down wind turbine control systems.

The probability that a site will experience significant icing can be assessed by a meteorologist. The meteorologist may also be able to estimate the frequency of significant icing events at a given site. This frequency can also be measured (see Appendix G).

A site that receives an excessive snowfall could also present a problem to wind turbine operations. Frequent large snowfalls could greatly increase the cost of operating and maintaining a wind turbine facility, particularly if the location of the site requires maintenance of long access roads by the utility.

Extreme Winds

Sites that frequently experience hurricane-force winds could be unsatisfactory for some turbines. The frequency with which a site would experience extreme winds and the magnitude of these winds can be estimated from existing climatological data. This information can be used to select turbine designs that are compatible with these extremes.

Turbulence

Turbulence is the technical term that refers to the gustiness of the wind. In a turbulent flow, the velocity vectors at every point in the fluid undergo random-like fluctuations in magnitude and direction. These fluctuations span a wide range of

time and space scales and are largely responsible for the buffeting experience by structures in a high wind. Wind turbines are designed to withstand the rigors of normal service; so, unless a wind turbine is sited near some obstacle or topographic feature that generates severe levels of turbulence, this wind characteristic should not be a threat to the structural integrity of a machine.*

Although turbulence may not be a structural threat, it could affect service life or maintenance costs. Atmospheric scientists know that the turbulence in flow over rough, complex terrain (e.g., mountain ridges, broken, hilly land, etc.) is different from the turbulence observed in flow over flat, level ground. There is very little data, however, to document these differences. The vast majority of measurements have been made over very flat, very homogeneous terrain, where simple, testable theories can be devised to describe the behavior of the flow. Even if documentation of the differences existed, however, it might be difficult to interpret these differences in turbulence structure in terms of service life or maintenance costs. The capability to interpret information on turbulence structure in terms of its effect on a wind turbine system will require more experience with a range of wind turbine designs under a wide range of meteorological and topographical conditions. In the meantime, it would be prudent, all other things being equal, to choose sites more likely to experience lower levels of turbulence.

Airborne Salt

Wind turbines located near coastlines will be subjected to considerable salt loading. Some wind turbine components may have to be modified or receive special protection in order to reduce corrosion problems. These modifications could increase the cost of turbines sited in coastal environments.

Abrasive Particles

If a wind turbine is sited in an arid environment, it may be subjected to frequent occurrences of blowing dust, sand and grit. These abrasive materials could damage protective coatings or infiltrate machinery, lubricants and so forth. Design modifications or special maintenance procedures might be required in order to maintain satisfactory service under these conditions. These modifications and procedures could increase the cost of the electricity generated.

*Chapter 5 of Hiester and Pennell (17) provides guidelines on siting with respect to obstacles and other turbulence-generating terrain features.

PUBLIC ACCEPTANCE

In the final analysis, the successful development of a parcel of land as a wind turbine site will hinge upon public acceptance. The general public, or at least the portion of the general public that is most affected, should feel that development of a site as a wind turbine installation is an appropriate use of the land and fits with the scenic character of the surroundings. Public attitudes will be influenced both by their perceptions of wind turbines in general and their perceptions of the economic benefits of wind turbines at a particular site.

At present, public perceptions of large wind turbines are probably fairly positive since wind turbines do not pollute, use a renewable resource and could conserve oil. These perceptions are probably not strongly rooted, however, since few people have any idea how a large wind turbine installation will look. Acceptance in theory may not always translate to acceptance in practice; thus, work towards gaining public acceptance of a wind turbine site should begin as early as possible. At the present time, environmental concerns such as visual impact and noise impact seem to be the issues of greatest public concern. Early and repeated communication among utility representatives, community representatives and public officials will be helpful in assuring that public concerns are addressed in the siting process.

DYNAMIC IMPACTS ON UTILITY SYSTEMS*

Wind turbine generators are subject to output fluctuations on time scales that range from seconds to years. These fluctuations are an inherent feature of wind-driven machinery. Fluctuations that occur on a scale of seconds to minutes are a particular concern to utilities since these fluctuations could affect short-term transient stability, system frequency control and the load-following capabilities of a utility's conventional generating equipment. Recently, Zaininger Engineering Company (18) completed an EPRI-sponsored study of the effects of wind turbines on utility system dynamics. Other studies have been performed as part of the Federal Wind Energy Program by General Electric (19) and by Schlueter et al. (20).

In the EPRI study, Zaininger Engineering studied the effect of a significant penetration of wind turbines on the Hawaiian Electric Company's system on Oahu. The report concluded that dynamic problems could limit the penetration of wind turbines into a utility system in some situations. The importance of dynamic impacts will also be

*This discussion focuses on system-wide dynamic impacts of wind turbines. Fluctuations in wind turbine output could also affect local transmission and distribution subsystems, depending on case specifics.

site specific. Dynamic impacts would be most likely to limit penetration in small, isolated utility systems. For the Oahu system, frequency excursion limitations and limitations imposed by the allowable ramping rates on conventional generators were the most important factors. Transient stability was not a problem - at least on Oahu.

A major limitation to the study was the lack of a method for simulating how the electrical output from a cluster of wind turbines would behave. Hence, the study was done indirectly. In this indirect approach, the maximum system load and wind turbine output change were determined for a given constraint, such as the maximum allowable frequency excursion. The likelihood of such a system load/wind turbine output change was then assessed. Without good wind data from a site or a tested model for converting such data to simulations of wind turbine output fluctuations, an indirect procedure is the best approach for determining the importance of system dynamics for a given installation.

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Section 3

A SYNOPSIS OF THE SITING PROCESS

Sections 4 through 7 describe a siting procedure for utility-scale wind turbines. Stages I and II of the procedure can also be used as a tool for estimating the size of the contribution wind power could make to a utility's future generation mix. The objective of the siting procedure is to identify as rapidly as possible potential wind turbine sites that have the greatest probability of being economically viable and publicly acceptable. The procedure applies to the siting of single turbines as well as groups of turbines (i.e., clusters), and has been made as general as possible so that it can be used by both large and small utilities. Since wind measurements are costly and time-consuming, the procedure has been designed to make maximum use of existing data and information. The collection of site-specific data has been delayed to as late in the siting process as possible.

A schematic of the siting process is shown in Figure 3-1. The entire siting process is divided into five stages, although the fifth stage, where the utility decides whether or not to install wind turbines, is not covered in this report. As Figure 3-1 shows, the only difference between a site prospecting procedure (see Section 1) and a procedure where one starts with a set of preselected sites is in the first two stages. When faced with the latter problem, one simply bypasses those stages.

In describing the methodology, a terminology is introduced that may not be familiar to utility planners or siting engineers. Several of the more important terms are:

- Region of Interest - A large land area in which a utility is looking for wind turbine sites.
- Candidate Resource Area - A subdivision of the Region of Interest that has a wind resource strong enough to appear to be economically viable.
- Potential Candidate Site - A plot of land in the Candidate Resource Area where the installation of wind turbines would be practical from an engineering standpoint.
- Candidate Site - The Potential Candidate Sites considered to be most favorable for wind turbine installation.

Figure 3-1. Synopsis of the Wind Turbine Siting Process

- Preferred Candidate Site - Those Candidate Sites that show the greatest potential as wind turbine sites after on-site verification of the magnitude of the wind resource, and analysis of engineering, economic, and environmental factors.

These and other unfamiliar terms are also defined in a Glossary (Appendix H).

In Stage I, a screening procedure is applied to the utility's Region of Interest, and Candidate Resource Areas with high wind energy potential are identified. The Region of Interest might include all or part of a utility's service area as well as neighboring areas in which the utility has wheeling agreements. Depending on the size of the utility, the Region of Interest could range from a few to several thousand square miles. After completing the screening procedure, which uses existing information, a much smaller area remains in which wind turbine installation appears to be both economically viable and publicly acceptable. This remaining land area is subdivided into conveniently sized Candidate Resource Areas.

Each Candidate Resource Area will have the following properties:

- sufficient wind resource for potential economic viability
- homogeneous wind resource at well-exposed locations (insofar as can be determined from existing data)
- homogeneous topographical characteristics
- convenient size.

The size of these areas is variable and will be a function of the size of the utility, the amount of detail available in the existing wind resource information, and the judgment of the person doing the analysis. Once the boundaries of the Candidate Resource Areas are defined, they are ranked according to their potential for containing a viable site or sites.

In Stage II, the Candidate Resource Areas are screened for Potential Candidate Sites. There are two options for screening:

Option A

1. Identify the best wind zones within the Candidate Resource Area.
2. Screen these zones with nonmeteorological factors and select Potential Candidate Sites.

Option B

1. Screen the Candidate Resource Area using nonmeteorological criteria.
2. Identify locations with the best wind resources and select Potential Candidate Sites.

The most efficient option is the one that eliminates the largest fraction of land in the option's first step. Thus, Option A would be chosen if the well-exposed areas with good wind resources (i.e., the best wind zones) were a small fraction of the total land area within the Candidate Resource Area. Option B would be chosen if the wind resource were fairly uniform over the Candidate Resource Area and non-meteorological factors (such as land use restrictions) were more important in dictating the location of viable sites.

Stage III of the siting process ranks the Potential Candidate Sites identified in Stage II and selects a smaller set of Candidate Sites for more extensive analysis. Each of the Potential Candidate Sites is visited by a team having engineering and meteorological expertise. Sufficient data are collected for making rough estimates of the cost of developing the site, installing the machines and providing necessary maintenance. The meteorologist records information on how nearby topography could affect flow over the site and estimates the likelihood of meteorological hazards.* Using this information, the economic potential of each site is evaluated by estimating the probability that the site is exposed to a wind resource that is greater than some break-even value. This break-even value will depend on the performance characteristics of the wind turbine, cost of installing a turbine at the site, and the production costs for other units on the utility's system. Once the most viable sites are identified, they are examined for potential meteorological hazards and other nonmeteorological factors (such as public acceptance) that could affect their suitability as Candidate Sites. The most acceptable of the economically viable sites are chosen as Candidate Sites.

Stage IV calls for more definitive studies of the economic potential of each Candidate Site. The analyses of Stage III are meant to identify the Potential Candidate Sites having the greatest economic potential. In many situations, this analysis will not be based on wind data measured at the site; in addition, the costs of site development, wind turbine installation and operation and maintenance will be rough estimates. They are only intended to detect gross differences between Potential

*Such an estimate should be treated as an educated guess.

Candidate Sites. Stage IV analyses, however, are intended to be more accurate and to give a truer picture of the economic value of wind turbines at each Candidate Site. The Stage IV studies will require wind data from each Candidate Site. This data must be sufficiently accurate to estimate how the wind turbines will perform over their lifetime and how they will affect future energy production costs. Preliminary designs of the site layout will be required in order to determine accurate costs for site development and turbine installation. Several preliminary designs may be required if more than one type of wind turbine is under consideration. Given the wind data and the site layouts, then, detailed economic analyses are performed. Economic analyses are based on models that account for the effects of wind-generated electricity on production costs or on simpler alternatives (such as cost of energy comparisons) if the latter are deemed appropriate. Additional information on meteorological hazards and the nonmeteorological factors affecting site selection would also be collected. Finally, the Preferred Candidate Sites - those sites most suitable for wind energy development - would be chosen on the basis of differential value comparisons.

The first two stages of the siting procedure can be completed very rapidly since they rely, primarily, on existing data. Completion of Stages I and II can be accomplished in a few weeks. At the end of Stages I and II, the utility should have a good idea of the number and the location of potential wind turbine sites. The last two stages of the siting process will take longer to accomplish since they require onsite measurements. The minimum time for completion of Stages III and IV is 15 to 18 months; however, they could require several years to complete if a utility needed thorough documentation of the wind resource at the Candidate Site before it could make a decision on wind turbine installation.

Section 4

STAGE I: IDENTIFICATION AND RANKING OF CANDIDATE RESOURCE AREAS

In Stage I, a Region of Interest is defined and screened for Candidate Resource Areas. Candidate Resource Areas are conveniently sized land areas that appear, on the basis of existing data and experience, to contain possible wind turbine sites.* The size of the Candidate Resource Areas will vary with the size of the Region of Interest, the complexity of the terrain and the meteorology within the Region of Interest, and the detail to which the wind resource is known within the Region of Interest. Once the Candidate Resource Areas are defined, they are ranked according to their potential for containing a viable site or sites. Figure 4-1 is a flow chart depicting the procedure for completing Stage I.

Before beginning Stage I, it is necessary to define the scope of the project and to gather the information and data needed to carry out the selection process. The following definitions are required:

- the Region of Interest
- the particular models or types of wind turbines under consideration
- the minimum number of wind turbines to be installed at a given site.

As indicated in the previous section, the Region of Interest is the area in which a utility is searching for wind turbine sites. This area could be all or part of the utility's service area, plus neighboring areas where the utility has wheeling arrangements. The particular models of wind turbines under consideration by the utility must be identified because the cost and performance of each wind turbine defines the minimum wind resource required for an economically viable installation. As will be seen below, the first step in the siting methodology is to eliminate from further consideration all portions of the Region of Interest having wind resources lower than the minimum required for potential economic viability. Since this threshold value could vary from model to model, different portions of the Region of Interest could be eliminated for different wind turbine models.

*In this report, the term "site" refers to the area that contains an entire cluster of wind turbines.

Figure 4-1. Activity Flow Chart for Stage I: Identification and Ranking of Candidate Resource Areas

In developing this methodology it has been assumed that each utility will look for sites capable of accommodating a minimum number of wind turbines. This number could range from a single machine to a cluster of several, and it will be based on economic considerations and land-use patterns within the Region of Interest. For example, if the cost of land within a Region of Interest is low, a cluster of several wind turbines may be the minimum-sized site. By installing several wind turbines at a given location, site development costs could be reduced on a per machine basis. Moreover, siting wind turbines in clusters may also reduce the cost of routine maintenance. If, on the other hand, land within the Region of Interest is highly developed and expensive, or if one finds no economic justification for grouping wind turbines in clusters, siting on the basis of one machine per site may be the proper choice. In any case, the number of wind turbines in the minimum-sized site defines the geographical size of the site and affects the installed capital cost per machine.

In order to carry out the steps in Stage I of the siting process, the following data are required:

- existing wind resource data
- location of transmission and distribution lines
- location of substations
- location of suitable roads
- federal, state and local siting requirements or regulations
- geological constraints on siting
- general performance characteristics of the machines under consideration
- typical installed costs for the machines under consideration.

Existing wind resource data include DOE wind energy resource atlases* and any additional sources of wind data known to the utility. Suitable roads are regularly maintained roads capable of carrying the equipment needed during construction of a wind turbine cluster. The road requirements are available from manufacturers of wind turbines. Applicable siting requirements or regulations include laws and regulations that could prohibit or constrain the use of land as a site for wind turbines. Geological constraints include any seismic constraints on turbine construction. Wind

*The U.S. Department of Energy has sponsored wind resource assessments for each state, the Commonwealth of Puerto Rico and U.S. possessions. Appendix A describes the content of these assessments, lists the report numbers, and indicates the areas covered by each report.

turbine costs and performance characteristics are needed in establishing the minimum useful wind resource. These costs and performance characteristics are available from wind turbine manufacturers.

SCREENING FOR POTENTIAL CANDIDATE RESOURCE AREAS

Step I-1: Eliminate Areas With Uneconomic Wind Resources

The first step in identifying Candidate Resource Areas is to define the minimum annual mean wind speed for which a given wind turbine generator could be economically viable. At this point in the siting process, fairly liberal assumptions should be made. *It is suggested that the minimum useful wind speed should be the annual mean wind speed at which the levelized cost of energy (COE) for the machine in question equals the levelized production cost of peaking power over the lifetime of the wind turbine.* This does not mean that wind turbines can be considered peaking units; nor does it mean that any site with a COE less than the levelized cost of peaking power will be economic. Many installations with COEs less than this value will not be viable, for only a fraction of the wind-generated electricity will go towards displacing power generated by the highest cost units. The levelized production cost of peaking power has been chosen as the target COE because it gives the lowest annual mean wind speed for which there is any chance of economic viability.*

The minimum useful wind speed for a given wind turbine can be determined as follows:

I-1a: Estimate the generic installed costs for each machine (dollars in year of installation). These costs include the cost of the machine delivered at the site, cost of access roads, cost of the land, cost of site preparation, cost of installation and cost of electrical intertie.

I-1b: Estimate the generic annual operating and maintenance costs (dollars in year of installation).

I-1c: Determine the target COE (dollars per MWh in year of installation).

I-1d: Compute the annual energy production (AEP) required to meet the target COE.
The AEP (in MWh) is given by

*The cost of energy for early prototype wind turbines may not be lower than production costs for peaking power in many parts of the country. A utility may still wish to install such a turbine for experimental purposes, however. In this case, the utility should concentrate its search for sites in areas that come closest to being economically viable.

$$AEP = \frac{IC \cdot FCR + AOM \cdot LF}{COE} \quad (4-1)$$

where

IC = the installed capital cost

FCR = the fixed charge rate

AOM = the annual operation and maintenance cost

LF = a levelizing factor that accounts for the effect of inflation on maintenance costs.

I-1e: Given the required AEP for each machine, determine the minimum annual mean wind speed needed to meet this AEP. This step requires knowing the annual energy production as a function of annual mean wind speed. The exact relationship between AEP and mean annual wind speed will vary from site to site and even from year to year at a given site; however, there are approximate relationships that have sufficient accuracy for selecting a minimum useful wind speed. These relationships may be obtained from manufacturers or they can be developed from raw performance characteristics (output vs. wind speed) and statistical models of wind behavior as shown in Appendix B. Figure 4-2 is an example of AEP as a function of mean wind speed for a given machine. In using curves like that in Figure 4-2, make sure that the height at which the wind speed is defined is specified.

In theory, the minimum annual wind speed will differ for each wind turbine under consideration. Installation costs and net energy production as a function of mean wind

Figure 4-2. Annual Energy Production as a Function of Mean Wind Speed for a Hypothetical Wind Turbine

speed both vary from machine to machine. It is important, however, to recognize the approximate nature of the relationship between net energy production and mean wind speed. The net electric energy produced by the actual wind turbine at a real site could differ from the approximate relationship by 25 percent or more. Therefore, a relatively large class of wind turbines might be represented by the same relationship. The minimum annual wind speed for such a class of turbines would only vary if there were large differences in installed costs.

I-lf: If the DOE wind resource assessments are being used as the primary source of wind information, convert the minimum acceptable wind speed to the minimum acceptable wind power density class (see Appendix A for a definition of terms).* Unfortunately, there is no unique relationship between wind power class and mean wind speed. The wind energy resource atlases give an approximate relationship that is accurate enough for this step in the siting process; however, the effect of altitude on air density should still be included.

Once the minimum acceptable wind power density class (or annual mean wind speed) has been defined, *all areas with less than this class are eliminated from further consideration.*** This is a fairly drastic step. It is possible that viable sites could be found in the eliminated areas; after all, the DOE-sponsored wind resource atlases are not infallible. They are, by necessity, fairly gross analyses of wind energy potential based on data from widely scattered (and not always representative) wind measurement stations. Nevertheless, there is solid justification for eliminating areas with less than the minimum acceptable wind power density class: It is impossible to examine in detail every conceivable wind turbine site in a large area. This procedure, therefore, concentrates on those portions of the Region of Interest that have the highest probability of containing viable sites. The DOE wind resource assessments complement this approach to siting since the wind power density classes are supposed to be representative of land with good wind exposure. Because of this philosophy, it is unlikely that large numbers of viable sites would be located in the eliminated areas. This conclusion is further reinforced by the liberal manner in which the minimum acceptable wind power density class has been defined in this procedure (wind turbine availability has been assumed to be 100%, for example).

*The DOE wind resource assessments do not have to be used. If they are not used, the utility, or its consultants, will have to produce its own analysis of the wind resource to identify the location of Candidate Resource Areas.

**These areas could be reexamined at a later date, however.

In some exceptions, however, an area with less than the minimum acceptable power class may be retained. Most of these exceptions will be found in areas where confidence in the accuracy of the wind resource analysis is low. In order to give users of the atlases an indication of the accuracy of the assessments, a confidence rating was assigned to each portion of the wind resource estimates. Table 4-1 provides an abbreviated definition of this rating. More thorough definitions of the confidence ratings are given in Appendix A or in any of the DOE wind resource atlases.

Table 4-1
WIND RESOURCE CONFIDENCE RATING

Confidence Rating	Abbreviated Definition
1	Low degree of certainty (e.g., little or no wind data plus complicated terrain or meteorology)
2	Low-intermediate degree of certainty (e.g., little or no wind data but terrain and meteorology are not complex; resource will be similar to that in better documented, nearby areas)
3	High-intermediate degree of certainty (e.g., considerable data but terrain is moderately complex)
4	Highest degree of certainty (e.g., high quality, representative wind data combined with simple terrain and meteorology)

The confidence ratings can be interpreted in the following manner:

- Confidence rating is 4: Wind power class should be representative of well-exposed areas.
- Confidence rating is 2 or 3: Uncertainty in the wind power class of well-exposed areas may be $\pm 1/2$ to 1 wind power class.
- Confidence rating is 1: Uncertainty in the wind power class of well-exposed areas may be ± 1 wind power class or greater.

Given these considerations, if exclusion of all areas with less than the minimum acceptable wind power density class eliminates all of the land within the Region of Interest, the following points should be reviewed before concluding that wind energy is impractical:

- Is existing wind resource information accurate?
- Are the target COEs realistic?
- Are the generic installation costs unrealistically high?
- Would other wind turbines be more economically viable?

When reviewing a decision on the economic viability of wind-generated electricity, the first thing to consider is the accuracy of wind resource information. One check is the confidence ratings of the wind resource assessments. Another check is the opinions of local experts.* If the assessed wind resource conflicts with these opinions, local knowledge should prevail. Lastly, portions of the Region of Interest with the highest wind power class should be checked to determine whether they might contain areas with greater wind resources than indicated by existing data. This situation could be brought about by certain meteorological or topographical features, and the procedures that could be used to locate these areas are outlined in (1).

Next, the target cost of energy and generic installation costs should be reviewed. Future fuel escalation rates are probably the greatest source of uncertainty in the target cost of energy, while the greatest source of error in the installation costs is that they may have been based on prototypes or preproduction machines. Installation costs could come down as production rates for the machines go up. In addition, costs per unit could be lowered by multiple unit orders or by increasing the number of machines installed at a given site. Installing the wind turbines in clusters rather than individually could lower the installed cost per unit considerably.

The final step in reviewing a decision on economic viability is to review cost and performance information for other wind turbines. It is possible that a machine may have been overlooked that has lower installed cost or exhibits performance characteristics better suited to the characteristics of the wind resource in the Region of Interest.

As an example of Step I-1, consider Figure 4-3, which is a map of the annual average wind power density for the state of New York, and Figure 4-4, which is a map of the confidence ratings for that state. If the minimum useful wind resource for a certain

*Local experts are meteorological or engineering professionals having extensive experience with wind-related problems in the area.

Wind Power Class	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density, watts/m ²	Speed, ^(b) m/s (mph)	Wind Power Density, watts/m ²	Speed, ^(b) m/s (mph)
0	0	0	0	0
1	100	4.4 (9.8)	200	5.6 (12.5)
2	150	5.1 (11.5)	300	6.4 (14.3)
3	200	5.6 (12.5)	400	7.0 (15.7)
4	250	6.0 (13.4)	500	7.5 (16.8)
5	300	6.4 (14.3)	600	8.0 (17.9)
6	400	7.0 (15.7)	800	8.8 (19.7)
7	1000	9.4 (21.1)	2000	11.9 (26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

Figure 4-3. Map of Annual Average Wind Power Density Class for the State of New York

Figure 4-4. Confidence Ratings for Wind Resource Analyses in New York. The ratings are defined in Table 4-1 and apply over the $1/4^\circ$ latitude by $1/3^\circ$ longitude grids shown in the figure

wind turbine were judged to be Class 4,* all areas on the map classified as Class 3 or lower would be removed from further consideration. However, Class 3 areas with a confidence rating of 1 or 2 might be given a closer examination. If there is reason to believe that these areas might contain viable sites, they could be retained for further examination.

Step I-2: Eliminate Areas With Unfavorable Land Use

This step eliminates those areas with good wind resources where the construction of wind turbines could be difficult or impossible (see Section 2). This step requires

*Wind power density classes are explained in Appendix A. A legend that indicates the correspondence between power density class and mean wind speed is shown in Figure 4-5.

considerable local judgment since limitations on land use can vary drastically between locales. Typical areas that might have unfavorable land use restrictions include:

- parks
- seashores
- wilderness and roadless areas
- certain scenic areas
- bird or waterfowl refuges
- wetlands
- military reservations.

Step I-3: Eliminate Areas With Obviously Unfavorable Geology

Information on allowable seismic loads and on the soil conditions needed for turbine foundations should be obtained from the manufacturers. Any areas identified at this stage of the siting process as unsuitable or as requiring inordinately expensive site preparation are eliminated from further consideration.

Step I-4: Define Candidate Resource Areas

Now, the remaining area is divided into conveniently sized Candidate Resource Areas (CRAs). The divisions are purely subjective, but they should make logical use of geographical features and boundaries of political jurisdictions. Each Candidate Resource Area should have the following properties:

- homogeneous wind resources at exposed locations (insofar as determined by the resource assessments)
- homogeneous geological and topographical characteristics.

If Steps I-2 and I-3 have eliminated all of the land in the Region of Interest, some of the eliminated areas should be reexamined for feasibility. Consideration should also be given to portions of the land area eliminated in Step I-1 that have the highest wind power density class. It is still possible that some of these areas could contain viable sites.

In some cases, the Candidate Resource Areas may be so small that Potential Candidate Sites could be identified immediately. In this situation, one would proceed directly from Step I-4 to Stage III, bypassing the rest of Stage I and all of Stage II.

RANKING CANDIDATE RESOURCE AREAS

Once Candidate Resource Areas have been identified, they should be ranked according to the probability that they contain economically viable and publicly acceptable sites. The search for actual wind turbine sites should be concentrated in the highest ranking CRAs. One approach to ranking CRAs is to treat the economic and public acceptance issues separately. In this approach, the cost of energy (or differentials in installation costs, see Appendix D) is computed for a typical site in each CRA. Public acceptance of wind energy development in each CRA is then rated on a separate scale. The search for Potential Candidate Sites is concentrated in the CRAs showing the lowest cost of energy and the highest public acceptance.

In many situations, however, the above approach may not be practical. Installation costs, for example, could vary greatly within a Candidate Resource Area making the definition of a typical site impossible. Because of this problem, a different approach has been developed. In this approach a number of ranking criteria are identified and the various Candidate Resource Areas are evaluated on the basis of these criteria. The criteria cover economics and public acceptance. All criteria concentrate on issues that apply over an entire Candidate Resource Area and would make the probability of finding a viable site in one CRA significantly different from the probability of finding a viable site in another.

In any case, the reader should remember that siting is not a cookbook procedure. The steps outlined in this and following sections are intended for guidance only. The procedure should be modified as required to meet the needs of each individual utility.

Ranking Criteria

The criteria used in ranking Candidate Resource Areas are listed in Table 4-2. The first ranking criterion is the amount of electric energy a wind turbine would be expected to produce at a typical well-exposed site within a given CRA. The second criterion indicates the likelihood that wind-generated electricity would displace higher cost electricity. The third criterion is associated with transmission losses between the turbines and the load, while the next three criteria are the costs of developing a site within the CRA. The seventh criterion is indirectly related to the economics of a wind turbine installation since meteorological hazards could affect service life of the turbines and operation and maintenance costs. The last criterion is a measure of the public acceptance of wind energy development at a typical site in a given CRA.

Table 4-2

CRITERIA FOR RANKING CANDIDATE RESOURCE AREAS

<u>Criterion Number*</u>	<u>Ranking Criterion</u>
1	Magnitude of wind resource
2	Seasonal load match between electrical system load and the wind
3	Distance to load centers (load centers defined by cluster size)
4	Existence of transmission and distribution lines in the Candidate Resource Area
5	Existence of suitable roads in the Candidate Resource Area
6	Characteristics of terrain in the Candidate Resource Area
7	Severity of meteorological hazards in the Candidate Resource Area
8	Public acceptance of wind turbines in the Candidate Resource Area

*The number assigned to each criterion is for identification only. It does not reflect the relative importance of the criteria.

The user should note that there is no explicit ranking criterion for environmental impact (although public acceptance is affected by this factor). The environmental impact of wind turbines is very localized and cannot be evaluated until the exact site is known.

Ranking Procedure

A suggested ranking procedure is to score each Candidate Resource Area with respect to each ranking criterion. The scores for all eight ranking criteria are combined to give an overall score for each Candidate Resource Area. Since the importance of each ranking criterion is not the same, the score for each criterion should be multiplied by a weighting factor that reflects its relative importance. The score for each ranking criterion is multiplied by its weight and then summed with all the other weighted scores to produce an overall ranking value (RV) for each Candidate Resource Area:

$$RV = \sum_{i=1}^8 W_i S_i \quad (4-2)$$

where RV is the ranking value for a given Candidate Resource Area, W_i is the weighting factor for the i th ranking criterion and S_i is the score for the i th criterion. The ranking values for each Candidate Resource Area should then indicate those CRAs with the highest probability of containing practical wind turbine sites.

In addition to computing ranking values for each CRA, it is useful to examine all scores in a matrix format. A hypothetical example of such a matrix is given in Table 4-3. When the scores are displayed in this manner, it becomes easier to analyze the influence of the scores in individual criteria on the overall ranking of CRAs. For example, a CRA may emerge with a relatively low ranking value because it scored particularly low in one or two criteria. In this case one may wish to reexamine the scores awarded in these criteria, or one may wish to reexamine the relative weights for each criterion.

These procedures are common in the analysis of complex decisions (2). They are useful in that they force one to list the factors considered in making the decision and to make a definite judgment (in terms of a score) on how each alternative compares with respect to the decision factors. The principal difficulty is in choosing (and justifying) the scores and determining the weights. For some ranking criteria, scoring is not a problem. For example, if annual average energy production for a given wind turbine doubles with a doubling of annual mean wind speed, scores for criterion number 1 (magnitude of wind resource) would be scaled accordingly. However, picking scores for other criteria can be more difficult. In scoring Candidate Resource Areas with respect to public acceptance (criterion number 8), how could one say that one CRA had twice the public acceptance of another? The answer is that it is frequently very difficult to set up a completely objective, rational scoring procedure. Considerable reliance may have to be given to "professional judgment". One approach to handling the more subjective ranking criteria is to establish a table with a list of scores and a series of descriptors of the attributes a CRA must have to be given that score. This approach at least helps to keep the scoring consistent.

Determining weights is an even more difficult task. The weighting should obviously reflect the importance of each ranking criterion to the overall success of the project. Selecting the weights for criteria that affect costs is easier than selecting weights for criteria that reflect personal or community values (e.g., public acceptance). The method most widely used in dealing with similar problems is to rely

Table 4-3

EXAMPLE OF A RANKING MATRIX FOR CANDIDATE RESOURCE AREAS

Suggestions for Scoring Site Selection Criteria
Are Given in Steps I-5 Through I-12

Weights*	Criterion Number								Weighted Total
	1 10	2 .9	3 5	4 6	5 6	6 3	7 4	8 8	
Candidate Resource Areas	Unweighted Scores								
South Fork	0.96	0.82	1.0	1.0	1.0	1.0	0.5	1.0	47.0
South Shore Islands - I	0.06	0.82	1.0	1.0	0.25	1.0	0.5	1.0	40.9
North Shore - I	0.96	0.82	1.0	1.0	1.0	1.0	0.5	0.5	43.0
North Fork	0.96	0.82	1.0	1.0	1.0	1.0	0.5	0.5	43.0
South Shore - I	0.96	0.82	1.0	1.0	1.0	1.0	0.5	0.5	43.0
Eastern Highland	0.68	0.82	1.0	1.0	1.0	1.0	0.5	0.5	40.2
South Shore - II	0.96	0.82	1.0	1.0	1.0	1.0	0.5	0	39.0
South Shore Islands - II	0.96	0.82	1.0	1.0	1.0	1.0	0.5	0	39.0
Central Peninsula	0.51	0.82	1.0	1.0	1.0	1.0	0.5	0.5	38.5
North Shore - II	0.71	0.82	1.0	1.0	1.0	1.0	0.5	0	36.5
Western Shirley County	0.51	0.82	1.0	1.0	1.0	1.0	0.5	0	34.5
Eastern Shirley County	0.51	0.82	1.0	1.0	1.0	1.0	0.5	0	34.5

Criterion NumberCriterion

1	wind resource
2	seasonal load match
3	distance to load centers
4	distance to transmission and distribution lines
5	distance to suitable roads
6	terrain characteristics
7	meteorological hazards
8	public acceptance

*These are weights that were assigned to the various selection criteria by a given utility. They represent the relative importance that this particular utility attached to each criterion. Other utilities with different concerns might assign weights differently.

on a panel of experts. The expertise of the panel should span the issues involved, and the points of view of the panelists should represent the points of view of people affected by the decision. The panel discusses each issue (or criterion in this case), and the relative importance of each issue emerges from the give and take of the discussion.

Formal procedures have been developed for organizing and running such panels; one of the better known is "Delphi". Delphi procedures attempt to circumvent the tendency for committees to be dominated by a few members either by keeping all interactions between panelists anonymous or by keeping only the final decision process anonymous. References (3) through (9) discuss Delphi and other related procedures in more detail.

Scoring the Ranking Criteria

The following steps describe a procedure that a utility could use in scoring each of the eight ranking criteria. The procedure is a suggestion only and should be modified if it does not fit the problem at hand. The reader should also realize that Delphi-like procedures can be used for assigning scores to criteria if that technique is preferred to the one described below.

Step I-5: Magnitude of wind resource (Criterion #1). If the DOE wind resource assessments are the principal source of wind resource information on the scale of the Candidate Resource Areas, this criterion can be scored as follows:

I-5a: Determine the annual energy production (AEP) as a function of wind power density class for each wind turbine under consideration. This has probably been done in Step I-1 (see Figure 4-2).

I-5b: Determine the maximum wind power density class in your Region of Interest.

I-5c: Determine the annual energy production at the midpoint of the range of values covered by this wind power density class. This value is denoted $(AEP)_m$.

I-5d: Determine the wind power density class and the certainty rating for the Candidate Resource Area under consideration. If the certainty rating is 4, determine the AEP for the Candidate Resource Area at the mid-point of the range for the CRA's wind power density class. If the certainty rating is 2 or 3, AEP is determined at the bottom of the range for that wind power density class. If the certainty rating is 1, AEP is determined at the midpoint of the next lowest class.

I-5e: Determine the score for the wind resource criterion as follows:

$$S_1 = \frac{AEP}{(AEP)_m} \quad (4-3)$$

For example, Figure 4-5 shows annual energy production as a function of the annual mean wind speed for a certain wind turbine. The figure also shows the range of outputs that would be expected for the seven wind power density classes. Assume that the maximum wind power density class in a certain Region of Interest is 6. From the figure we see that

$$(AEP)_m = 860 \text{ MWh}$$

Figure 4-5. Annual Energy Production Versus Annual Mean Wind Speed and Wind Power Density Class for a Hypothetical Wind Turbine

Next, assume that a certain Candidate Resource Area has a wind power density class of 5. If the confidence rating in that CRA is 4, annual energy production for a typical site is assumed to be 780 MWh and

$$S_1 = \frac{780}{860} = 0.91$$

from Eq. 4-3. If the certainty rating is 2 or 3, however, the typical AEP is taken as 750 MWh and

$$S_1 = \frac{750}{860} = 0.87$$

Finally, if the certainty rating is 1, the AEP is assumed to be 700 MWh. This gives

$$S_1 = \frac{700}{860} = 0.81$$

As can be seen from this example, the value of the wind resource score is downgraded for uncertainty in a manner that reflects the sensitivity of wind turbine output to errors in the mean wind speed.

Step I-6: Seasonal load match (Criterion #2). In scoring a Candidate Resource Area with respect to this criterion, first determine the annual peak load (APL) for your system. Next, determine the peak system load for the season of maximum wind in the Candidate Resource Area under consideration.* This quantity is denoted SPL. The score for this criterion is

$$S_2 = \frac{SPL}{APL} \quad (4-4)$$

If the seasonal modulation of wind power density is weak or if marginal production costs do not vary a great deal from season to season, this criterion could be given a low weight.

This scoring procedure assumes that production costs are closely related to system load. This is not always the case. One utility in the Pacific Northwest, for example, experiences its peak load in the summer, but its production costs at this

*Maps showing season of maximum wind are contained in the DOE wind resource assessments.

time of year are relatively low since large amounts of hydroelectric power are usually available. Peak production costs for this utility are in the fall when stream flow rates are low. In this case, wind-generated electricity might have a greater value during the fall than during the season of peak load. Basing the score for criterion 2 on a ratio of seasonal-averaged marginal production costs (see Appendix C) might make more sense for this utility.

Step I-7: Distance to load centers (Criterion #3). In scoring with respect to this criterion, preference is given to Candidate Resource Areas where the installation of wind turbines would reduce load flow into the CRA. A binary scoring method is suggested for this and the next two criteria. The reader will also note that in scoring criteria 3, 4 and 5, a tacit assumption is that all Candidate Resource Areas are of approximately the same size (it is assumed, for example, that the distance from a typical site to the boundaries of the CRA is the same for all CRAs).

The distance to load centers criterion is scored as follows: If all the electricity generated by the cluster could be consumed within the CRA,

$$S_3 = 1.0$$

If wind-generated electricity must be shipped out of the CRA,

$$S_3 = 0.0$$

Step I-8: Distance to transmission and distribution lines (Criterion #4). Preference is given to Candidate Resource Areas with transmission or distribution lines capable of carrying the load from the wind turbine cluster. It is assumed that the costs of tying the cluster to the utility system will be lower in such Candidate Resource Areas. Thus, if suitable transmission and distribution lines are found within the CRA,

$$S_4 = 1.0$$

If suitable transmission and distribution lines lie outside the CRA,

$$S_4 = 0.0$$

Step I-9: Distance to suitable roads (Criterion #5). The installation of large wind turbines requires bringing fairly heavy equipment onto the site. For most sites,

this will require construction of roads with suitable load bearing and other physical characteristics (turning radii, grades, etc.). Wind turbine manufacturers must be consulted to determine what these requirements may be.

Preference is given to Candidate Resource Areas that have existing, regularly maintained roads capable of carrying the construction traffic. Therefore, if suitable roads are found within the CRA,

$$S_5 = 1.0 \quad .$$

If suitable roads lie outside the CRA,

$$S_5 = 0.0 \quad .$$

Step I-10: Terrain characteristics (Criterion #6). The nature of the terrain in and around a wind turbine site strongly affects installation costs. Thus, it is an important factor in site selection. Complex terrain also means that flow over the site will be complicated; for a multi-unit cluster, this means that fixing the position of each wind turbine in the cluster will require more extensive (and expensive) analysis for sites in complex terrain than for sites on flat, level plains. For these reasons, Candidate Resource Areas in regions with simple terrain are preferred over CRAs in regions with rugged topography.

The scoring procedure described in this step is based on a standard terrain classification code developed by Hammond (10). This code has also been used to classify terrain type in the DOE wind resource atlases. Hammond's classification code uses five parameters to describe the character of the land surface, although the DOE wind resource atlases only make use of three of the parameters. The parameters used in the atlases are:

- percentage of the land area comprised of gently sloping surface (i.e., less than 8% slope)
- local relief - the maximum difference in surface elevation within a unit square six miles on a side
- percentage of gently sloping surface that lies in the lower half of the local relief.

These parameters are expressed in a three-character code (e.g., B3a) that is defined in Table 4-4. Figure 4-6 is an example of the terrain classification maps found in the DOE wind resource atlases.

Table 4-4

TERRAIN CLASSIFICATION CODE

SLOPE (1st Character)

A	>80% of area gently sloping
B	50 to 80% of area gently sloping
C	20 to 50% of area gently sloping
D	<20% of area gently sloping

LOCAL RELIEF (2nd Character)

1	0 to 30 m (0 to 100 ft)
2	30 to 90 m (100 to 300 ft)
3	90 to 150 m (300 to 500 ft)
4	150 to 300 m (500 to 1000 ft)
5	300 to 900 m (1000 to 3000 ft)
6	900 to 1500 m (3000 to 5000 ft)

PROFILE TYPE (3rd Character)

a	>75% of gentle slope in lowland
b	50 to 75% of gentle slope in lowland
c	50 to 75% of gentle slope on upland
d	>75% of gentle slope on upland

Figure 4-6. Terrain Classification Map for New York

Table 4-5 is a suggested relationship between the Hammond classification code and the score for this criterion. As the table shows, preference is given to Candidate Resource Areas located in lowlands, on plains or in open hills where local terrain relief is less than 150 m (500 ft). For a given local relief, the score decreases, more or less linearly, as the percentage of gently sloping land decreases.

Step I-11: Meteorological Hazards (Criterion #7). Considerably more experience with large wind turbines is required before the identity and importance of all meteorological hazards are known. However, phenomena such as frequent icing conditions, frequent occurrences of strong winds, wind-borne salt, and wind-blown dust, sand or grit (abrasive aerosols) may adversely affect wind turbine operations.* Consequently,

*The probability of experiencing these hazards should be the same over the entire CRA. Potential hazards such as severe turbulence (including gusty winds or extreme wind shear) are site specific and cannot be evaluated until the exact site is known.

Table 4-5
SCORE FOR TERRAIN CHARACTERISTICS

Terrain Type	<u>S₆</u>	
<u>Plains</u>		
A1 - Flat Plains		1.0
A2 - Smooth Plains		1.0
B1 - Irregular Plains, Slight Relief		1.0
	Location of Exposed Area*	
	<u>Lowland</u>	<u>Upland</u>
<u>Plains with Hills or Mountains</u>		
A3 to B3a, b - Plains w/Hills	1.0	1.0
B4a, b - Plains w/High Hills	1.0	0.75
B5a, b - Plains w/Low Mountains	1.0	0.60
B6a, b - Plains w/High Mountains	1.0	0.45
<u>Open Hills and Mountains</u>		
C2 - Open Low Hills	1.0	1.0
C3 - Open Hills	1.0	0.95
C4 - Open High Hills	1.0	0.65
C5 - Open Low Mountains	1.0	0.50
C6 - Open High Mountains	1.0	0.35
<u>Hills and Mountains</u>		
D3 - Hills	1.0**	0.80
D4 - High Hills	1.0**	0.50
D5 - Low Mountains	1.0**	0.35
D6 - High Mountains	1.0**	0.20
<u>Tablelands</u>		
B3c, d - Moderate Relief	1.0	1.0
B4c, d - Considerable Relief	1.0	0.75
B5c, d - High Relief	1.0	0.60
B6c, d - Very High Relief	1.0	0.45

*These ratings assume that the load centers are located in the lowlands.

**The best wind resource is not likely to be found in these locations; however, there can be local exceptions.

Candidate Resource Areas exhibiting one or more of these undesirable characteristics should be downgraded. Determining whether the occurrence of a particular hazard is significant is obviously a subjective judgment, but information from wind turbine manufacturers on the tolerance of given machines to these hazards will be necessary in making such judgments.

A possible method of scoring CRAs relative to the risk of experiencing significant meteorological hazards is

$$S_7 = 1.0 - I - EW - ST - G \quad (4-5)$$

where the terms I, EW, ST and G are defined in Table 4-6.

Table 4-6
DEFINITION OF TERMS IN EQUATION (4-5)

<u>Meteorological Hazard</u>	<u>Significant Occurrence</u>	<u>Insignificant Occurrence</u>
Icing conditions	I = 0.25	I = 0.0
Frequent extreme winds (e.g., fastest mile exceeds 100 mph once per year*)	EW = 0.25	EW = 0.0
Airborne salt	ST = 0.25	ST = 0.0
Wind-blown dust, and grit	G = 0.25	G = 0.0

*The fastest mile is the minimum time in which a mile of air passes a point. It is a term that has gained some acceptance in wind engineering since it is a measure of the strongest wind gust likely to envelop a large structure.

Step I-12: Public Acceptance of Wind Energy Development (Criterion #8). This criterion attempts to gauge public attitudes towards the development of wind turbine sites within the Candidate Resource Areas. Gauging these attitudes is a very subjective matter, particularly when there has been no previous public exposure to large wind turbine installations. Nevertheless, public attitudes will undoubtedly be affected by

- the scenic impact of the wind turbine installation
- the public's support for wind energy development
- compatibility with existing land use
- attitudes of land owners
- impact of construction on the local environment.

At this stage of the siting process, assessment of public acceptance must be fairly crude since the exact location of the cluster within the Candidate Resource Area will not be known. Table 4-7 provides a guide for scoring CRAs with respect to this criterion.

Table 4-7
SUGGESTED SCORING PROCEDURE FOR PUBLIC
ACCEPTANCE CRITERION

<u>Probable Public Attitude</u>	<u>S₈</u>
Public acceptance is judged to be poor. Considerable opposition can be expected because of the scenic nature of land within the CRA, etc.	0.0
Public attitude is judged to be neutral.	0.5
Public attitude is judged to be highly favorable.	1.0

TIME REQUIRED TO COMPLETE STAGE I

The entire analysis described in this section can be completed in a relatively short period of time. Compiling the data required to complete the analysis will probably take the most time. Once this information has been assembled, the identification and ranking of Candidate Resource Areas will probably take one to two man-weeks, depending on the size and complexity of the Region of Interest.

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Section 5

STAGE II: SELECTION OF POTENTIAL CANDIDATE SITES

The product of Stage I is a set of Candidate Resource Areas. The highest ranking Candidate Resource Areas are assumed to contain at least one viable site for a wind turbine cluster; they may contain several such sites. The objective of this step is to identify Potential Candidate Sites within the most attractive Candidate Resource Areas. Since the area of a Candidate Resource Area may be several times larger than the land area of a wind turbine cluster, the Candidate Resource Areas must be screened for Potential Candidate Sites that look most attractive for wind energy development. There are two options for screening Candidate Resource Areas and for identifying potential sites:

Option A

1. Identify the best wind zones within the Candidate Resource Area.
2. Screen these zones with nonmeteorological factors and select Potential Candidate Sites.

Option B

1. Screen Candidate Resource Area using nonmeteorological criteria.
2. Identify locations with the best wind resources and select Potential Candidate Sites.

The most efficient option is the one that eliminates the largest fraction of land in the first step. For example, if the land is flat and the wind resource over the Candidate Resource Area is thought to be fairly uniform, use Option B. If terrain in the Candidate Resource Area is complex or if there are meteorological reasons to expect the wind resource over the area to show significant variation, use Option A.

Figure 5-1 is a flow chart depicting the sequence of tasks in Stage II. The data needed in carrying out Stage II include:

- the locations of wind measurement stations within the Candidate Resource Area and the wind data from these stations
- information on topography within the CRAs (the format will be specified by the techniques used in wind resource analysis - see below)

Figure 5-1. Activity Flow Chart for Stage II: Selection of Potential Candidate Sites

- all special information required by any of the techniques used in wind resource analysis (see Step IIA-1b)
- federal, state and local ordinances, regulations and siting requirements
- patterns of land ownership and existing or planned land use within the Candidate Resource Areas
- location and type of sensitive environments that could be affected by the construction or the operation of a wind turbine cluster
- geological constraints on siting (obtained from manufacturers) and pertinent geologic maps
- noise and electromagnetic interference (EMI) characteristics of wind turbines under consideration (obtainable from manufacturers)
- size of safety exclusion zones required to protect the public from the risk of possible blade-thrown debris (available from manufacturers)
- location of suitable roads, transmission or distribution lines and substations.

SCREENING THE CANDIDATE RESOURCE AREA WITH OPTION A

In Stage I of this siting methodology, the DOE regional wind resource assessments are assumed to be the primary source of wind resource information. These assessments are intended to indicate wind power densities at well-exposed locations. Thus, the wind power density indicated on a map in an atlas, such as the annual average wind power density map shown in Figure 4-3, could be representative of a large or a small fraction of the land surface - depending on the complexity of the terrain or of the meteorology at a particular location.

Consider the following example: Figure 5-2 is a map of the average wind power density for the state of Washington. For some utilities, an area of this size could be a Region of Interest. Within this Region of Interest, a ridge runs along the edge of the Columbia River gorge that appears to have a high wind resource. This ridge line is within the box shown in Figure 5-2. The vicinity of this ridge line, which is shown to have a class 6 wind resource, might be considered a Candidate Resource Area. Figure 5-3 is a topographical map of a *portion* of this ridge line. In Figure 5-3, the boundaries of the Candidate Resource Area have been defined as the Columbia River on the south and the 2000-ft contour on the north. As the figure indicates, there is considerable variation in the topography over the Candidate Resource Area. Because of this variation in topography, it is likely that there is also significant variation in the magnitude of the wind resource along the ridge. In situations such as this, it is prudent to identify the best wind zones within the

Figure 5-2. Map of Annual Average Wind Power Density Class for the State of Washington. The box encloses a possible Candidate Resource Area

Figure 5-3. Topographical Map of a Portion of the Candidate Resource Area Identified in Figure 5-2

Candidate Resource Area (these zones would be the most likely places to experience the wind resource class indicated on the resource maps) and to choose potential candidate sites from within these zones. This is the strategy of Option A, and it is accomplished in three steps.

Step IIA-1: Identify the Best Wind Zones Within the Candidate Resource Area

Four substeps are involved in identifying the best wind zones within a CRA:

IIA-1a: Locate measurement stations within each Candidate Resource Area and obtain wind records.

IIA-1b: Select techniques for analyzing the wind resource. Several techniques can be used to analyze the distribution of wind resource over a Candidate Resource Area. These techniques include:

- numerical modeling
- physical modeling
- topographical indicators
- biological indicators
- geomorphological indicators
- social and cultural indicators.

In numerical modeling, the flow patterns over a section of terrain are determined by a computer code, which solves a complex set of partial differential equations that approximate the even more complex interactions between the atmosphere and the earth's surface.

Numerical models require information on the behavior of the wind and other meteorological parameters at the edges of the modeled region and on conditions at the earth's surface. This information is called boundary conditions. The quantity of information that must be supplied as boundary conditions depends on the type of model used. For some models, the boundary conditions can be supplied by the routine observations of the National Weather Service. Other models, however, may require special measurements that would greatly increase the cost of using the model.

Because of time and funding limitations, the usual approach when using numerical models is to obtain solutions for a limited number of meteorological conditions that are believed to represent the climatology of the modeled region. These solutions are

then combined to produce information on the variation of the wind resource over the Candidate Resource Area. This information and the professional judgment of the person interpreting the model's results (who may put more credence in some of the model's predictions than in others) is used to identify good wind zones.

Numerical models in the hands of knowledgeable users can be useful tools for identifying good wind zones within a Candidate Resource Area. Numerical models are not, however, a substitute for site measurements. Fairly accurate information on the diurnal and seasonal behavior of the wind is required before the economic viability of a wind turbine installation can be determined. Numerical models cannot supply wind information of this accuracy. There are several reasons for this. First, the models are imperfect. They employ approximations to the actual physics that govern the flow; thus their results must also be approximations. Second, knowledge of the boundary conditions is imperfect. The wind portion of the boundary conditions is only available at a few, scattered locations and is usually not of the quality needed to establish the economic viability of a wind turbine installation.* Lastly, the spatial resolution of numerical model results is usually very coarse. When applied to Candidate Resource Areas having linear dimensions of 30 to 100 kilometers (approximately 20 to 60 miles), the minimum spatial resolution will usually be 1 to 5 kilometers (0.6 to 3.1 miles) in the horizontal and 50 to 100 meters (approximately 160 to 330 feet) in the vertical.

Physical modeling is another technique that can be used to determine the location of good wind zones within a Candidate Resource Area - as long as the Candidate Resource Area is fairly small. Physical modeling consists of placing a scale model of the terrain into a wind or water tunnel and measuring the flow over the model. The size of the region that can be successfully modeled is usually limited only by the size of the wind or water tunnel facility. Very large facilities can probably model Candidate Resource Areas up to 20 to 30 kilometers (12 to 20 miles) in size.

One might think that physical modeling would be inherently more accurate than numerical modeling since the former is based on the flow of a real fluid over an accurate scale model of the terrain. Nevertheless, there can be problems when large reductions in scale are involved. Flow over modeled terrain may not always behave like flow over actual terrain when scale reductions of 5,000:1 or 10,000:1 are involved. Matching boundary conditions in a wind or water tunnel with the types of boundary

*These data will usually be routine surface wind observations, taken every three hours at elevations of a few meters above the surface. These observations may not represent conditions at the heights of wind turbine blades.

conditions observed in nature is also a problem; the limitation on the types of boundary conditions that can be addressed in physical modeling limits the accuracy of physical modeling results and the range of meteorological conditions to which physical models can be applied.

The term "topographic indicators" covers the techniques that have been traditionally used to find good wind sites. The traditional approach has been to analyze the available meteorological data, deduce the weather patterns that produce usable winds, determine the direction of these winds over the area of interest and locate the good wind zones by interpreting how local topography interacts with the air flow and other meteorological factors to either enhance or reduce the magnitude of the wind resource. Most of this interpretation is based on experience, intuitive understanding of how topography and flow interact, analogy with other apparently similar situations (a factor of experience), empirical guidelines (1) and meteorological "folklore". The accuracy of the traditional approach is difficult to assess. It obviously depends on the skill of the person doing the analysis and on how well he knows the area. The approach does work, however, as was shown by the British wind turbine siting program of the early 1950s (2).

When biological indicators are used, the effects of wind on the growth of vegetation identify the best wind zones. The effect of wind speed on the shape of trees is the most widely used biological indicator. Tree shapes (i.e., flagging) have been calibrated in terms of annual mean wind speed for various types of conifers and some deciduous trees by Hewson et al. (3) (also, see (1)). The use of this technique will require reconnaissance of the Candidate Resource Area by automobile or on foot, although skilled observers may be able to locate areas of significant tree flagging from low-level aerial photography (4). Users of biological techniques should realize that the relationships that exist between, say, tree shape and mean wind speed are approximate. Calibrations of tree shape in terms of mean velocity show large scatter and should not be taken literally; and even though the existence of a strongly flagged tree usually indicates a good wind site, the absence of flagging does not always mean that the winds at that location are light.

Geomorphological indicators of wind energy potential include active sand dunes and other landforms indicative of persistent wind erosion (1). These features, which can be detected from satellite or aircraft photographs, can be useful techniques for spotting windy areas in arid regions. The principal problem with geomorphological phenomena is that they do not discriminate between areas that experience strong persistent winds, and would make good wind turbine sites, and areas that only

occasionally experience strong winds. This discrimination must be made on the basis of other evidence.

Social and cultural indicators of wind energy potential include the opinions of persons who live or work in the Candidate Resource Area, patterns of land use and local folklore. For example, people dislike living or working in areas of persistently high wind speeds; therefore, high wind areas seldom coincide with population centers. Agricultural land use is another indicator of wind energy potential, since the windiest locations within a Candidate Resource Area are more likely to be used for grazing than for row crops. Place names and the impressions of local residents can be useful clues to the location of areas with good wind resources, but in using place names or opinion surveys as screening tools, one should realize that people tend to overestimate average wind speeds. The public's judgment is also highly biased by storms. Some areas that are thought to be windy could have fairly low average wind speeds and their reputations as windy places could be due to occasional strong wind storms.

Additional information on the strengths and weaknesses of individual techniques for wind resource analysis is provided in Appendix F of this report and in (1). Appendix F and (1) also indicate when and how these techniques can be applied to the siting process. As the previous paragraphs have indicated, each technique has its strengths and weaknesses; thus, the use of more than one analysis technique is strongly recommended. The proper combination of techniques as well as their accuracy will be site specific. Therefore, the assistance of a professional meteorologist or atmospheric physicist, experienced in the problems of flow over terrain, is essential to the design of appropriate procedures for the analysis of the local wind resource. Most meteorologists and atmospheric physicists have not had specific experience in wind turbine siting; thus, one should look for experience in related areas. Specializations that would indicate experience relevant to wind turbine siting include: air pollution meteorology (especially experience in complex terrain), boundary layer meteorology, and mountain meteorology.

IIA-1c: Obtain terrain data. For large Candidate Resource Areas, 1:250,000 scale maps give sufficient resolution and are appropriate, although larger scale maps (1:62,500 or 1:24,000) are available. In areas with significant terrain relief, raised relief maps (available in 1:250,000 scale) are helpful in visualizing topography, but details of the terrain shape may not be accurate. If numerical models are used in analyzing the wind resource, digitized terrain data will be needed. Topographic maps are available from

U.S. Geological Survey
1200 South Eads Street
Arlington, VA 22202

or

Branch of Distribution
U.S. Geological Survey
P.O. Box 25286
Federal Center
Denver, CO 80225

while digitized terrain data can be obtained from

The National Cartographic Information Center
U.S. Geological Survey
507 National Center
Reston, VA 22092

Attn: Information Unit/Digital Terrain Data Tapes.

The digitized terrain data available from the National Cartographic Information Center have been produced from standard USGS 1:250,000 maps by the Defense Mapping Agency. The maps contain only elevation data, data stored in a rectangular grid pattern. The horizontal resolution of the data is 208.33 ft, which should be sufficient at this stage of the siting process. If better resolution is required, standard 1:24,000 or 1:62,500 USGS maps can be digitized by the user.

IIA-1d: Identify best wind zones using appropriate analysis techniques. Once the appropriate analysis techniques have been selected, they are combined with the available wind and terrain data and the best wind zones within the CRAs are identified (see Appendix F and (1)). Some numerical modeling techniques may require additional wind data before they can be applied to CRAs with poor documentation of the wind resource (1). In this case, supplementary wind data would be required. The type of supplementary data would be dictated by the type of model, but it would probably entail the installation of several wind measurement stations around the CRA and the collection of data for at least one year.* The type of instrumentation that would be required to collect such data is discussed in Appendix G.

Step IIA-2: Screen the Best Wind Zones With Nonmeteorological Factors and Select Potential Candidate Sites

Once the best wind zones in a Candidate Resource Area have been identified, they are screened for parcels suitable for the installation of wind turbines (Potential Candidate Sites). This process will probably be fairly subjective because of the many

*The cost versus the potential benefits of such a step would have to be carefully considered. In the authors' opinion, such a step will seldom be justified. Existing wind resource data, combined with other site criteria, will usually be sufficient to locate potential candidate sites.

complicated and interacting factors involved. Potential Candidate Sites should be selected by a team experienced in the siting of other facilities. Potential Candidate Sites will be selected on the basis of their proximity to existing roads and power lines, the ease of access from these roads and power lines, the availability of the land for wind energy development and the acceptability of this development to local residents and the general public. Although all of these factors will be considered more or less simultaneously, the selection process can be thought of as proceeding in the following substeps:

IIA-2a: Evaluate location of best wind zones with respect to existing roads and transmission lines. Zones or portions of zones in reasonable proximity to suitable existing roads, transmission or distribution lines and substations should be favored as Potential Candidate Sites. Locations that would require running new access roads and transmission lines through sensitive environments or difficult terrain should be downgraded.

IIA-2b: Evaluate current and future anticipated land use. Because of the spacing required between individual units, a large wind turbine cluster will cover a significant land area. The use of this land does not have to be dedicated exclusively to the cluster. Other uses are possible, but they must be compatible. Uses that would be incompatible are those that call for fixed concentrations of people (such as dwellings) within or near the site. A primary concern would be safety - the remote possibility that someone would be injured by debris thrown from a turbine blade. Any existing or anticipated land use that would impede the free flow of wind into the cluster or would significantly alter the nature of the ground cover (i.e., surface roughness) would also be incompatible (see Section 2). Land uses that would be compatible with a wind turbine cluster are open space, grazing or farming (except tree farming). Land with incompatible uses would be passed over as Potential Candidate Sites, unless these uses could be changed.

IIA-2c: Identify places where a cluster of the desired size will fit. Areas must be identified that are large enough to contain a cluster of the desired size. Determining whether a plot of land is large enough to contain a given cluster is not as simple as it might seem, for the exact layout of the machines in a wind turbine cluster is dictated by the patterns of wind flow over the site and by the shape of the terrain. Constructing a wind turbine cluster having a regular geometric pattern will be impossible on land with any sort of terrain relief.

The exact placement of wind turbines within a site will not be determined until Stage IV of the site-selection process. The final layout of a wind turbine cluster will be the result of trade-offs between installation costs, which include the costs of obtaining the land occupied by the cluster, and revenue losses due to wake effects.* These trade-off studies will require better documentation of wind speed and wind direction patterns over the site than will probably be available by Stage II of the siting process.

In order to make sure that a given plot of land is large enough to contain a cluster of a given size, a preliminary layout should be made using conservative values for intermachine spacing and following the natural contours of the site. If the site were along a ridge, for example, the layout would follow the crest of the ridge. If the site were flat, a more geometrically regular layout could be used.

Current information on wind turbine wakes indicates that wind turbines can probably be spaced as close as 7 to 8 rotor diameters** in the prevailing wind directions and as close as 5 to 7 diameters (or even less) in the direction the wind rarely blows (1). In practice, however, a regular spacing between machines may not be possible since, as has been noted, the exact placement will be dictated by small-scale features of the topography and local variations in soil conditions. In order to provide sufficient land that final placement of the turbines can be flexible, a spacing of 10 to 15 diameters in the prevailing wind directions is a good number to use in constructing approximate cluster layouts. Spacings of 5 to 10 diameters can be used in the other directions. In some situations, however, the local prevailing wind direction may not be known; this is especially true in areas with significant terrain relief. In this case, it would be prudent to use a spacing of 10 to 15 diameters between machines in all directions. The approximate layouts can be done on maps with scales as small as 1:62,500.

In setting up these layouts, safety exclusion zones must be considered. The safety exclusion zone is a buffer around each turbine within which land use must be restricted in order to protect the general public from the remote possibility of rotor-thrown debris (contact wind turbine manufacturer for guidance). A Potential

*Each wind turbine in a cluster produces a wake with lower mean wind speeds and higher turbulence levels than the surrounding undisturbed flow. When one wind turbine is in the wake of another, the performance of the downwind machine will be reduced.

**The rotor diameter is the maximum distance across the area swept by the turbine blades.

Candidate Site would have to be large enough to ensure that these safety exclusions were not violated.

Protection of wind rights is also an important issue in identifying Potential Candidate Sites. As mentioned in Step IIA-2b and in Section 2, a cluster should be sited so that there will be no land use developments upwind of the site that would impede or reduce the flow of air into the cluster. For a ridge-top site, protection of wind rights would probably not be an issue, but on flat land, wind rights protection could require some restrictions on land use within a strip of land surrounding the perimeter of the cluster. In the prevailing wind directions, the width of this strip should be about ten times the height of the top of the rotor disk. If the minimum-sized cluster will not fit into a given plot of land, the cluster size that will fit should be noted, one may wish to reconsider this site for a smaller-sized installation.

The result of Step IIA-2c is a preliminary set of Potential Candidate Sites. This preliminary set is now screened, in Steps IIA-2d through IIA-2h, for any factors that could render one location less desirable than another as a potential site for a wind turbine cluster. This screening is preliminary and based on existing knowledge, not necessarily on site visits.

IIA-2d: Screen for unsuitable geology and meteorological hazards. Each of the preliminary Potential Candidate Sites is screened for any geological characteristics (such as soil or seismic conditions) that would render it unsuitable as a wind turbine site. Information on geological characteristics that would affect the suitability of a site should be available from turbine manufacturers. Each site is also reviewed for any topographical features in or around it that could result in high turbulence levels or strong wind shear (large gradients in wind speed or direction). The types of topographical features that could cause problems are discussed in (1).

IIA-2e: Review siting regulations and permit procedures for each site. A preliminary review is made of how Federal, state and local regulations affect each site. Particular attention should be given to FAA regulations (Section 2). Sites near airports or along the approaches to airports could pose problems. A list should also be made of the permits that would probably be required at each site in order to put a wind turbine cluster into operation.

IIA-2f: Evaluate probable public acceptance. Next, a preliminary assessment is made of probable public response to the development of a wind turbine cluster at each

location. Particular attention should be given to the probable attitudes of local public officials and land owners in and around the sites.

The following issues, among others, may be important in determining public acceptance (see Section 2):

- visual impact (both turbines and new transmission)
- electromagnetic interference
- noise
- compatibility with existing land use
- attitudes of local land owners.

IIA-2g: Evaluate environmental impacts. A preliminary evaluation of environmental impacts should be made at each site. The environmental impact of a wind turbine cluster should be similar to the impact of constructing and operating a major transmission line. The need for tree removal, for example, will be an issue if a wooded ridge or hilltop is chosen as a site. The possible effects of wind turbines on bird populations (Section 2) will also be an issue if the site is near a migration route or a place where birds congregate.

IIA-2h: Select Potential Candidate Sites. The preliminary set of Potential Candidate Sites is reviewed, and those that appear to have the best prospects for becoming sites for wind turbine clusters are chosen as Potential Candidate Sites. The reasons for eliminating sites should be fully documented. Conditions change. At a later date, some of the eliminated sites may become more attractive.

Constructing a site attribute matrix, analogous to Table 4-3, could be a useful tool in decision making. Instead of numerical scores, the matrix would consist of rows and columns of concise definitions of a site's attributes with respect to the various selection criteria (e.g., perceived magnitude of wind resource, current and future land use, probable environmental impact, and so forth).

SCREENING THE CANDIDATE RESOURCE AREA WITH OPTION B

Option B is used when the location of Potential Candidate Sites is more strongly influenced by nonmeteorological parameters (such as the location of roads) than by variations in the magnitude of the wind resource. The principal difference between the options is the order of the two steps.

Step IIB-1: Screen Candidate Resource Area Using Nonmeteorological Criteria

A preliminary set of potential candidate sites is identified through a process identical to substeps IIA-2a through IIA-2g.

Step IIB-2: Identify Locations With Best Wind Resources and Select Potential Candidate Sites

Each site in the preliminary set of Potential Candidate Sites is reviewed for its wind resource potential. All poorly exposed sites are eliminated and the remaining ones are designated Potential Candidate Sites. Analysis of the wind resource potential of the sites can be accomplished by applying any of the techniques outlined in Step IIA-1c.

TIME REQUIRED TO COMPLETE STAGE II

The time required to complete this stage of the siting process depends on the number, size and complexity of the Candidate Resource Areas. It also depends on the amount of information the utility may already have on the areas under consideration. Much of this knowledge may have been gathered during siting studies for conventional power plants. For relatively simple situations, Stage II can be completed in a man-week or less. More complicated problems will take longer. Completion time depends a great deal on the procedures used to analyze the distribution of the wind resource over the Candidate Resource Areas. Modeling studies require more time to complete than subjective analyses. Analysis of the wind resource distribution by means of biological indicators can also be time-consuming, particularly if this analysis is based on ground-based surveys. Considering all of these variables, completion of Stage II could take from one man-week to several man-months.

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Section 6

STAGE III: SELECTING CANDIDATE SITES

The product of Stage II is a set of Potential Candidate Sites. In Stage III, each Potential Candidate Site is ranked according to its economic potential, and the most viable sites are reviewed for any environmental impact, public acceptance, safety, and operational problems that would adversely affect their suitability as wind turbine sites. After this review, the most attractive sites are selected as Candidate Sites.

Stage III requires collecting data at each site. Therefore, provisions must be made for site access. These provisions will depend on land ownership and the number and the size of the Potential Candidate Sites involved. For government-owned land, the prospects for obtaining use of the land, as well as the probable terms of this use (purchase or trade, lease and terms on the lease), should be determined. For privately held land, an option to buy might be appropriate if owning the site is perceived to have advantages over a long-term lease. The problems of obtaining land access should not be different for wind turbines than for other, more conventional, facilities. Therefore, a utility should be able to follow its customary procedures.

It is assumed that a reasonable number of Potential Candidate Sites have been identified in the previous step. If the number of Potential Candidate Sites is too large, the sites should be given a rough priority ranking and the highest-ranking sites investigated first. This ranking is based on a subjective judgment of the cost of installing turbines at the sites, magnitude of the wind resource and the certainty of this wind resource.

A flow chart depicting the selection process in Stage III is shown in Figure 6-1. As with all other portions of this methodology, those steps that are unnecessary or inappropriate in a particular application should be bypassed.

Data that could be needed for completing Stage III are:

- all data that were obtained to carry out Stage II
- wind turbine performance characteristics and wind turbine costs

Figure 6-1. Activity Flow Chart for Stage III:
Selecting Candidate Sites

- all data needed to estimate complete installation costs and operation and maintenance costs
- detailed characteristics of the site - topography, ground cover and surface roughness, prevailing wind directions, risk of meteorological hazards
- specific information on public attitudes to wind turbine development at each Potential Candidate Site
- information on potential environmental impacts at each Potential Candidate Site.

DETERMINING ECONOMIC POTENTIAL

The approach to determining economic potential is to make preliminary estimates of installation costs and operation and maintenance costs at each Potential Candidate Site. These costs should include all factors affecting installation and operation and maintenance (access roads, substations, new transmission, site preparation, travel time to site, cost of maintaining access, etc.). These estimates should account for the specific factors that will cause these costs to vary from site to site. Based on these improved cost estimates, the minimum wind speed required to meet a cost of energy goal is determined at each site. Sites are ranked according to a judgment of the probability that the site will exceed the required wind speed minimum. These probability estimates should be made by people experienced in analyzing flow over terrain.

The approach of letting the economics dictate the required wind speed has been chosen because at this stage of the siting process, estimates of capital and operation and maintenance costs at each site should be more accurate than knowledge of wind characteristics. In situations where there are little onsite data, it is easier to estimate (and to justify) the probability that a site will experience a mean wind speed greater than some given value than it is to estimate the mean wind speed itself.

The process of determining the economic potential of the Potential Candidate Sites is as follows:

Step III-1: Site Visit

Each site is visited by a team with experience in site engineering, meteorology and environmental impact assessment. All data needed to estimate the costs of installing the machines (including costs of land and of solving potential problems, such as electromagnetic interference), operating the machines at the site and performing necessary maintenance are determined. The data needed for obtaining these estimates

are given in Appendix D. Any site-specific information needed to estimate potential environmental impact should also be gathered.

The team should note the topography within and surrounding the site, ground cover, prevailing wind direction (if indicated by vegetation at the site), vegetative indices of wind power potential, and the likelihood of meteorological hazards such as large wind shear, turbulence or icing. Measurements with wind sensing kites or tethered balloons could be made if the opportunity arose. The purpose of the kite or balloon measurements would be to document possible wind shear or turbulence problems.

Step III-2: Compute Break-Even Wind Speed

Using site-specific installation and operation and maintenance costs, break-even hub-height wind speeds are computed for the cost of energy goal. The procedure is identical to the one used in Step I-1; the only difference is that the estimates are now based on site-specific estimates of installation and maintenance costs. Thus, the estimates of the break-even wind speed will vary from site to site.

III-2a: Determine cost of energy goal. In Step I-1, the levelized production cost for peaking power was chosen as the cost of energy goal. This is a very liberal assumption and it was made so that all areas that had any chance of containing viable sites would be kept under consideration. Now, more realistic cost goals must be established, since the objective in Stage III is to identify only those sites with the best economic potential. The levelized average marginal production cost is suggested as the most logical cost of energy goal to use at this stage of the siting process. Determining this cost is discussed in Appendix C.

III-2b: Determine site-specific installed capital cost and operation and maintenance expenses. Using the information obtained during the site visits, installation costs and annual operation and maintenance expenses are estimated at each site and for each turbine under consideration (see Appendix D). Consultation with wind turbine manufacturers is strongly recommended. Given specific information on the sites under consideration, a manufacturer will be able to provide more accurate estimates of installation costs. Manufacturers may also be able to advise the utility as to which sites are most feasible for their turbines.

III-2c: Determine annual fixed-charge rate and levelizing factor. The annual fixed-charge rate is a factor that when multiplied by the installed capital cost of a wind turbine yields the levelized revenue required over the lifetime of the equipment to

support the fixed costs of that investment. The levelizing factor is a parameter that, when multiplied by the estimate of operation and maintenance expenses, yields the levelized revenue required to operate and maintain the turbine. The levelizing factor accounts for the effect of inflation on operation and maintenance costs. The determination of fixed-charge rates and levelizing factors is discussed in more detail in the EPRI Technical Assessments Guide (1).

III-2d: Determine required annual energy production. The amount of electric energy that must be produced annually in order to meet the cost of energy goal is now determined. This quantity will vary from site to site and it will depend on the wind turbine model under consideration. This quantity is determined by the following equation:

$$EP = \frac{(IC) \cdot FCR + (OM) \cdot LF}{COE} \quad (6-1)$$

where

IC = installed capital cost per wind turbine

FCR = annual fixed-charge rate

OM = operation and maintenance cost

LF = levelizing factor

COE = levelized cost of energy goal.

III-2e: Determine the annual break-even wind speed. The annual break-even wind speed is the minimum average wind speed that a given wind turbine must experience in order to produce a quantity of electric energy equal to EP. This requires knowledge of the relationship between annual energy production and the annual average wind speed (see Figure 4-2).

Step III-3: Score Potential Candidate Sites

As mentioned in the introduction to this section, the economic potential of each site is evaluated by estimating the probability that the annual average wind speed exceeds the break-even value. This probability is assessed for each site, and the site is scored on the basis of whether exceeding the break-even wind speed is *highly probable, likely, unlikely or highly unlikely*.

Exceeding the break-even wind speed is judged highly probable if at least one year's wind data have been measured at the site, and a conservative vertical extrapolation

of these data (see Appendix F) indicates that the break-even hub-height wind speed would be exceeded in most years. A site's potential could also be scored *highly probable* if corroborative wind data were available from nearby locations (less than about 10 to 20 miles away) and both the nature of the terrain and climatology indicated that the wind at the measurement station should have characteristics similar to the site. Examples of situations where this assumption is appropriate are large, flat plains well removed from mountains or flat coastal areas where the wind measurement station is about as far inland as the potential site.

Exceeding the break-even wind speed is likely if strong climatological evidence supports the conclusion that winds at the site equal or exceed break-even values in most years even though there may not be any supporting measurements at or near the site. An example of a situation that would be scored *likely* is as follows: Assume that a Potential Candidate Site is located along the top of a ridge line. Examination of climatological data (such as maps of mean wind speed) shows that wind speeds in the free atmosphere and at the elevation of the ridge top are large enough that when reasonable allowances are made for the retardation of the wind due to surface effects (see (2), Chapter 5), the expected mean wind speed still equals or exceeds the break-even value.

Exceeding the break-even wind speed would be rated unlikely if climatological evidence supports the conclusion that winds at the site are below break-even values in most years. A site could also be rated *unlikely* if short-term onsite data (i.e., wind data collected at the site over a period of one year or less) indicated that the annual average wind speed was slightly below break-even values (see (3) for a method of estimating annual average wind speed with less than one year's data).

Exceeding the break-even wind speed would be rated highly unlikely if representative wind data or strong climatological evidence showed the expected wind speed to be well below the break-even value.

Table 6-1 suggests a scheme for assigning numerical values to these probability judgments.

Table 6-1

SUGGESTED METHOD FOR SCORING THE PROBABILITY
OF EXCEEDING THE BREAK-EVEN WIND SPEED AT A SITE

<u>Probability of Exceeding Break-Even Wind Speed</u>	<u>Value of Break-Even Wind Speed (BE) Parameter</u>
highly probable	3
likely	2
unlikely	1
highly unlikely	0

In scoring each Potential Candidate Site, the scorer determines the probability that the average wind speed for a given season would exceed the break-even value for a particular wind turbine. The scheme presented in Table 6-1 requires choice of an integer value for the break-even wind speed parameter. Fractional values are not allowed. In other words, the scorer must definitely decide whether the probability of exceeding the break-even wind speed is *highly probable*, *likely*, *unlikely*, or *highly unlikely*. In each case, the scorer is required to note the evidence that led him to his decision.

Scoring of the Potential Candidate Sites could be done by a single individual or a Delphi-type panel of experts. In the panel approach, each panelist would score the sites anonymously and the individual scores would be averaged. The panel approach has definite advantages. It recognizes that many of the probability judgments will be difficult and that there will be a diversity of opinions.

Step III-4: Eliminate Uneconomic Sites

Once the economic potential has been evaluated at each Potential Candidate Site, those sites having poor prospects are eliminated. Eliminating a site is obviously a severe, but necessary, step. In doing it, one must be certain the judgments on the magnitude of the wind resource at the site are accurate and that the required break-even wind speed is based on realistic cost estimates.

Important Note: Knowledge of the wind resource and estimates of wind turbine costs will both improve and change over the next 10 to 15 years. A utility should periodically reevaluate previously unacceptable sites to see if changes in knowledge of the resource, changes in wind turbine costs or changes in economic conditions have caused previously uneconomic sites to become economically attractive.

Step III-5: Select Economically Viable Sites

Next, the most economically attractive sites are identified for consideration as Candidate Sites. The number selected for consideration will depend on the number of sites desired and the number of Potential Candidate Sites that truly appear to be economically attractive. Sites with the highest probability of exceeding the break-even wind speed ($BE \sim 3$ from Table 6-1) are obvious candidates for further consideration. High values of the break-even wind speed parameter indicate a high degree of confidence in the magnitude of the wind resource at the site and a significant differential between the expected and break-even wind speeds. The difficult decisions will center on the sites that consistently show break-even wind speed parameters of about 2 (that is, the probability of exceeding the break-even wind speed is "likely"). Sites show break-even wind speed parameters in this range when there are no representative wind data at or near the site and evidence of economic viability is indirect.

If Candidate Sites must be chosen from Potential Candidate Sites in the "likely" category, a preliminary site measurement program may be necessary.* Each site selected for a preliminary measurement program would be instrumented with one or more meteorological towers. The size of the towers would be set by the trade-offs between desired accuracy and cost. The number of measurement locations would depend on the size and topographical complexity of the Potential Candidate Site. Hub-height wind data are desired; thus, the higher the tower, the greater the accuracy in estimating wind turbine output (see Appendix B). Higher towers cost more, however, and cost would limit the number of Potential Candidate Sites that could be monitored. A preliminary measurement program should last at least one year; this is the minimum time in which reasonably accurate estimates of annual energy production can be determined.

Once a decision to conduct a preliminary site measurement program has been made, at least two options are opened. The least expensive option is to measure average mean wind speed over some period such as a week or a month. This type of data can be collected with very simple and very inexpensive equipment such as a wind-run anemometer (see Appendix G). Mean wind speed measurements could be made on fairly low towers

*A preliminary measurement program is not mandatory. Such a program will increase the length of time it takes to identify Potential Candidate Sites, and many utilities may wish to delay all site measurements until Stage IV of the siting process. A preliminary measurement program is suggested when a utility is faced with selecting Candidate Sites from a large number of Potential Candidate Sites with poor wind documentation. The preliminary measurement program is designed to identify the Potential Candidate Sites that have real economic potential.

(higher than surrounding trees or obstacles, however) and the mean values extrapolated to hub height using conservative procedures.* Once one year's data had been collected, annual average wind speeds at hub-height would be compared with the corresponding break-even values, and the Potential Candidate Sites would be ranked by applying the procedure of Step III-3.

A more expensive option is to measure the wind speed probability density function (PDF) directly.** Since this type of data is sufficient for estimating wind turbine output, the ranking of Potential Candidate Sites would be based on the differences between the estimated annual energy production and the annual energy production required to meet the cost of energy goal (Eq. 6-1). The ranking procedure is outlined as follows:

III-5a: Determine annual probability density function. At each Potential Candidate Site that is equipped with a meteorological tower, fit a Weibull function (see Appendix F) to the observed wind speed probability density function.***

III-5b: Compute range of expected energy production. Given the observed mean wind speeds and the Weibull fits to the observed probability density functions, estimate the expected uncertainties in the Weibull parameters (see Eq. B-12, for example). Estimate the range of expected annual energy production based on the uncertainties in the Weibull parameters (see Appendix B).

III-5c: Rank Potential Candidate Sites. The minimum and maximum differences between the expected annual energy production and the annual energy production required to meet the levelized cost of energy goal are computed for each Potential Candidate Site.

*Mean wind speeds are usually extrapolated by means of the so-called "power law": $v_2/v_1 = (z_2/z_1)^\alpha$ where v_2 and v_1 are the wind speeds at altitudes z_2 and z_1 , respectively. Formulae exist for estimating α but they are very imprecise. Assuming $\alpha = 0$ is the most reasonable conservative assumption, particularly for sites on ridges or hilltops; however, one may wish to look at a range of α s based on the prediction formulae.

**If it is not too expensive, a utility may wish to begin collecting data on the temporal behavior of the wind in order to get a head start on completing the next stage of the siting process (Stage IV). These data could be time series of wind speed and direction or they could be summarized data that can be converted into PDFs as a function of time of day and joint frequency distributions of wind speed and direction. The format would depend on the way the wind turbine performance is to be modeled (Appendix B). Data on the temporal behavior of the wind should only be collected at or near hub height, however. Extrapolating this type of data from near-surface measurements to the hub height of large wind turbines could result in significant errors (see Section 7).

***Basing energy estimates on a Weibull fit allows one to perform a sensitivity analysis as is described below.

Sites are ranked on the basis of the differences between expected and required energy production. Estimates of the maximum and minimum values indicate the degree of uncertainty in the rankings.

This ranking procedure (Steps III-5a through III-5c) is repeated for all wind turbines under consideration.

EVALUATING ENVIRONMENTAL AND SOCIAL FACTORS

The most economically viable of the Potential Candidate Sites are now reviewed for any noneconomic factors that could affect their suitability as sites for wind turbine clusters. Each site was screened during Stage II, so sites grossly deficient in this area should have been eliminated. Many environmental and social factors, however, cannot be evaluated properly on the scale of a candidate resource area (the scale considered in Stage II). Thus in this screening, one should emphasize those noneconomic factors that can only be properly evaluated after each site has been visited. The purpose of the screening is to review each factor and note any problems.

Step III-6: Environmental Impact

An assessment of environmental impact will be required before development of any of the sites can proceed. At this stage of the siting process, the only environmental factors of interest are those that could significantly complicate the development of a site. A full environmental impact assessment would not be performed until after a decision has been made to install turbines at a particular site (i.e., until after Stage IV). The data needed for an environmental impact assessment will dictate the observations needed at a Potential Candidate Site. As mentioned in Stage II, the environmental impact of wind turbine clusters will be similar to that of transmission facilities. The problems unique to wind turbine systems were reviewed in Section 2.

Step III-7: Evaluate Public Acceptance

The issues affecting public acceptance were reviewed in Section 2 and a preliminary assessment of probable public assessment was made in Stage II (Section 5). At this stage of the siting process, however, a more definitive reading of probable public attitudes is needed. If the number of Potential Candidate Sites is not too large, public hearings might be appropriate. As mentioned previously, the attitudes of local public officials and nearby land owners are important. The best approach to gauging public opinion will depend on local circumstances. It is assumed that each utility has developed its own approach in this matter.

Step III-8: Review Regulations and Permit Procedures

The effects of Federal, state and local ordinances, siting regulations and permit procedures should be reviewed for each site. Any significant differences in how these regulations and procedures could affect site development costs and schedule should be noted.

Step III-9: Evaluate Safety and Security

Safety problems can arise in two ways: injury to the general public from the remote possibility of rotor-flung debris and injury to the public from unauthorized access to equipment. Maintaining proper exclusion zones will solve the flying debris problem. The problem of unauthorized access will be similar to that at substations and transmission towers. Vandalism by hunters or shooters is likely to be the most serious security problem. The magnitude of this problem will be proportional to the amount of use of the area by these individuals. Problems of unauthorized access and vandalism are not new; utilities will be able to determine whether these problems will be a serious concern at a particular site on the basis of previous experience.

Step III-10: Evaluate Meteorological Hazards

Each site should be reviewed for meteorological hazards that could affect wind turbine operations, maintenance costs, or in extreme cases, structural integrity. The most important hazards are (see Section 2):

- icing
- extreme winds
- turbulence
- salt
- dust, grit, etc.

The review of potential hazards will be based on the local climatology, the exposure of the site, the elevation of the site and the nature of the topography in and around the site. Given such information, and input from persons familiar with the general area of the sites (utility maintenance personnel and transmission design groups, for example), a meteorologist can make a subjective estimate of the risk of experiencing these hazards. The meteorologist should be able to quantify these risks (how much icing, whether turbulence levels might be low or high, and so forth) - at least approximately.* However, a judgment on the significance of these hazards at any site would require information from the wind turbine manufacturers.

*See (2), Chapters 5 and 6.

SELECTING CANDIDATE SITES

Results of the survey of environmental and social factors should be noted for each Potential Candidate Site. The sites having the best economic prospects and showing no significant environmental or social problems should be selected as Candidate Sites. One way of making the selection is to score each site according to the scoring procedure presented in Table 6-2. The results of the scoring could then be displayed in a matrix format similar to that shown in Table 4-3.

Table 6-2
CATEGORIZING THE RESOLVABILITY OF ENVIRONMENTAL FACTORS,
SOCIAL FACTORS AND METEOROLOGICAL HAZARDS

<u>Resolvability Score</u>	<u>Description</u>
0	Factor presents unresolvable problems
1	There is currently insufficient information to determine resolvability
2	Factor appears resolvable, but at a high cost
3	Factor appears resolvable at a negligible cost
4	Factor does not exist at the site

TIME REQUIRED TO COMPLETE STAGE III

The amount of time spent at this stage is largely dictated by the number of Potential Candidate Sites to be analyzed and whether or not a preliminary site measurement program is conducted. Actual site visits should take only a few hours to complete. Most of the time involved will be consumed in travel to and from the site locations. A preliminary site measurement program will take more than a year. Time will be required to plan and organize the program, order the equipment, install it, collect the data and analyze it.

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Section 7

STAGE IV: SELECTING PREFERRED SITES

By this stage, the siting problem has been reduced to the analysis of a small number of Candidate Sites. The goals of Stage IV are:

- to document the wind characteristics at each site with sufficient accuracy that accurate estimates of wind turbine energy production can be made
- to develop preliminary engineering designs for each site and to determine accurate costs for developing those sites
- to estimate the economic value of each site
- to determine the effects of wind turbine output at each site on the utility system
- to ensure that the character of the wind resource is compatible with the design criteria from which the wind turbine's service lifetime has been projected
- to conduct a final review of the environmental and social impact of each wind turbine installation.

Up to this point in the siting process, the economic evaluation of wind turbines has been based on cost of energy considerations. However, in most situations cost of energy is not a very good indicator of the value of wind turbines compared to conventional generating equipment (see Section 2 and Appendix C). Wind, of course, is an intermittent and somewhat unpredictable energy source. The value of wind energy will depend on a utility's generation mix and on how wind-generated electricity interacts with its load. If wind-generated electricity is consistently available during periods of peak load, it will have more value than if it is available at other times. Determining how wind-generated electricity will affect a utility's load requires site-specific wind data with sufficient temporal resolution to enable estimates of energy production to be made on at least an hourly averaged basis. The wind data gathered at a site must be representative of the flow through the rotor disks of each machine in a wind turbine cluster. For large, multi-turbine sites, wind measurements might be required at a number of locations in order to characterize flow over the entire site. These measurements will be more extensive than any that may have been made in Stage III.

Current experience suggests that wind turbine performance can be estimated with acceptable accuracy using hub-height wind data (see Appendix B). There are two ways of obtaining such data: by making wind measurements at the hub heights of the various wind turbines under consideration or by extrapolating near-surface wind data to these elevations. Collecting hub-height wind data for large, horizontal-axis wind turbines is considerably more expensive than measuring at altitudes of 10 to 15 meters. However, hub-height measurements are highly desirable because the uncertainties in extrapolating near-surface wind data to altitudes of 60 to 80 meters are great. The behavior of the wind profile over height differences of this magnitude is not very predictable, particularly over surfaces with nonuniform surface roughness or significant variations in elevation. As is shown in Appendix B, errors of 50% or more between estimates of wind turbine output based on extrapolated data and estimates of output based on the actual observations are possible and errors greater than 25% are common. Nevertheless, the installation of a data system for measuring hub-height wind data will have to be justified. This justification depends on the cost of making the measurements, the cost of the wind turbine installation and the consequences of failure. If the cost of a detailed program of wind measurement and economic analysis such as outlined in this section is a significant fraction of the cost of installing a wind turbine at a site, one might consider bypassing many of the steps in Stage IV and installing a turbine at one of the higher ranking Potential Candidate Sites. If the site proved to be a poor choice, the turbine could be moved to a new location (one would not want to make too many such moves, however). If, on the other hand, the cost of a detailed analysis program were small compared to the cost of the installation, or if an initial failure might prove fatal to future wind turbine projects, one should probably follow the procedure outlined for Stage IV in detail.

A rigorous application of the steps in Stage IV requires knowledge of the flow through a section of the atmosphere 100 to 150 m deep and having horizontal dimensions equal to the size of the wind turbine site. Thus, the first step in accomplishing the goals of Stage IV is to determine the number and location of the meteorological towers needed to document the wind resource. At the same time, collection of the data needed to assess environmental impact should begin. Collection of the engineering data needed to establish the costs of site development could also begin, but the final layout of the cluster would await the collection of sufficient meteorological data to establish both the nature of the flowfield (both speed and direction) over the site and whether or not the wind resource is sufficient to be truly economic. Once sufficient documentation of the wind resource has been obtained, a detailed analysis of the economics of each site can be made. Selection of preferred sites

would be based on differential value comparisons. More than one type of wind turbine could be under consideration at each Candidate Site; thus, a complete analysis could be required for each prospective turbine.

A major unresolved question is how long the meteorological measurement program should last at a given site. This measurement program has three objectives: to determine the wind characteristics needed to lay out the individual turbines in a cluster; to document the wind characteristics needed to model the cluster's performance; and to ensure that machines installed at the site will be operationally successful (for example, that the number of startup and shutdown cycles will not be excessive, and so forth). The time needed to satisfy these issues will vary with the nature of the site and the nature of the utility system. Consider the question of economic value as an example: Sufficient wind data must be collected in order to determine how the electric energy produced by a wind turbine cluster will affect production costs for the utility. If the economic impact of wind-generated electricity can be estimated with sufficient accuracy from the net energy production of the cluster over a given period (such as a season), a single year of data collection might be sufficient.* With a year's data, estimates could be made of the average annual energy production and of the average energy production for each season. It would also be possible to make reasonable estimates of the uncertainties in these values (see Appendix B). If the consequences of the uncertainties were acceptable, a utility could conclude that sufficient data had been taken. If the consequences of the uncertainties were not acceptable, a longer period of measurement might be required. If, on the other hand, the economic impact were a strong function of how the cluster modifies the utility's load, more than a year's data collection would probably be necessary. In this latter case, the length of the data collection period would depend on how the wind characteristics that affect load modification (such as the diurnal modulation of wind speed) might vary from season to season and from year to year. In the final analysis, a decision on how long to measure would rest on the differentials between costs and savings and on the sensitivity of these differentials to uncertainties in the key wind characteristics (see Appendix B for more information on the uncertainties in predicting how wind turbines will behave at potential sites).

Figure 7-1 is a flow chart outlining the sequence of steps required to complete Stage IV. The data that might be needed to complete these steps are:

*This case could occur if production costs were not strongly dependent on load or if wind-generated electricity was potentially cheaper than the electricity generated by the lowest cost unit in a utility's generating mix.

Figure 7-1. Activity Flow Chart for Stage IV: Selecting Preferred Sites

- meteorological data required to simulate electric energy production and to determine probable performance (see Appendix B)
- all environmental and social data needed to satisfy siting regulations and to obtain required permits
- all engineering data needed to design a complete wind turbine cluster (see Appendix D)
- all data needed to estimate site development costs
- all nonmeteorological data needed to run production cost models
- performance characteristics and operating strategy for wind turbines under consideration (see Appendix B)
- information on potential meteorological hazards.

As in Stage III, consultation with the wind turbine manufacturers is advised. The manufacturer may be able to recommend hardware modification, changes in wind turbine control software or changes in installation procedures that could improve performance or reduce installation costs.

COLLECTING THE REQUIRED DATA AND REASSESSING PRELIMINARY ECONOMIC VIABILITY

Step IV-1: Design Required Meteorological Measurement System

The first step in Stage IV is to design the measurement system that will be needed to collect the required meteorological data. Good wind data are critical, and the resulting measurement system must give sufficient understanding of the air flow over the site to determine the location of each wind turbine and to simulate the performance of these turbines. The principal wind turbine performance issues are:

- Electric energy production by the wind turbine cluster - How does it affect production costs for the utility system?
- Operational behavior of individual turbines - How do estimates of the number of startup and shutdown cycles and yawing maneuvers vary between sites?
- Dynamic behavior of the cluster - What are the power flows between the cluster and the utility system and what effects might they have on the local transmission and distribution system substations, utility system stability, system frequency excursions, and ramping limitations on conventional generation?

Appendix B discusses the modeling of wind turbine performance and the meteorological data required for addressing the performance issues. Appendix G reviews current instrumentation and discusses the type of instrumentation systems (platforms, transducers, data recording devices) that are appropriate to wind turbine siting. At the

present time, conventional instrumentation (towers equipped with standard, rugged anemometers) makes the most sense. The choice in data loggers, however, is broader. It is limited mainly by recording format, required data rate, and price.

Current experience suggests that satisfactory estimates of wind turbine performance can be made with hub-height wind data. For large horizontal-axis wind turbines, hub-height wind measurements may require meteorological towers higher than 61 m (200 ft); such towers require proper lighting and FAA approval (see Section 2). The data requirements for estimating turbine performance are:

- horizontal components of the wind vector (1 to 10 min averages, time series format - see Appendices B and G for details)
- temperature.*

The number of towers needed to determine the distribution of the wind resource over a Candidate Site and their placement will depend on the size of the site and the complexity of its topography. Numerical and physical models can be useful in addressing this problem. Hiester and Pennell (1) discuss designing the layout of such a measurement system in more detail.

Step IV-2: Prepare Environmental Impact Statement for Meteorological System Installation

Placement of large meteorological towers on a Candidate Site may require preparation of an environmental impact statement. During preparation of the statement (if required), one should also note any environmental or social issues that might affect the eventual installation of wind turbines. Collection of the detailed information that will be needed in preparing an environmental impact statement for the wind turbine installation will wait until an actual site has been identified (that is, until after the completion of Stage IV).

Step IV-3: Collect Required Meteorological Data

Once the meteorological data system has been designed and the necessary approvals and permits obtained, the system is installed and data collection begins. As previously mentioned, the minimum period for data collection should be one year. Particular attention should be given to quality control. Tests must be conducted in order to assure calibration of the sensors. Methods for assuring high data recovery rates

*Temperature is needed for computing air density. However, temperature may also be estimated from nearby weather station measurements. Barometric pressure can be estimated from site altitude with sufficient accuracy for making density calculations.

must be devised. This will require continuous analysis of the data as it is obtained and development of procedures for the rapid correction of data system failures. Quality control is discussed in more detail in Appendix G.

Step IV-4: Reassess Economic Viability of Wind Turbines at Each Site

Once a year of site wind data has been collected, one should reassess the economic viability of a wind turbine cluster at each site in question. In this reassessment one examines the effect of wind turbine energy production on production cost savings using an appropriate production cost model. The impact of wind turbine generators on the energy production costs of utilities has been the subject of several recent studies (see Section 2), and suggestions have been made as to how to modify existing generation expansion models to account for wind turbines. Procedures for estimating the economic value of wind turbines are discussed in more detail in Appendix B. The estimates of annual production cost savings are compared with Stage-III estimates of installation costs. If the comparison is favorable, one moves to the next step in this siting procedure. If the comparison is unfavorable, one could abandon the site, collect additional wind data, or hold the site in reserve until changes in economic factors make the site more attractive.

Step IV-5: Collect Engineering Data Necessary for Cluster Design

All data that are necessary to complete the design of a wind turbine cluster are collected at each candidate site. These data are discussed in Appendix D.

DESIGNING CLUSTER LAYOUT AND ESTIMATING COSTS

Step IV-6: Determine Cluster Layout and Wake Effects

Before designing the layout of a multiple-turbine cluster, sufficient meteorological data must be collected to establish the prevailing wind directions and the distribution of the wind resource over the site. However, design of the cluster layout is not dictated solely by the distribution of the wind resource. Design of the cluster is an iterative process that considers installation costs, distribution of the wind resource, wind turbine wake effects, environmental impacts, electromagnetic interference problems, and so forth. The proper solution is the one that results in the largest differential between production cost savings and installation costs while still satisfying the pertinent environmental constraints.

It is important to realize that each time a significant change is made in the position of machines in the cluster, the performance of the cluster (i.e., its power or energy output) may also change. These changes could result from variations in the

strength of the wind resource over the site or from changes in how the wakes of individual machines affect the performance of downstream units. Wake effects could be important factors in the design of large clusters with several rows of machines along the prevailing wind directions. Chapter 9 of (1) reviews current knowledge of wind turbine wakes and discusses procedures for determining the effect of wake interactions on the performance of wind turbine clusters.

Step IV-7: Determine Dynamic Impacts on the Utility System

Because the wind driving a group of turbines is turbulent, the power output of a cluster will show rapid (and sometimes large) fluctuations. These fluctuations could affect the dynamics of a utility system, so this possibility should be investigated (see Section 2). Zaininger (2) has identified three classes of dynamic problems that could affect the entire utility system:

1. short-term transient stability
2. system frequency excursions
3. minute-to-minute unit ramping limitations of the conventional system generation.

Intercluster dynamics (i.e., interactions between individual machines) and the potential effects of wind turbine output fluctuations on local transmission and distribution lines may also be important and should be investigated.

Looking at the impacts on the entire utility system, Zaininger found that dynamic impacts could limit wind turbine penetration, especially for small, isolated utilities. Zaininger also found that the nature and magnitude of these impacts are site specific. Thus, a proper evaluation of the dynamic impacts problem requires site-specific wind data. The principal problem is that there are no verified models currently available for converting site wind data into realistic simulations of the minute-to-minute output of individual turbines or clusters (see Appendix B). In the absence of such models, one must be satisfied with an indirect analysis of the problem (2). In using this approach one would determine the time scale and magnitude of the power fluctuations that could cause problems. A judgment would then be made on whether such fluctuations are probable.

The dynamic impacts of wind turbines on utility systems is a topic that clearly needs more work. The Electric Power Research Institute is sponsoring a project to develop a procedure for analyzing dynamic impacts. This procedure will be available to utilities in the near future. In the meantime, more information on the subject can be found in a DOE-sponsored study (3).

Step IV-8: Estimate Site Development Costs

Installation costs are now estimated for each of the wind turbine installations. These estimates include the costs of purchasing and installing each machine; the costs of access roads, electrical interties, substations and transmission lines; and the costs of any modifications that must be made to the existing utility system to make it compatible with the turbine installation. Estimates of the operation and maintenance costs for the proposed installations should also be made. Procedures for making these estimates are discussed in Appendix D.

DETERMINING FINAL ECONOMIC AND OPERATIONAL VIABILITY

Step IV-9: Update Economic Analyses

If there has been a significant time delay between the completion of Step IV-4 and the beginning of this step, analysis of production cost savings should be updated using the additional wind data collected. In addition, the sensitivity of calculated production cost savings to uncertainties in the wind resource should be tested. If this sensitivity is large enough to affect differences between production cost savings and site development costs significantly, an additional year of wind measurement at the site may be necessary. Methods for testing the sensitivity of estimates of net energy production to uncertainties in wind characteristics are discussed in Appendix B.

Step IV-10: Evaluate Wind Characteristics Affecting Wind Turbine Operations

The most important wind characteristics affecting the operational behavior of wind turbines are wind direction variability and the behavior of the wind speed in the neighborhood of a wind turbine's cut-in and cutout speeds. These wind characteristics govern the number of startup, shutdown and, in the case of horizontal-axis turbines, yawing operations that a machine would undergo in normal operation. Since startup, shutdown and yawing put significant stresses on a wind turbine system (4), the annual number of these operations could affect wind turbine maintenance costs as well as service life of the equipment. Differences in the number of these operations could be an additional factor to use in comparing sites; however, their significance as a site-selection factor would have to be determined in consultation with the wind turbine manufacturer.

If a "quasidynamic" simulation of wind turbine energy production has been performed (see Appendix B), the number of startup, shutdown and yawing operations over the period of the simulation is easily determined. If a "static" simulation has been used (again, see Appendix B), the number of startup, shutdown and yawing operations

could be assumed to be proportional to the variances of the two horizontal wind components; however, the exact relationships would have to be determined for each wind turbine model.*

Step IV-11: Update Estimates of Meteorological Hazards

As was mentioned in previous sections, the most important meteorological hazards are:

- icing
- extreme winds
- airborne salt
- dust, grit, etc.
- turbulence.

Information sufficient to estimate the importance of the first four hazards should have been gathered in Stage III, so sites that would be unsatisfactory due to any of those problems should have been eliminated. In addition, sites suspected to experience high levels of turbulence due to nearby topographical features should also have been eliminated. Picking sites on the basis of rules developed through the study of flow over simple, isolated terrain features in wind tunnels or in numerical models, however, does not guarantee that a site will be free of turbulence-related problems. These generic guidelines are seldom infallible. This conclusion is particularly true when topography in and around the site is complicated.

It should also be noted that there has not been sufficient experience with large wind turbines to establish how important turbulence might be as a siting factor (see Section 2). Many persons associated with the design of large turbines believe that turbulence is not a factor at all, arguing that turbulence-related loads are not significant when compared with other design loads. Others, however, think that more operational experience is needed before this conclusion can be made for all models of wind turbines and all types of sites.

Since atmospheric turbulence is fairly well-behaved over flat ground, turbulence would only be a selection factor for sites in or near complicated terrain, that is, in places where the local terrain relief in and around the site equals or exceeds the rotor diameter of the wind turbine. Selecting sites in rugged terrain might

*Variance as a function of wind speed would probably be a most appropriate parameter to use since variance in the neighborhood of the cut-in and cutout wind speeds would be a factor in determining the number of startups and shutdowns.

require onsite measurements for proper evaluation of the turbulence factor. Some turbulence information (e.g., turbulence intensities) could be obtained from properly sampled hub-height wind data, but a more thorough documentation would require measurements representative of flow through the rotor disk. The design of any special measurement programs for documenting turbulence at a Candidate Site would require input from the wind turbine manufacturer. The manufacturer would need data that could be interpreted in terms of its probable effect on the wind turbine system.

CHOOSING PREFERRED SITES

Step IV-12: Perform Differential Value Comparisons

Once site development costs and production cost savings have been determined for each candidate wind turbine and at each Candidate Site, differences in development costs are analyzed by differential value comparisons. Costs are broken down according to various categories, and they are compared to some appropriate base case. This type of analysis isolates the source of cost differences and motivates reanalysis of costs in categories where there are large differences between sites or candidate turbines. This type of analysis is standard practice in the utility industry.

Step IV-13: Choose Preferred Sites

In this final step each wind turbine installation is ranked according to the difference between production cost savings and site development and turbine maintenance costs.* The highest-ranking systems are given a final review for any environmental or social issues that could render a site unfavorable for wind energy development. Issues such as dynamic impacts of the cluster on the utility system, operating characteristics of the wind turbines (number of startup, shutdown, yawing cycles) and meteorological hazards are reviewed for any factors that could be serious enough to change the ranking order. The most attractive candidates from an economic, environmental and operational perspective are selected as the sites preferred for wind energy development.

TIME REQUIRED TO COMPLETE STAGE IV

The length of Stage IV is largely dictated by the length of the wind measurement program. If the site measurement program were as short as one year, selection of the Preferred Candidate Sites could take less than two years from the time the Candidate Sites were selected. This period would include the time required to design and

*A wind turbine installation consists of a particular wind turbine installed at a particular Candidate Site.

install the wind measurement system, the time required to collect and analyze the data and the time required to design the installation, estimate costs and perform the required economic analyses. As the length of the site measurement program increased, the total time required to complete Stage IV would approach the length of time required to complete the site measurement program.

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Section 8

CONCLUSIONS AND RECOMMENDATIONS

The result of this project has been the development of a step-by-step, utility-oriented procedure for identifying viable wind turbine sites. The procedure has also been tested by applying it to the service areas of two utility subcontractors (Consumers Power Company and Long Island Lighting Company). Suggestions and criticisms that resulted from the trial applications have been factored into the final site-selection procedure. A detailed description of the trial applications will be published in a companion report.

At first glance, the siting process outlined in Sections 4 through 7 may appear to be an excessively formal procedure to use to site a few hundred megawatts of wind turbines. Part of this formality is inevitable: explaining how to do something is frequently more involved than actually doing it. Some of the formality, however, is intentional. A formal procedure causes the user to think about his problem before acting; it reduces the risk that critical issues will be overlooked. A formal procedure results in better documentation of the decision process, and in siting, documentation of the reasons for making various siting decisions can be very important. Finally, it is hoped that following a formal siting procedure will reduce the possibility of error. This latter point is the most important one of all. With wind turbines, finding a suitable site is the key to economic viability.

In developing this site-selection procedure, the authors have found that there is sufficient understanding of the siting issues for the problem to be attacked in a systematic, rational manner. Methods for analyzing wind turbine economics are well developed. Methods for finding potentially windy sites are also known, and the wind data that should be measured in order to determine the economic potential of these sites have been identified. The environmental impacts of wind turbines are minor. Those issues that do exist (such as visual impact) are not unique and are familiar to all utilities. In summary, the only factor that would inhibit a utility from applying this siting procedure (or some modified form of it) in a routine manner is lack of verified information on installation costs, maintenance costs, service life and performance characteristics of the production-run wind turbines that might be available in the near future.

Although most of the technical issues in wind turbine siting are well understood, there are a few issues that require further research. Clarification of these issues would improve the quality of siting decisions. These issues are summarized below.

ESTIMATING WIND TURBINE ENERGY PRODUCTION

There is still some uncertainty in the accuracy of procedures that are currently used to estimate wind turbine energy production. As shown in Appendix B, there are two approaches to simulating wind turbine performance. The most common approach is to take wind data from the site and to convert it into estimates of average power output by means of the wind turbine's steady-state performance characteristics. The second approach is to attempt to mimic the dynamic behavior of the wind turbine - to account for the effects a turbine's operating strategy (start-up, shutdown and yawing procedures) can have on its power output. Comparisons of the two modeling approaches have shown discrepancies in estimates of net energy production of 10 to 30 percent.

An additional uncertainty is the type of wind data that should be collected for obtaining energy production estimates. What is the proper averaging time for wind data collected at a site? Will the proper averaging time be a function of machine type, and how can it be determined? The heights at which wind data should be collected are also an uncertainty. Theoretical studies indicate that wind data from a single level - hub height - should be sufficient; however, this conclusion should probably be tested.

Resolution of these uncertainties will require analysis of wind turbine performance at sites with high quality wind measurements. Many of these uncertainties should be resolved when the analyses of the data from DOE wind turbine sites are completed; however, similar studies should also be conducted at other installations in order to increase the sample of wind turbine types and meteorological conditions.

WIND TURBINE WAKE EFFECTS

Designing a wind turbine cluster requires some understanding of the effects that wind turbine wakes will have on the performance of downstream machines. A great deal of speculation and research has already been directed at this problem, particularly in Europe. Most of this research, however, has been based on wind tunnel studies and simple numerical models. When wind turbines are separated by large distances (greater than eight rotor diameters) and are on fairly flat terrain, current methods for estimating the effects of wind turbine wakes on cluster output will probably yield reasonable, conservative results. For clusters sited in nonflat terrain, physical

(i.e., wind tunnel) modeling is the only method that can be used to study the problem. Numerical models of wake decay have yet to be adapted to non-level terrain.

The greatest uncertainties about the behavior of wind turbine wakes lie in the near-wake region (less than 5 to 8 rotor diameters downstream of the turbine). In this region, the accuracy of current numerical and physical modeling techniques is questionable, and the ability to predict the net performance of wind turbine clusters becomes more uncertain as the clusters become more compact. At large separation distances, the reduction in downstream wind speeds is the only factor that would significantly affect cluster performance. At closer separations, however, an additional factor could become important. This factor is the turbulence in the wakes, especially the tip vortices shed from each blade of a horizontal-axis wind turbine. The extent to which wake turbulence could limit wind turbine spacing is unknown. The wake turbulence question and the behavior of wind speed deficits in the near wake region are uncertainties that require additional theoretical and experimental research.

VARIABILITY OF WIND CHARACTERISTICS AND ITS EFFECT ON WIND TURBINE ECONOMICS

One question that inevitably arises in any wind turbine siting program is the following: How long must one make wind measurements at any given site? The answer depends on how accurately one needs to know wind turbine economics. The minimum length for any site measurement program is obviously one year, because a year is the shortest time period in which some knowledge of the seasonal characteristics of the wind can be established. Determining when to end the measurement program, however, is more involved.

The best way to determine when to end a measurement program is through a sensitivity study. In such a study, one takes the available wind data and estimates the amount of uncertainty in key wind characteristics, such as the diurnal and seasonal behavior of the wind. The effect that these uncertainties could have on the economic value of the wind installation is determined. If the effect of the uncertainties is large enough to change decisions on economic viability, more measurements may be needed.

When wind turbine performance is modeled by statistical techniques (see Appendix B), the procedures for determining the effects of uncertainties in wind characteristics on wind turbine output are well known. When wind turbine performance is modeled by a quasi-dynamic approach (see Appendix B), the procedures for performing sensitivity tests are not as obvious. Procedures for performing sensitivity tests with quasi-dynamic models need to be developed, and they need to be made compatible with utility

production cost models. The entire sensitivity testing procedure needs to be developed as a systematic methodology that could be easily applied by utility personnel.

Appendix A

DOE WIND RESOURCE ATLASES

To provide a basis for estimating wind energy potential, three national wind energy resource assessments were performed early in the Federal Wind Energy Program (1-3). Although a large portion of the data used in these assessments was common to all, the analysis techniques differed considerably. Not surprisingly, significant discrepancies in the magnitude and the distribution of wind power density can be found among the three national assessments. A re-analysis and synthesis were also completed (4) to determine the causes of the discrepancies and to include the most plausible results in a single assessment.

As interest in wind energy increased, a need arose for resource assessments that were more refined and reliable than the national assessments so that energy planners, wind turbine manufacturers and public utilities could assess the wind power potential on a state and regional basis. Assessments for twelve regions of the United States have been prepared by the Department of Energy (Figure A-1).^{*} Each regional assessment consists of a regional wind energy atlas and a narrative report describing the procedures used in producing the assessment. The regional assessments can be the starting point for a utility considering the inclusion of wind turbines into its mix of generating equipment. The analyses provide preliminary information for assessing the potential for wind energy utilization within a utility's area. The assessments also indicate likely areas for finding sites. This appendix presents a summary of the analysis methods used to develop each regional wind resource assessment.

THE WIND ENERGY ATLASES

Each wind energy atlas contains wind resource information summarized by region and by state. The atlas also contains more detailed resource information for individual weather stations. Information that is provided in a regional format includes:

- maps of cultural geography, topography, and land-surface form classification

^{*}Copies of the regional assessments are available from the National Technical Information Service. A list of titles is provided at the end of this appendix.

Figure A-1.. Geographic Divisions for Regional Wind Energy Assessments

- a map of the annual available wind power
- a map showing the season of maximum wind power.

An example of the level of detail provided in the regional format is given in Figure A-2, which shows annual average wind power for the Northwest region.

Considerably more detail is provided on a state-by-state basis. State features include:

- maps of cultural geography, topography, and land-surface form classification
- maps showing the location of data stations
- maps of annual and seasonal wind power
- maps showing areal distribution of wind power
- maps of confidence level of resource estimates.

Figures A-3 and A-4 show average available wind power during summer and winter for the state of Washington. Maps of this type are useful for identifying areas where the seasonal variations in wind power best match the seasonal needs of the utility.

The numbers shown on the maps correspond to wind power classes defined in the figure legends. The number displayed reflects the wind resource estimate at the best exposed sites within the overall area associated with that wind power class. Mountainous areas are stippled on the map to indicate that the values shown on the map are estimates of the wind resource on exposed mountain ridge crests or summits. Most of the structure shown in the analysis is a result of interpreting meteorological and topographical indicators.

For the purpose of mapping the geographical variation of the wind resource, wind power density was chosen over wind speed since the power density incorporates in a single number the combined effect of the distribution of wind speeds and the dependence of the power density on air density and on the cube of the wind speed. Quantitative wind data in three formats were evaluated for mean wind power density: digitized, summarized, and unsummarized. The average wind power density $\bar{P}$ (watts/m²) in a vertical plane perpendicular to the wind direction for stations with one- or three-hourly digitized data was calculated from:

Figure A-2. Northwest Region Annual Average Wind Power

Figure A-3. Washington Summer Average Wind Power

Figure A-4. Washington Winter Average Wind Power

$$\bar{P} = \frac{1}{2n} \sum_{i=1}^n \rho_i V_i^3 \quad (\text{A-1})$$

where

n = the number of observations in the averaging period

ρ_i = the air density (in kg/m^3) computed from the station pressure and temperature

V_i = the wind speed (in m/s) at the i^{th} observation time.

For stations with wind summaries, $\bar{P}$ was calculated from:

$$\bar{P} = \frac{1}{2} \bar{\rho} \sum_{j=1}^c f_j V_j^3 \quad (\text{A-2})$$

where

$\bar{\rho}$ = the mean air density

c = the number of wind speed classes

f_j = frequency of occurrence of winds in the j^{th} class

V_j = the median wind speed of the j^{th} class.

In those cases for which unsummarized wind data were assessed, the seasonal and annual average speeds, $\bar{V}$, were estimated from a visual examination of one year's original weather records. The wind power density, $\bar{P}$, was then estimated by assuming that the speed frequency distribution followed a Rayleigh distribution (5):

$$\bar{P} = 0.955 \bar{\rho} \bar{V}^3 \quad (\text{A-3})$$

The anemometer height above the surface rarely was at either the 10-m or 50-m reference levels chosen for the presentation of the wind resource. A power law was used to adjust the long-term mean wind speed or power density to the reference level:

$$\frac{\bar{V}_r}{\bar{V}_a} = \left(\frac{Z_r}{Z_a} \right)^\alpha \quad \text{or} \quad \frac{\bar{P}_r}{\bar{P}_a} = \left(\frac{Z_r}{Z_a} \right)^{3\alpha} \quad (\text{A-4})$$

where

$\bar{V}_{a,r}$ and $\bar{P}_{a,r}$ = the mean wind speed or wind power density at heights $Z_{a,r}$
(the anemometer and reference level, respectively)

α = the power law exponent.

An examination of long-term mean wind speeds at airport locations at which the anemometer height was changed and at tower sites with multiple levels of anemometry indicated an $\alpha \sim 1/7$ to be widely applicable to low surface roughness (e.g., airport runways) and well exposed sites from which conventional NCC data are available (6).

The quantitative estimation of wind power over mountains made use of the northern hemisphere upper-air wind climatologies for the 850, 700 and 500 mb constant pressure levels by Crutcher (7). Since earlier studies had shown a strong correlation between mountaintop and free-air wind speeds (8), the free-air wind speed at mountain summit or ridge crest height was extrapolated (or interpolated) from the mean scalar speeds on the constant pressure surfaces. Estimates of the mountaintop wind speeds were made on a grid one-fourth degree latitude by one-third degree longitude. In each such cell of the grid over mountainous areas, the mean ridge crest or mountain summit elevation and appropriate constant pressure surface mean wind speeds were estimated. Linear extrapolation provided the mean free-air wind speed at the terrain elevation and the application of a Rayleigh speed distribution gave the mean free-air wind power. The mean wind power at the 10-m and 50-m reference heights was taken to be one-third and two-thirds of the free-air value, respectively, to account for the frictional slowing of the wind near the surface.

These estimates are considered lower limits for exposed ridge crests and mountain summits. Local terrain features in these mountainous regions can enhance the wind power considerably. However, a major uncertainty in mountainous terrain is the representativeness of some of the data upon which the free-air estimates are based (e.g., sheltering by nearby mountains can bias rawinsonde winds).

Wherever possible, these estimates were compared with surface data from ridge crests and mountain summits. Over some of the mountainous areas, the estimates were adjusted based on the location of the upper-air recording station and/or the surface data from ridge crests.

Wind power density is proportional to the third moment of the wind speed distribution and to air density (see Eq. A-1); therefore, a unique correspondence between power density and mean wind speed (the first moment of the speed distribution) does not

exist. However, by specifying a Rayleigh wind speed distribution and a standard sea-level air density (1.22 kg/m^3) a mean wind speed can be determined for each wind power class limit (see Eq. A-3).

Table A-1 gives the power density limits for the wind power classes used in the atlases. The limits apply at the 10-m (33-ft) and 50-m (164-ft) reference levels and standard sea-level conditions. The decrease of air density with elevation requires the Rayleigh mean speed to increase by about 3%/1000 m elevation (1%/1000 ft) to maintain the same power density. If the wind speed distribution is more sharply peaked than the Rayleigh distribution, the equivalent mean speed will be slightly higher than the value in Table A-1. Conversely, a broader distribution of wind speeds will slightly reduce the equivalent mean speed.

Table A-1
CLASSES OF WIND POWER DENSITY AT 10 M AND 50 M*

Wind Power Class	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density, watts/m ²	Speed,** m/s (mph)	Wind Power Density, watts/m ²	Speed,** m/s (mph)
	0	0	0	0
1	100	4.4(9.8)	200	5.6(12.5)
2	150	5.1(11.5)	300	6.4(14.3)
3	200	5.6(12.5)	400	7.0(15.7)
4	250	6.0(13.4)	500	7.5(16.8)
5	300	6.4(14.3)	600	8.0(17.9)
6	400	7.0(15.7)	800	8.8(19.7)
7	1000	9.4(21.1)	2000	11.9(26.6)

* Vertical extrapolation of wind speed based on the 1/7 power law.

**Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

One of the principal problems in wind resource assessment is characterizing the spatial variability of the wind. Available wind power can change by several wind power classes over the distance of a few miles; therefore, one must account for the percentage of land that is not well exposed to prevailing winds in order to realistically assess the total wind resource. Each region was divided into a grid one-third of a degree in longitude by one-fourth of a degree in latitude, and the representative value of the wind power density at exposed sites within the grid box was determined. A percentage of the land area falling into several categories of wind exposure was estimated using the land-surface form classification system of Hammond (9). From this information, an estimate was made of the percentage of the land area within a grid box experiencing available wind power densities greater than, equal to, slightly less than, or far less than the value for the grid box. The assignment of wind power classes to these percentage areas was based on the land-surface form classification and the amount of local terrain relief. The fractional values for each area in each grid box were summed to determine the areal distribution of the annual average wind power density. Figure A-5 shows the percentage of land area in each grid box where the wind resource exceeds class 3 for the state of Washington.

The analyses of wind power density at exposed sites shown on the wind power maps depend on the subjective integration of several factors: quantitative wind data, qualitative indicators of wind speed or power, the characteristics of exposed sites in various terrain and familiarity with the meteorology, climatology and topography of the region. As a result, the degree of certainty with which the wind power class can be specified depends on

- the abundance and quality of wind data
- the complexity of the terrain
- the geographical variability of the resource.

A certainty rating from 1 (low confidence) to 4 (high confidence) of the wind energy resource estimate was made for each grid box; this rating considered the influence of the above three factors on the certainty of the estimate of the wind power class for each cell. The definitions for the certainty ratings are adopted from those used by Voelker et al. (10) in a resource assessment of U.S. Forest Service tracts. The certainty ratings for the wind resource assessment are defined as follows:

Class 3

Figure A-5. Areal Distribution of Wind Resource in Washington.
Percent of land area with or exceeding power class 3

<u>Rating</u>	<u>Definition</u>
1	<p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"> 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	<p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	<p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	<p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>

The assignment of a certainty rating requires subjective evaluation of the interaction of the factors involved. Figure A-6 shows the certainty rating for the state of Washington.

Figure A-6. Certainty Rating of Washington Wind Resource

For the smallest space scale treated in the atlas (a single weather station), the wind resource can be described in considerable detail. Stations selected for this level of analysis are those for which hourly or three-hourly data are available on magnetic tape at the NCC. Information provided for individual stations includes:

- a map of station location
- tables of station location and wind power
- graphs of monthly speed and power
- graphs showing interannual variation
- plots of speed frequency
- plots of speed-direction frequency
- plots of speed duration
- graphs of power duration
- plots of diurnal variation by season.

Examples of weather station data presented in graphical form are provided in Figures A-7 through A-13.

Figure A-7. Monthly Average Wind Power and Speed for Washington

Figure A-8. Interannual Wind Power and Speed for Washington

Figure A-9. Diurnal Wind Speed by Season for Washington

Figure A-10. Annual Average Wind Speed Frequency for Washington

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 - - - WIND SPEED RIGHT ORDINATE - M/S
 PNL-3195 WERA-1
 ABSCISSA - WIND DIRECTION

Figure A-11. Directional Frequency and Average Speed for Washington

ORDINATE - PERCENT

ABSCISSA - M/S

PNL-3195 WERA-1

Figure A-12. Annual Wind Speed Duration for Washington

ORDINATE - PERCENT
ABSCISSA - WATTS/M²
PNL-3195 WEHA-1

Figure A-13. Annual Wind Power Duration for Washington

NARRATIVE REPORTS

Summary reports of the methods used to evaluate the wind energy resource in each region were also prepared. In addition to the methodology descriptions, lists of all data stations and some data are included. Titles of these reports are listed below, after the list of atlas titles.

LIST OF ATLAS TITLES

All atlases and narrative reports are available from the National Technical Information Service in Springfield, Virginia.

- D. L. Elliott et al. 1980. Wind Energy Resource Atlas: The Northwest Region.
PNL-3195 WERA-1.
- D. L. Freeman et al. 1980. Wind Energy Resource Atlas: The North Central Region.
PNL-3195 WERA-2.
- D. L. Paton et al. 1980. Wind Energy Resource Atlas: The Great Lakes Region.
PNL-3195 WERA-3.
- K. E. Pickering et al. 1980. Wind Energy Resource Atlas: The Northeast Region.
PNL-3195 WERA-4.
- R. Brode et al. 1980. Wind Energy Resource Atlas: The East Central Region.
PNL-3195 WERA-5.
- J. M. Zabransky et al. 1980. Wind Energy Resource Atlas: The Southeast Region.
PNL-3195 WERA-6.
- L. Graves et al. 1980. Wind Energy Resource Atlas: The South Central Region.
PNL-3195 WERA-7.
- S. P. Anderson et al. 1980. Wind Energy Resource Atlas: The Southern Rocky Mountain Region. PNL-3195 WERA-8.
- G. L. Norman et al. 1980. Wind Energy Resource Atlas: The Southwest Region.
PNL-3195 WERA-9.
- J. E. Wise et al. 1980. Wind Energy Resource Atlas: Alaska. PNL-3195 WERA-10.
- T. A. Schroeder et al. 1980. Wind Energy Resource Atlas: Hawaii and Pacific Trust Territories. PNL-3195 WERA-11.
- H. L. Wegley et al. 1980. Wind Energy Resource Atlas: Puerto Rico and U.S. Virgin Islands. PNL-3195 WERA-12.

The narrative reports describing the development of each of the wind energy atlases are:

- D. L. Freeman et al. 1981. Techniques for Assessing the Wind Resource in the North Central Region. PNL-3667.

- D. L. Paton et al. 1981. Techniques for Assessing the Wind Resource in the Great Lakes Region. PNL-3668.
- K. E. Pickering et al. 1981. Techniques for Assessing the Wind Resource in the Northeast Region. PNL-3452.
- R. Brode et al. 1981. Techniques for Assessing the Wind Resource in the East Central Region. PNL-3451.
- J. M. Zabransky et al. 1981. Techniques for Assessing the Wind Resource in the Southeast Region. PNL-3669.
- S. R. Anderson et al. 1981. Techniques for Assessing the Wind Resource in the Southern Rocky Mountain Region. PNL-3671.
- G. T. Norman et al. 1981. Techniques for Assessing the Wind Resource in the Southwest Region. PNL-3672.
- T. Wentink et al. 1981. Techniques for Assessing the Wind Resource in Alaska. PNL-3519.
- T. A. Schroeder et al. 1981. Techniques for Assessing the Wind Resource in Hawaii and the Pacific Trust Territories. PNL-3673.
- H. L. Wegley et al. 1981. Techniques for Assessing the Wind Resource in Puerto Rico and the U.S. Virgin Islands. PNL-3674.

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- 4. D. L. Elliott. Synthesis of National Wind Energy Assessments. Richland, Wa.: Pacific Northwest Laboratory, 1977. BNWL-2220 WIND-5.
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- 6. D. L. Elliott. "Adjustment and Analysis of Data for Regional Wind Energy Assessments." Paper presented at the Workshop on Wind Climate, Asheville, North Carolina, November 12-13, 1979.
- 7. H. L. Crulcher. Upper Wind Statistics of the Northern Hemisphere. Asheville, North Carolina: National Climatic Center, 1959. NAVAER 50-IC-535, Vol. 1.
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Appendix B

PROCEDURES FOR MODELING WIND TURBINE PERFORMANCE

THE PROBLEM

A key problem in wind turbine siting is estimating how a given wind turbine will perform at a given site. Solving this problem requires a model for converting wind information from a site into a simulation of how a wind turbine installed at that site would behave. The various wind turbine performance issues that could be of interest to a utility are:

- net energy production for a given time period
- impact on hourly (or subhourly) system load
- operational behavior of the wind turbine (number of startup/shutdown or yawing cycles)
- dynamic impacts on the utility system.

Different types of wind turbine performance models could be required for addressing each of these problems.

The purpose of this appendix is to review current procedures for modeling wind turbine performance, to evaluate how well each of these modeling techniques addresses the performance issues and to designate those areas requiring further research.

STEADY-STATE PERFORMANCE CHARACTERISTICS OF WIND TURBINES

The most commonly available information on wind turbine performance is the steady-state performance characteristic. The steady-state performance characteristic gives the relationship between electric power output and wind speed for a wind turbine immersed in a steady, homogeneous flow (i.e., zero yaw error and no variation in wind speed or wind direction across the rotor disk). Figure B-1 is an example of a steady-state performance characteristic for a hypothetical wind turbine. The relationship between power output and wind speed is a function of density altitude. Usually, these relationships are given for sea-level conditions. Steady-state performance characteristics are also given in terms of the coefficient of performance

Figure B-1. Steady-State Performance Characteristic for a Hypothetical Wind Turbine. Rated power is frequently, but not always, the maximum power output

$$C_p = \frac{P}{1/2 \rho A V^3} \quad (B-1)$$

where

P = electric power output of the wind turbine

ρ = local air density

A = swept area of the rotor disk

V = wind speed.

The two ways of expressing steady-state performance characteristics are completely equivalent since

$$p(v) = \frac{1}{2} \rho A V^3 C_p(v) \quad (B-2)$$

where $p(v)$ is the steady-state performance function (the curve in Figure B-1).*

*The coefficient of performance, C_p , is actually a function of blade airfoil shape, blade angle of attack, tip speed ratio (the ratio of the speed of the rotor tip to the wind speed), and the characteristics of the mechanical to electrical power conversion system of a particular wind turbine. For a given wind turbine design, however, C_p can be expressed as a function of wind speed only, as is done in Eq. B-2.

The usual method for simulating electric power output from a wind turbine is to combine wind data representative of the site with the steady-state performance characteristic to obtain the power output estimate (1). Suppose, for example, the wind data consist of hourly average measurements of wind speed at the hub height of the wind turbine in question. The usual assumption is that the average power output for that hour can be estimated from the steady-state performance characteristic of the machine (i.e., Figure B-1, where the wind speed is taken as the hourly averaged wind speed, or Eq. B-2, where v is the hourly averaged wind speed). The accuracy of this assumption is not self-evident. The natural wind is unsteady and nonhomogeneous, and the response of a turbine to this nonsteady, nonhomogeneous forcing function is fairly complicated.

Some of the differences between the actual performance of a wind turbine and the performance that would be predicted by the steady-state performance characteristic can be understood if the wind turbine system is assumed to behave like a linear filter. This assumption is an oversimplification of the actual dynamic behavior of a large wind turbine system. A real wind turbine is definitely a nonlinear device. Over most of a wind turbine's performance envelope, however, the linear assumption is probably a reasonable approximation - as long as fluctuations in wind speed and wind direction are not too large. Given the linear assumption, the power output at any time t can be expressed as

$$P(t) = \int_0^{\infty} k(\tau) V(t-\tau) d\tau \quad (B-3)$$

where $V(t)$ is some suitably weighted average of the component of the wind speed normal to the plane of the rotor disk and $k(\tau)$ is the response function (or impulse response) of the machine. For a given time interval, say $2T$, the average actual power output is

$$\bar{P}(t_m) = \frac{1}{2T} \int_{t_m-T}^{t_m+T} \int_0^{\infty} k(\tau) V(t-\tau) d\tau dt \quad (B-4)$$

As Eq. B-4 shows, average power output is a function of the temporal behavior of the wind vector over the rotor disk and the response characteristics of the wind turbine. Thus, there can be no unique relationship between average wind speed and average power output. The difference between the average power output that would be obtained by an actual wind turbine and an estimate of the average power obtained by using

steady-state performance characteristics usually increases as the length of the time interval increases. The difference between actual and predicted performance is also increased when wind information from a single height is used to represent flow through the entire rotor disk.*

Figures B-2 and B-3 show observed differences between actual measurements of average wind turbine output and the steady-state performance characteristic. Figure B-2 shows the scatter between measured and expected power outputs for a two-second averaging time (2), and Figure B-3 shows the scatter for a 30-minute average (3). The

Figure B-2. Comparisons of Measured and Design Power Outputs for the DOE/NASA MOD-1 Wind Turbine at Boone, North Carolina. Error bars show dispersion of two-second averages of power output and hub-height wind speed

*Parametric studies of the effects of wind shear on estimates of power output have shown that the error introduced by using wind information from a single level to represent the flow across the rotor disk may not result in as large an error as one might intuitively expect (private communication, J. C. Doran, Battelle, Pacific Northwest Laboratories).

Figure B-3. Comparisons of Measured and Design Power Outputs for the DOE/NASA MOD-OA Wind Turbine at Clayton, New Mexico. Points correspond to half-hour averages of power output and hub-height wind speed

figures show significant variations between individual observed and expected values, but the figures also show that the medians of the observed power outputs agree very well with the values expected from the steady-state performance characteristics.

Assumptions Inherent to Steady-State Modeling of Turbine Performance

As illustrated by Figures B-2 and B-3, as well as by Eq. B-4, there can be a considerable discrepancy between an estimate of average power output for a given time interval (such as an hour or a fraction of an hour) and the actual average power output that would have been delivered over that same interval by a real wind turbine. If, however, one is only interested in the net energy delivered by a wind turbine over a long time period, such as a month, a season or a year, these discrepancies may not be important.

Discrepancies between estimated and actual electric energy output may not be important if the estimate tends to scatter about the actual value. Assume, for example, that one wished to obtain an estimate of the actual quantity of electric energy, E_a ,

that would have been delivered by a given wind turbine over a given time period, Δt . For obtaining this estimate, one has the wind turbine's steady state, density corrected, performance function, $p(v)$, and wind data consisting of time series of hub-height wind speed, $\bar{v}$, averaged over a time interval $\Delta \tau$. The steady-state performance estimate of the net energy production, E_e , would be

$$E_e = \sum_{n=1}^N p(\bar{v}_n) \Delta \tau_n \quad (B-5)$$

where $\Delta t = N\Delta \tau$ and $\bar{v}_n$ is the average wind speed for the n^{th} time interval $\Delta \tau_n$. If the individual estimates of average power output, $p(\bar{v}_n)$, tend to scatter about the values that would have been delivered by the actual wind turbine, then $E_e \approx E_a$ as long as Δt is large compared to $\Delta \tau$.*

Figures B-2 and B-3 would seem to indicate that estimates of average power output would indeed scatter about the actual values and that, given a sufficiently long time period Δt , Eq. B-5 would yield a reasonably accurate estimate of net energy production. This deduction, however, is not necessarily true. Figures B-2 and B-3 show the results of some very restricted measurements. The purpose of these measurements was to verify the performance curve, $p(v)$, of the turbines. As a result, measurements were only made during times the turbine was operating stably and synchronized with the utility system. This is an important point, for Eq. B-5 assumes that the wind turbine will be synchronized with the grid for the full time interval $\Delta \tau_n$ as long as $\bar{v}_n$ is greater than the cut-in wind speed but less than cutout. Eq. B-5 also assumes that any yaw errors between the wind turbine axis and wind direction have an insignificant effect on $p(\bar{v}_n)$, and that the average power output over any time interval is completely independent of the previous behavior of the wind or the wind turbine.

The above assumptions are not completely valid, for they neglect the effects of a wind turbine's operating strategy or dynamic response on its performance. Most large wind turbines employ some sort of microprocessor-controlled system that governs machine startup and shutdown and, for non-free yawing horizontal-axis wind turbines, its yawing motions. Usually, for example, the wind speed must remain above cut-in for some period of time before the microprocessor will allow the turbine to start up.

*How much larger depends on the amount of scatter between individual estimates of average power output, $p(\bar{v}_n)$, and the actual power output.

There is always some lost operating time due to a wind turbine's control or operation strategy that is not accounted for by Eq. B-5. The effects of neglecting startup, shutdown and yawing behavior on energy production estimates are discussed in more detail in a later section of this appendix.

STATISTICAL MODELING OF ENERGY PRODUCTION

Basic Principles

If effects due to a wind turbine's dynamic behavior are neglected, Eq. B-5 can be used to obtain estimates of net energy production for a given time period. Net energy production can also be computed if the probability density function (PDF) for wind speed is known at the site. The PDF gives the probability (or the fraction of time) that the wind speed will fall within a given wind speed interval. At a given location, the exact form of the PDF will depend on the time interval over which the wind speed is averaged ($\Delta\tau$ in the terminology of Eq. B-5) and the total period to which the PDF applies (i.e., Δt). Since an hour is the shortest time scale for conventional meteorological observations, it is the averaging time usually used to develop PDFs.

Once the PDF is known, the average power output of a particular wind turbine for a given time period can be estimated as

$$\bar{P} = \int_0^{\infty} p(v) f(v) dv \quad (B-6)$$

where $f(v)$ is the PDF. Multiplying $\bar{P}$ by the length of the time period gives the net energy production.

The most obvious way of determining the PDF at a site is, of course, to collect the pertinent data and compute it. If this is not done, however, there are several analytic (i.e., algebraic) PDFs that can be used to approximate the wind characteristics at a site. The most commonly used model for wind speed PDFs is the Weibull function:

$$f(v) = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (B-7)$$

The Weibull function has two adjustable parameters (c and k) that enable it to fit a wide range of observed PDFs. A simple relationship exists between the parameters c and k and the mean and the second moment of the Weibull function:

$$\bar{v} = c\Gamma\left(1 + \frac{1}{k}\right) , \quad (B-8)$$

$$\overline{v^2} = c^2\Gamma\left(1 + \frac{2}{k}\right) , \quad (B-9)$$

where $\Gamma(n)$ is the Gamma function

$$\Gamma(n) = \int_0^{\infty} x^{n-1} e^{-x} dx \quad (B-10)$$

and can be found tabulated in most handbooks of mathematical tables. The second moment of a PDF, $\overline{v^2}$, is a measure of its "spread" or shape. Substituting Eq. B-8 into Eq. B-9,

$$\overline{v^2} = \bar{v}^2 \frac{\Gamma(1 + 2/k)}{\left[\Gamma(1 + 1/k)\right]^2} ; \quad (B-11)$$

thus, k controls the spread or shape of the Weibull PDF for a given $\bar{v}$. Figure B-4 depicts two PDFs having the same mean wind speed, $\bar{v} = 7$ m/s. Curve a has a small second moment ($k=4$) and curve b has a larger second moment ($k=1.1$). A small second moment indicates that the wind consistently blows at or near the mean wind speed. This type of PDF might be observed at sites exposed to a steady, persistent wind resource such as the trade winds. A large second moment, however, indicates that the wind resource is more capricious. This behavior is more typical of inland sites.

The problem with the Weibull function is that one must know the mean and the second moment of the wind speed in order to determine the parameters c and k. Determining both of these wind characteristics with any precision requires measurements at the site, and if measurements are required, one might as well measure the probability distribution directly. In practice, however, there seems to be an empirical relationship between the Weibull parameter k and the mean wind speed. Justus (4) analyzed

Figure B-4. Comparison of Two Hypothetical Probability Distribution Functions (Weibull Function). Curve a has a small second moment ($k=4$), while the second moment of curve b is larger ($k=1.1$)

data from a number of sites in the continental United States and obtained the following relationships for "low", "average" and "high" variance sites:*

$$\left. \begin{aligned} k &= 1.05 \sqrt{\bar{v}} \quad (\text{low variance}) \\ k &= 0.94 \sqrt{\bar{v}} \quad (\text{average variance}) \\ k &= 0.83 \sqrt{\bar{v}} \quad (\text{high variance}) \end{aligned} \right\} \quad (B-12)$$

where $\bar{v}$ is the annual mean wind speed in m/s. The parameter c is then determined from Eq. B-8.

Cherry (5) has also found empirical relationships between $\bar{v}$, c and k by examining data from several sites in New Zealand. Cherry's relationships are:

$$c = \frac{1.39 \bar{v}}{(\bar{v}-2)^{0.089}} \quad (B-13)$$

*The variance, denoted as σ^2 , is related to the second moment in the following way:
 $\sigma_v^2 = \overline{v^2} - \bar{v}^2$.

$$k = 1 + 0.48 (\bar{v}-2)^{0.51} \quad (\text{B-14})$$

where $\bar{v}$ is, again, the annual mean wind speed in m/s. Cherry's and Justus's results are compared in Figures B-5 and B-6.

Figure B-5. Comparison of Empirical Relationships Between Weibull Parameter k and Annual Mean Wind Speed in m/s

Figure B-6. Comparisons of Empirical Relationships Between Weibull Parameter c and Annual Mean Wind Speed

Another mathematical function that is frequently used to represent wind speed PDFs is the Rayleigh distribution:

$$f(v) = \frac{\pi v}{2 \bar{v}^2} \exp\left[-\frac{\pi v^2}{4 \bar{v}^2}\right] \quad (\text{B-15})$$

As can be seen from Eqs. B-7 through B-9, and some knowledge of the behavior of the gamma function,* the Rayleigh distribution is a special case of the Weibull function with $k=2$. The Rayleigh distribution is popular because it is specified once the mean wind speed is determined. It has also been found to fit observed PDFs at a large number of sites reasonably well (6).

* $\Gamma(T+n) = n\Gamma(n)$; $\Gamma(1.0) = 1.0$ and $\Gamma(1/2) = \sqrt{\pi}$.

Using Statistical Models to Estimate Wind Turbine Performance

Once the probability distribution function has been determined, average power output or net energy production can be determined for any time period represented by the PDF. For example, Eq. B-6 can be used to determine the diurnal variation in average energy output. Suppose one wished to determine average power output as a function of time of day for a particular season. Equation B-6 would be used, but $f(v)dv$ would now be the probability of experiencing a wind speed between v and $v+dv$ at that particular time of day and for that particular season. In theory, the mathematical form of the PDF depends on the site, the time interval over which wind speeds are averaged and the time period to which the PDF applies. In practice, however, the PDFs are not nearly so sensitive. Weibull-like distributions appear to fit most observed distributions well enough to be useful in estimating net energy production. As an example, Figure B-7 shows estimates of average power output as a function of time of day for a three-month period at six different sites. The estimates were based on the steady-state performance characteristics of the residential-sized wind turbine shown in Figure B-8. The average output depicted by the circles is based on the observed PDFs, while the results depicted by the triangles were obtained by using a Rayleigh approximation to the real distribution. The agreement is good considering the probable accuracy of computations of this sort.

The statistical approach to estimating wind turbine performance can produce more than simple estimates of average power output. Suppose one wished to determine the number of hours the wind turbine would generate power greater than some value, say P_0 . One could examine the steady-state performance curve (Figure B-1) and determine the wind speed interval, v_2-v_1 , for which $p(v) \geq P_0$. The total number of hours that the wind turbine would be operating $p(v) \geq P_0$ is

$$\Delta t \int_{v_1}^{v_2} f(v)dv$$

where Δt is the period for which $f(v)$ is defined.*

*This computation neglects lost operating time due to the startup and shutdown cycle of the wind turbine in question. The magnitude of the discrepancy between this simple estimate and actual performance would depend on the steadiness of the wind and the responsiveness of the wind turbine to changes in wind speed.

Figure B-7. Comparisons of Seasonal Average Power Output as a Function of Time of Day for Six Sites. Points denoted by circles are based on measured wind characteristics; points denoted by triangles assume a Rayleigh function can be used to describe the wind speed probability density function. Power output computations are based on the steady-state performance characteristic shown in Figure B-8

Figure B-8. Steady-State Performance Characteristics for a Hypothetical Wind Turbine

Equations such as B-6 are usually not solved by formal integration. This is particularly the case when observed PDFs are used. It can also be the case, however, when model PDFs such as the Weibull or Rayleigh are used. The steady-state performance function, $p(v)$, could be a complicated enough function of wind speed that the product $p(v)f(v)$ may not be integrable in terms of a simple algebraic expression. One then takes advantage of the following definition:

$$\int_a^b f(x)dx = \lim_{\substack{n \rightarrow \infty \\ \max \Delta x_i \rightarrow 0}} \sum_{i=1}^n f(x_i^*) \Delta x_i \quad (B-16)$$

where x_i represents a sequence of numbers $a = x_0 < x_1 < x_2 < \dots < x_n = b$, the interval $\Delta x_i = x_i - x_{i-1}$ and x_i^* is some number within the i^{th} interval; that is, $x_{i-1} \leq x_i^* \leq x_i$. Thus, Eq. B-6 can be approximated

$$\bar{P} = \int_0^\infty p(v)f(v)dv \approx \sum_{i=1}^n p(v_i^*)f(v_i^*)\Delta v_i \quad (B-17)$$

where v_i represents a sequence of wind speeds $v_a = v_0 < v_1 < v_2 < \dots < v_b$ and the interval (v_a, v_b) is the range of wind speeds for which $p(v)$ has non-zero values (in other words, v_a is the cut-in wind speed and v_b is the cutout wind speed). Usually, Δv_i are chosen to be equal in size and $v_i^* = (v_{i-1} + v_i)/2$.

Equation B-17 is easily determined on a hand-held calculator. The values of $p(v_i^*)$ are found either by reading them off the steady-state performance curve (e.g., Figure B-1) or by determining them from a table of $p(v)$ versus wind speed, v . The values of the $f(v_i^*)$ are either read from a table (especially when measured PDFs are used) or computed using the appropriate Weibull approximation. For each successive v_i^* , the product of $p(v_i^*)$ and $f(v_i^*)$ is multiplied by the size of the wind speed interval, Δv_i , and then summed in order to get $\bar{P}$. Table B-1 presents tabulated values of $f(v_i^*)\Delta v_i$ for 1 m/s wind speed intervals and for a range of mean wind speeds.*

Table B-1 assumes that the PDF, $f(v)$, can be approximated by a Rayleigh function (Eq. B-15). If the mean wind speed is known, this table, along with information on steady-state performance characteristics, can be used to produce estimates of average power output (or net energy production) for any wind turbine and for any time period in which the PDF can be represented by a Rayleigh function. Examination of available wind data indicates that a Rayleigh function is a reasonable representation of wind speed PDFs for periods of a month, a season or a year at many sites. Figure B-7 indicates that Rayleigh function can also be used to produce estimates of the diurnal behavior of average power output if the diurnal behavior of the mean hub-height wind speed is known.

Example of the Use of Table B-1

At a particular wind turbine site, the mean hub-height wind speed for the month of January is 8 m/s. One wishes to estimate net energy production for an average January, and the number of hours in an average January that certain power output levels will be experienced. The estimates are for a wind turbine with the following characteristics:

*Actually, the values tabulated in Table B-1 are $\int_{v_{i-1}}^{v_i} f(v)dv$, where v_{i-1} and v_i are the lower and upper limits of the wind speed interval Δv_i .

Table B-1

PERCENTAGE OF TIME WIND SPEED FALLS WITHIN THE
GIVEN WIND SPEED INTERVALS

Wind Speed Interval (m/s)	Percentage of Time Wind Speed is Observed in the Given Interval as a Function of Mean Wind Speed					
	Mean Wind Speed, m/s					
	4	6	8	10	12	14
0-1	0.0479	0.0216	0.0122	0.0078	0.0054	0.0040
1-2	0.1304	0.0620	0.0357	0.0231	0.0161	0.0119
2-3	0.1788	0.0947	0.0567	0.0373	0.0263	0.0195
3-4	0.1869	0.1164	0.0737	0.0498	0.0357	0.0267
4-5	0.1628	0.1257	0.0859	0.0602	0.0439	0.0332
5-6	0.1223	0.1237	0.0929	0.0680	0.0508	0.0390
6-7	0.0806	0.1126	0.0948	0.0732	0.0562	0.0439
7-8	0.0470	0.0958	0.0921	0.0756	0.0601	0.0479
8-9	0.0245	0.0767	0.0859	0.0756	0.0625	0.0510
9-10	0.0114	0.0580	0.0770	0.0734	0.0633	0.0530
10-11	0.0047	0.0415	0.0666	0.0693	0.0627	0.0541
11-12	0.0018	0.0282	0.0557	0.0639	0.0609	0.0542
12-13	0.0006	0.0182	0.0451	0.0575	0.0581	0.0535
13-14	0.0002	0.0111	0.0354	0.0507	0.0545	0.0521
14-15	0.0001	0.0065	0.0270	0.0437	0.0502	0.0500
15-16	0.0000	0.0036	0.0200	0.0369	0.0456	0.0474
16-17	0.0000	0.0019	0.0144	0.0306	0.0408	0.0444
17-18	0.0000	0.0010	0.0101	0.0248	0.0359	0.0411
18-19	0.0000	0.0005	0.0068	0.0198	0.0312	0.0376
19-20	0.0000	0.0002	0.0045	0.0155	0.0267	0.0341
20-21	0.0000	0.0001	0.0029	0.0119	0.0226	0.0305
21-22	0.0000	0.0000	0.0018	0.0090	0.0189	0.0270
22-23	0.0000	0.0000	0.0011	0.0067	0.0155	0.0237
23-24	0.0000	0.0000	0.0007	0.0048	0.0126	0.0206
24-25	0.0000	0.0000	0.0004	0.0035	0.0101	0.0177
25-26	0.0000	0.0000	0.0002	0.0024	0.0080	0.0151
26-27	0.0000	0.0000	0.0001	0.0017	0.0063	0.0127
27-28	0.0000	0.0000	0.0001	0.0011	0.0049	0.0107
28-29	0.0000	0.0000	0.0000	0.0008	0.0037	0.0088
29-30	0.0000	0.0000	0.0000	0.0005	0.0028	0.0072
30-31	0.0000	0.0000	0.0000	0.0003	0.0021	0.0059
31-32	0.0000	0.0000	0.0000	0.0002	0.0015	0.0047
32-33	0.0000	0.0000	0.0000	0.0001	0.0011	0.0038
33-34	0.0000	0.0000	0.0000	0.0001	0.0008	0.0030
34-35	0.0000	0.0000	0.0000	0.0000	0.0006	0.0024

<u>Wind Speed Range</u>	<u>Power Output</u>
0 - 6 m/s	$P = 0 \text{ kW}$
6 - 12 m/s	$P = [(v-6)/6] 2500 \text{ kW}$
12 - 20 m/s	$P = 2500 \text{ kW}$
Over 20 m/s	$P = 0 \text{ kW}$

The PDF is assumed to be a Rayleigh function.

Between 0 and 6 m/s, the turbine produces no power. Each value of $f(v_i^*)\Delta v_i$ for the six wind speed intervals between 0 and 6 m/s is summed. This quantity (0.357) is multiplied by the number of hours in January (744) to give the number of hours that the wind will be below cut-in in a typical January (266 hours).

Multiplying $f(v_i^*)\Delta v_i$ for the next wind speed range (6 to 7 m/s) by the number of hours in an average January that the wind speed will fall between 6 and 7 m/s (35.7 hr), one can see that the mean power output for this wind speed range is 208 kW, and the contribution to the net energy production is 7425 kWh (35.7 hr x 208 kW).

This procedure is repeated for each successive wind speed interval between cut-in and cutout. Summing the contributions of each wind speed interval gives the estimate of net energy production.

Sensitivity of Mean Power Estimates to Uncertainties in Probability Distribution Function

Whether the PDFs used in Eqs. B-6 or B-17 are based on measurements at the site or whether they are based on some Weibull approximation, there is always some uncertainty about how well the PDF used in estimating expected performance represents the actual average or typical PDF that would be experienced over the lifetime of the wind turbine, which could be 20 years or more. Any modeled or measured PDF will be an approximation; therefore, it is useful to have some idea of the sensitivity of mean power estimates to the shape of the PDF. Figure B-9 shows probability density times mean velocity ($f(v) \cdot \bar{v}$) as a function of $v/\bar{v}$ for four PDF shapes that should fairly well span the range of shapes that might be encountered at typical sites. Curve 1 is the Rayleigh distribution (Eq. B-15). Curve 2 is a Weibull function (Eq. B-7) with fairly low variance ($k \approx 3$). Curve 3 is an observed PDF based on measurements made at a DOE candidate site on the island of Culebra, Puerto Rico; it is typical of sites exposed to steady, persistent winds such as the trades. Curve 4 is also based on measurements (San Geronio Pass, California) and shows a two-peaked

Figure B-9. Typical Wind Speed Probability Density Functions for Wind Speed. Curve 1 is the Rayleigh function and Curve 2 is a Weibull ($k \approx 3$). Curves 3 and 4 are observed distributions

or bimodal distribution; this type of distribution is typical of sites where very different wind regimes are associated with very different meteorological conditions.

In order to show the effects of PDF shape on mean power estimates, the four PDFs of Figure B-9 were applied to two small wind turbines having very different steady-state performance characteristics. These characteristics are shown in Figure B-10. Machine A shows characteristics typical of a fixed-pitch turbine, while Machine B has a performance more typical of many large wind turbines. The results are shown in Figures B-11 and B-12 for a range of typical hub-height (~ 10 m) wind speeds. The figures show that the sensitivity of mean power estimates to PDF shape is a function of both mean wind speed and machine performance characteristics. Wind turbines with steady-state performance characteristics similar to Machine A show little sensitivity

Figure B-10. Steady-State Performance Characteristics for Two Hypothetical Wind Turbines

Figure B-11. Average Power Output for Machine A as a Function of Average Wind Speed. Four possible wind speed probability density functions (PDFs) are shown. Each line corresponds to the PDF that is plotted with the same type of line in Figure B-9

Figure B-12. Average Power Output for Machine B as a Function of Average Wind Speed. Four possible wind speed probability density functions (PDFs) are shown. Each line corresponds to the PDF that is plotted with the same type of line in Figure B-9

to PDF shape. Wind turbines with performance characteristics similar to Machine B show greater sensitivity. Figures B-11 and B-12 also show that the Rayleigh distribution produces an average estimate that is within $\pm 15\%$ to $\pm 20\%$ of the estimates provided by the other PDFs - at least for the PDFs depicted in Figure B-9.

Estimating Wind Turbine Performance From Non-Hub-Height Data

Estimates of wind turbine performance should be made using hub-height wind data if at all possible. The reason is that wind behavior at the heights of many large wind turbines may not be strongly related to the behavior of the wind near the surface. Under some meteorological conditions, the flow at elevations of several tens of meters can become decoupled from and completely unrelated to the flow at lower levels. In addition, local terrain features can have different effects on flow very near the surface (less than, say, 10 to 15 m) than on the flow higher up. Nevertheless, there are instances when estimates of wind turbine performance must be based on data collected at elevations very different from hub height. In this situation one needs a rational procedure for extrapolating the data from the height at which it was measured to the height at which it is needed.

When the wind data are given in terms of a PDF, the most straightforward approach to vertical extrapolation is to assume that the general form of the PDF remains the same at all levels. Each wind speed is scaled up or down according to how the wind speed is presumed to change with height. This procedure can be expressed mathematically as

$$f_h(v_h) = f_m(v_h) \quad (B-18a)$$

where

$$\frac{v_h}{v_m} = F\left(\frac{z_h}{z_m}, z_0, \phi\right) \quad (B-18b)$$

In Eqs. B-18a and B-18b, the subscript h refers to hub height and the subscript m denotes the height at which the data were collected. The wind speed adjustment (Eq. B-18b) is assumed to be a function of the elevation difference (z_h/z_m), the roughness of surface ground cover (z_0) and a parameter, ϕ , that accounts for the hydrostatic stability of the flow. The stability parameter, ϕ , depends on wind speed and the rate at which the earth's surface either heats or cools the flow. Since the rate of surface heating or cooling is rarely known, these effects are seldom taken into account in a direct way.

At first glance, Eq. B-18b might seem to cover all factors that could possibly affect the change of wind speed with height. This is not true, however. Equation B-18b neglects the effects of upwind changes in terrain on the behavior of the downwind flow. In many situations these changes can dominate all other effects. Unfortunately, the effects of upwind changes in terrain cannot be predicted with consistent accuracy for many real-world situations. Nevertheless, Eqs. B-18a and B-18b represent the best available procedure for extrapolating wind data in the vertical.

Since the magnitude of the adjustment defined by Eq. B-18b is a function of wind speed (ϕ is a function of wind speed), the shape of the extrapolated PDF will differ from the shape defined by the measurements. If, for instance, the measured and extrapolated PDFs are expressed as Weibull functions, both parameters c and k will be found to change with height. Justus and Mikhail (7) have produced formulas for extrapolating the Weibull parameters based on the approach summarized in Eqs. B-18a and B-18b:

$$\frac{k_h}{k_m} = \left[1 - 0.0881 \ln(z_m/10) \right] / \left[1 - 0.0881 \ln(z_h/10) \right] , \quad (B-19)$$

$$\frac{c_h}{c_m} = \left(\frac{z_h}{z_m} \right)^n \quad (B-20)$$

where

$$n = \left(0.37 - 0.0881 \ln c_1 \right) / \left[1 - 0.0881 \ln(z_m/10) \right] .$$

In expressions B-19 and B-20, z_h and z_m are expressed in meters, while the dimensions of c_h and c_m are m/s.

Doran and Verholek (8) tested Eqs. B-19 and B-20 using data from 41 nuclear power plant sites that had wind data from two or more levels and PDFs that could be accurately fitted by a Weibull function. Data from the nuclear power plant sites were combined with data from eight DOE Candidate Sites to produce a data base that provided 70 pairs of wind measurement levels for testing the extrapolation formulas. The values of c and k were extrapolated from the lower levels and compared with the values of c and k based on the measured distributions at the upper levels. On the average, the extrapolation formulas performed well, but there was a good deal of scatter. For example, the mean ratio of extrapolated k to measured k was 1.06 with

a standard deviation of 0.18; the mean ratio of extrapolated c to measured c was 1.01 with a standard deviation of 0.19.

In order to express their results in terms of its implications for performance computations, Doran and Verholek compared estimates of average power output based on extrapolated PDFs with estimates based on the measured distributions. The results are depicted in Figure B-13. The computations were made for a wind turbine having steady-state performance characteristics as shown in Figure B-14 with a cut-in wind speed of 4.5 m/s, a rated wind speed of 10.7 m/s and a cutout wind speed of 17.9 m/s. Figure B-13 shows that, on the average, estimates of average power output based on the extrapolated PDFs agree with estimates based on the measured PDFs; however, the results also show that in 46% of the cases, the estimates based on the extrapolations differed from the estimates based on the measurements by 25% or more. Doran and Verholek then tested the general validity of Figure B-13 by varying the cut-in,

Figure B-13. Comparisons of Estimates of Average Power Output Based on Measured Wind Speed Probability Distribution Functions and Extrapolated Probability Distribution Functions. Average power was computed for a turbine having steady-state performance characteristics depicted in Figure B-14. Line corresponds to perfect agreement

Figure B-14. Steady-State Performance Characteristics for a Hypothetical 200-kW Wind Turbine

rated and cutout speed over a wide range of values. The results did not change significantly.

Sensitivity Testing of Statistical Models

One of the major advantages of the statistical approach to estimating wind turbine performance is the straightforward manner in which conclusions can be tested for uncertainties in the wind characteristics. These uncertainties will always exist; for no matter how long one may gather wind data at a site, there is no guarantee that the wind will behave in the future in exactly the same way as it has in the past. The level of this uncertainty decreases, of course, as the amount of time one has been collecting data at the site increases. The effects of such uncertainties can be determined by fitting Weibull functions to the measured distributions and by varying the Weibull parameters over a reasonable range of values (see Figures B-5 and B-6, for example).

TIME-SERIES MODELING OF WIND TURBINE PERFORMANCE

The principal problem with statistical modeling of wind turbine performance is that the behavior of the wind turbine is greatly over-simplified. As has been pointed out previously, the statistical approach assumes that power output over the averaging time interval is independent of previous wind or wind turbine behavior. The statistical approach also assumes that the wind turbine will be on-line and generating power at the level indicated by its steady-state performance characteristics

during the entire period that the average wind speed is between cut-in and cutout. In the past, the effects that these assumptions might have on the accuracy of wind turbine performance calculations have been assumed to be negligible.

A Quasi-Dynamic Model of Wind Turbine Performance

The traditional approach to producing time series of wind turbine power output is simply to convert time series of wind speed into time series of power output using the steady-state performance characteristics (Eq. B-5). This approach retains all of the assumptions of the statistical method and would be preferred over the statistical approach only when sequential information on wind turbine output was required and when the consequences of neglecting a wind turbine's dynamic behavior could be assumed to be negligible. A more realistic simulation of wind turbine behavior would require a model that accounted for the dynamic response of a real turbine.

Miller (9) has developed a quasi-dynamic model of DOE's horizontal-axis MOD-2 wind turbine that attempts to give a realistic simulation of that turbine's temporal behavior. The quasi-dynamic model consists of a computer code that mimics the micro-processor controlling the operation of the MOD-2. The quasi-dynamic model is driven by time series of wind speed and wind direction at hub height. The code monitors the wind data, and when startup conditions are reached, the code mimics the startup procedure. The code also simulates the MOD-2's yawing behavior and its shutdown procedures. When the code indicates that the MOD-2 would have been synchronized with the utility system, it computes power output based on steady-state performance characteristics and the wind speed corrected for any yaw error.

A flow chart depicting the quasi-dynamic model of the MOD-2 is shown in Figure B-15. As the figure shows, the quasi-dynamic model is considerably more complicated than the traditional approach wherein the wind time series are merely converted to power output time series using steady-state performance information. The quasi-dynamic model is not particularly expensive to run, however. Simulating a year's operation using 30-sample per hour wind data costs about \$100 on a minicomputer such as a PDP-11/70. The real cost is in developing the code; although that, too, would not be prohibitively expensive once information on the wind turbine's operating strategy and its response to changes in wind direction had been obtained from the manufacturer. Quasi-dynamic codes may, in fact, be available from the wind turbine manufacturer.

Figure B-15. Flow Chart for a Wind Turbine Performance Model That Accounts for the Turbine's Startup, Shutdown, and Yawing Behavior (Quasi-Dynamic Model). This computer code was written to run on 30 samples per hour time series of wind speed and wind direction

Comparisons of Quasi-Dynamic Simulations With Traditional Simulations

- Figure B-16 compares time series of power output for a MOD-2 wind turbine based on a quasi-dynamic simulation and a traditional (or "static") simulation. The two simulations were based on instantaneous samples of wind speed and direction taken every two minutes. The figure shows considerable difference in simulated behavior between the two methods.

Figure B-17 compares quasi-dynamic and static simulations of the MOD-2 for an entire year (10). Three separate static simulations are shown. One is based on a static simulation that calculates machine output every two minutes, of which 30 separate power output values are used to calculate the hourly average power output. The second uses the 30th sample each hour to represent the entire hour. This is most like using National Weather Service data. The third simulation takes all 30 samples per hour to compute an hourly average wind speed to use in the simulation. Figure B-17 shows that differences between the estimates of monthly average power output for the three static simulations are trivially small. The differences between the static simulations and the quasi-dynamic model, on the other hand, are significant. The quasi-dynamic model consistently yields a lower estimate of average power output by an amount that ranges from 10 to 25%.

Intuitively, it would seem that a quasi-dynamic simulation of wind turbine operation would produce more accurate estimates of wind turbine energy production than the traditional or statistical approach (Eqs. B-5 or B-6). However, this hypothesis has not been thoroughly tested. There are simply not enough measurements of wind turbine output combined with high quality wind data to enable tests of the various simulation techniques to be made. Until these tests are completed, the accuracy of any of the methods for simulating wind turbine performance - traditional or quasi-dynamic - will be uncertain.*

Sensitivity Testing of Time Series Models

Testing the sensitivity of wind turbine performance to uncertainties in the future behavior of the wind is less straightforward when performance computations are based on time series models than when they are based on statistical models. With statistical models, the relevant wind characteristics are the PDFs, and the sensitivity of

*Nevertheless, preliminary comparisons between a quasi-dynamic simulation of the MOD-0A wind turbine and measurements of the turbine's actual performance support the hypothesis. A. H. Miller of Battelle, Pacific Northwest Laboratories has informed the authors that for the first few months of comparisons, agreement between actual turbine output and the quasi-dynamic estimate is better than 10%.

A. Hourly Average Wind Observations

B. Two-minute Wind Observations with MOD-2 Operating Strategy Applied

Figure B-16. Time-Series Record of MOD-2 Power Output for a Certain Wind Turbine Site. Curve A is a traditional "static" simulation; Curve B is a "quasi-dynamic" simulation (Figure B-15)

Figure B-17. Comparisons of Quasi-Dynamic and Static Simulations of MOD-2 Performance for One Year at a Certain Site. Solid line is the quasi-dynamic simulation using 2-minute data. The dashed line is from the average hourly power output computed from a static simulation using 30 samples per hour. The circles denote a static simulation using the 30th sample each hour and the triangles denote a static simulation using hourly wind speed from 30 samples per hour (10)

wind turbine performance computations to uncertainties in the shapes of the PDFs can be tested by varying a couple of parameters in a Weibull fit to the measured distributions. With quasi-dynamic time-series models, however, wind turbine output averaged over a given time interval depends on what the wind and the turbine have been doing over previous time intervals. This type of behavior is too complicated to be expressed in terms of a couple of independently adjustable parameters. More study is required of the effects of normal year-to-year variations in wind behavior on performance estimates from quasi-dynamic models. Once the response of quasi-dynamic models to interannual variations in wind characteristics is better understood, procedures for testing the models to these uncertainties can be developed. In the meantime, it is suggested that if quasi-dynamic models are used to estimate net energy production, the percentage uncertainty in these estimates should be assumed to be

about the same as the percentage uncertainty in a net energy production estimate obtained by a statistical modeling approach.

Modeling Wind Turbine Behavior for Dynamic Impacts

The electrical output of wind turbine generators can be expected to show large minute-to-minute fluctuations due to the turbulent behavior of the wind. As was mentioned in Section 2, these fluctuations, when combined with normal fluctuations in system load, could affect short-term transient stability, system frequency control and the load-following capabilities of a utility's conventional generating equipment. Fluctuations in power output could also affect local transmission and distribution systems.

The ability to simulate how power output fluctuations could affect utility systems is limited by the lack of tested models for translating minute-to-minute fluctuations in wind speed and wind direction into minute-to-minute fluctuations in wind turbine (or wind turbine cluster) output. The quasi-dynamic model described in this appendix (and summarized in Figure B-15) is not completely suitable. The quasi-dynamic model tries to account for the effect of a wind turbine's operation strategy on its total synchronization time. It does not attempt, however, to simulate the very complicated dynamics of the rotor, drive train, generator and governor system that dominate the behavior of the wind turbine system on the time scale of seconds to minutes. It is quite possible that the simulation of wind turbine behavior on this time scale will require a fairly realistic and sophisticated model. On the other hand, it is also possible that such behavior could be adequately simulated by simple modifications to a quasi-dynamic model.* Resolution of this matter will require more research.

SUMMARY AND CONCLUSIONS

Statistical Models and Their Accuracy

Statistical models are the most widely used techniques for predicting wind turbine performance at prospective wind turbine sites. Their principal advantage is their ease of application. The required computations can be easily performed on desk-top or hand-held calculators. Sensitivity testing is also simple and straightforward. The principal shortcoming of the statistical approach is in the way a wind turbine's

*This could be done by introducing a noise factor that would cause the simulated power output to scatter around the values given by the steady-state performance characteristics (as shown in Figures B-2 and B-3).

response to the wind is oversimplified. In the statistical approach, a wind turbine's output at any given time is assumed to be independent of its previous behavior. Lost time due to startup and shutdown procedures is neglected and the effects of yaw errors (differences between wind direction and the orientation of the turbine) on performance are neglected.

There are very few published accounts of comparisons between actual wind turbine performance and the performance predicted by statistical models (or their equivalents). One of the few published studies was performed by Juul (11) and reported by Golding (12). Juul's study was based on a 13-kW, fixed-pitch wind turbine having a rotor diameter of 8 m (~26 feet). Electric energy produced by the turbine was measured by a watt-hour meter, and wind speed measured at hub height on a nearby tower. Monthly energy production was compared with the energy production computed from hourly averaged wind speeds and the steady-state performance characteristics. After eight months, computed energy production agreed to within 10% of the actual energy production. There was, however, a great deal of scatter between computed and measured energy production on a monthly basis. Even for some of the windier months, the discrepancy between computed and measured output was ± 30 to 40%. Month-to-month scatter was so large that the good agreement between the eight-month averages could have been fortuitous and not representative of the true long-term accuracy of such estimates. Similar studies have yet to be reported for more recent wind turbine installations such as the DOE/NASA MOD-0A turbines. Recent summaries of operating experience have indicated, however, that there is some discrepancy between actual electric energy production and what would have been expected from energy production estimates based on statistical models (1). Given the very sketchy evidence, it would seem prudent to assume that any estimate of electric energy production based on statistical modeling could differ by 10 to 30% from what a real wind turbine would have actually generated.

Quasi-Dynamic Models and Their Accuracy

Presumably, a quasi-dynamic model will yield more accurate simulations of wind turbine energy production rather than approaches that neglect the effect of startup, shutdown and yawing behavior on power output. The quasi-dynamic model accounts for lost time due to startup and shutdown procedures and accounts for the effect of yaw errors on performance. Another advantage of the quasi-dynamic model is that it explicitly determines the effects of wind speed and wind direction fluctuations on a wind turbine's operating behavior. The number of startup, shutdown and yawing maneuvers that a wind turbine might undergo over its expected service life could be

a site-selection factor. Quasi-dynamic modeling enables this factor to be determined directly.

The disadvantages of quasi-dynamic models are that they require a digital computer in order to run, they require a certain amount of programming effort to develop, and they require input wind data in a time-series format (time-series data is more expensive to collect than measurements of probability density functions). These advantages would not seem serious, however, if the quasi-dynamic approach resulted in a more accurate and more realistic simulation of wind turbine performance.

Comparisons of monthly average energy production estimates between a quasi-dynamic model of a MOD-2 wind turbine and a "static" model of the same turbine have shown the static model, which is equivalent to a statistical model, to make higher energy production estimates. Production estimates from the static model were 10 to 20% higher than production estimates from the quasi-dynamic model for each month of the 12-month period studied. This result would appear to indicate that performance reduction due to startup and shutdown procedures and to the effects of yaw errors on turbine performance were significant. A note of caution should be expressed about this conclusion, however. Figures B-16 and B-17 are based on simulations that used 30 instantaneous samples of wind speed and wind direction per hour. This is not an optimum sampling rate for a quasi-dynamic model. Such a coarse sampling rate makes the wind appear noisier than reality, and it could result in an overestimate of operating time that is lost due to startup and shutdown. In spite of this caution, however, it should be noted that the differences between the static and quasi-dynamic models that are depicted in Figure B-17 are not inconsistent with the differences that have been noted between the actual output of large wind turbines and the output predicted by statistical models (1).

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Appendix C

WIND TURBINE ECONOMICS

The issue of economic viability overrides the entire wind turbine siting process. An analysis of the economic considerations in wind turbine siting employs a three-step approach:

1. economic analysis using generic wind turbine installation costs
2. economic analysis using site-specific installation costs
3. economic analysis using production cost modeling.

These three steps take place at different stages in the siting methodology, as shown in Figure C-1.

ECONOMIC ANALYSIS - GENERIC COSTS

The first stage in the siting process is to determine if the area under consideration has the minimum annual wind speed required for the economic operation of a given wind turbine generator. This minimum wind speed should be the annual mean wind speed at which the levelized cost of energy for the particular wind turbine equals the levelized cost of energy for the conventional utility system.

The minimum useful wind speed can be determined by using a simple cost of energy (COE) formula together with an annual energy production versus mean wind speed curve for the wind turbine under consideration.

The COE equation is given as:

$$COE = \frac{IC \cdot FCR + AOM \cdot LF}{AEP}$$

where

COE = levelized cost of energy over the lifetime of the wind turbine for the utility system in \$/MWh. Under the most liberal of assumptions, one may unrealistically assume that this cost corresponds to levelized peaking power costs. A more realistic approach is to assume that the COE is equal to the levelized average marginal cost

of power. Levelized marginal costs can be computed from the utilities' load duration curve, as shown in Figure C-2.

IC = generic "turn-key" installed costs for the wind turbine under consideration. These include generic costs for the installed wind turbine, land, access roads and the electrical interconnection. More specific costs are considered later in the methodology, after candidate sites are identified (see Appendix D).

FCR = fixed charge rate

Figure C-1. Economic Analyses Performed at Different Stages in a Wind Turbine Siting Study

AOM = annual generic operating and maintenance costs from manufacturers' projections

LF = levelizing factor that accounts for the impact of inflation on operation and maintenance costs over the lifetime of the wind turbine

AEP = annual energy production required to meet the COE.

By transposing the COE equation to

$$AEP = \frac{IC \cdot FCR + AOM \cdot LF}{COE}$$

the AEP required from the wind turbine under consideration to equal the projected levelized COE for the electric system can be calculated. By plotting the AEP on the vertical axis of the annual energy production versus mean wind speed curve for the wind turbine under consideration, the minimum annual wind speed required (or minimum useful wind speed) can be determined. Figure C-3 depicts the use of a "typical" AEP

$$\text{AVERAGE MARGINAL COST (AMC)} = 15\% \times \frac{\$120}{\text{MWH}} + 75\% \times \frac{\$60}{\text{MWH}} + 10\% \times \frac{\$30}{\text{MWH}} = \frac{\$0.07}{\text{KWH}}$$

$$\text{LEVELIZED AMC} = \frac{\$0.07}{\text{KWH}} \times (1.65) = \frac{\$0.12}{\text{KWH}}$$

Figure C-2. Determination of Levelized Average Marginal Production Cost Using a Load Duration Curve

UTILIZE WIND TURBINE MANUFACTURER'S PROJECTED ENERGY OUTPUT VERSUS MEAN WIND SPEED CURVE (OR YOUR OWN ESTIMATES OF THIS RELATIONSHIP) TO DETERMINE THE MINIMUM MEAN WIND SPEED REQUIREMENTS FOR A SITE.

ONCE THE MINIMUM MEAN WIND SPEED IS IDENTIFIED, ONE CAN UTILIZE WIND ENERGY RESOURCE ATLAS OR KNOWN LOCAL METEOROLOGICAL DATA TO SCREEN AREAS THAT MEET THIS REQUIREMENT.

Figure C-3. Using Information on Annual Average Energy Output as a Function of Annual Mean Wind Speed to Determine Minimum Useful Wind Speed

versus mean wind speed curve for this procedure. Once the minimum annual wind speed is determined, all areas identified in the wind resource atlases with lower wind resources can be eliminated from further consideration. If this procedure eliminates the entire region under consideration, the realism of the values assumed for the COE equation should be checked. Local wind resource data should be used wherever possible to replace that represented in the wind resource atlases. This procedure should be carried out for a variety of wind turbines to determine which (if any) is the most economic for a particular utility's characteristics.

ECONOMIC ANALYSIS - SITE-SPECIFIC COSTS

At the completion of the first step in the economic analysis, Candidate Resource Areas, which appear to have the minimum wind resources required for the economic viability of a wind turbine installation, are identified. The siting methodology then screens these resource areas using non-economic factors to identify Potential Candidate Sites within their boundaries.

In Stage III of the methodology, Potential Candidate Sites are ranked according to their economic potential and other pertinent characteristics. This second step in the economic analysis is virtually the same as that performed in Stage I, i.e., a COE calculation, except that in Stage III the costs are based on site-specific conditions rather than generic estimates. By developing estimates based on site-specific conditions, variances between sites in such factors as foundation costs, land costs, electrical interconnection costs, property tax rates, and operating and maintenance costs can be identified and factored into the COE computation. However, this will require a detailed breakdown of the generic costs from the wind turbine manufacturer, and a recognition of potential electromagnetic interference and other problems and possible solutions (see Appendix D).

Based on the COE calculations, a minimum wind speed requirement for each site is developed using the appropriate AEP versus wind speed curve, as in Stage I. With this information, each site is evaluated as to the probability that the local wind speeds will meet or exceed the minimum (or break-even) requirement. This requires some knowledge of local wind speeds and/or an evaluation by experienced meteorologists. Due to their large scale, the wind atlases will be of limited value in this analysis.

To more accurately depict the economic viability of wind turbines for a particular site, minimum (break-even) wind speed requirements are calculated for each season of the year, corresponding to COEs computed for each season. Such an analysis shows whether the seasons of peak wind speed correspond to those with the highest electrical generating costs.

As the conclusion of the economic analysis in Stage III, the Potential Candidate Sites are ranked according to their economic viability, i.e., the probability and degree to which each site will meet or exceed its break-even wind speed requirement. Figure C-4 is an example of the impact that site-specific cost differences can have on minimum (break-even) wind speed requirements.

EXAMPLE:

RANKING OF CANDIDATE SITES (SITE SPECIFIC COSTS)

<u>SITE A</u>	LEVELIZED AVERAGE MARGINAL COSTS	<u>SITE B</u>
ASSUMPTIONS: COE = \$0.12/kWh		\$0.12/kWh
INSTALLED COST = \$6,000,000 (1981 \$)		\$3,000,000 (1981 \$)
ACR = 22%		21%
O&M = \$50,000 PER YEAR (1981 \$)		\$40,000 PER YEAR (1981 \$)
LF = 2		2
$AEP = \frac{IC (FCR) + O\&M (LF)}{COE}$		
$AEP = \frac{\$6,000,000 (0.22) + \frac{\$50,000 (2)}{YR}}{\$0.12/kWh}$		$AEP = \frac{\$3,000,000 (0.21) + \frac{\$40,000 (2)}{YR}}{\$0.12/kWh}$
$AEP = 11.8 \times 10^6 \text{ YR}$		$AEP = 6.0 \times 10^6 \text{ YR}$
CORRESPONDS TO 14.5 mph MEAN BREAK-EVEN WIND SPEED		CORRESPONDS TO 12 mph MEAN BREAK-EVEN WIND SPEED

Figure C-4. Effect of Differences in Site-Specific Installation, Operation and Maintenance Costs on Break-Even Wind Speeds

ECONOMIC ANALYSIS - PRODUCTION COST MODELING

In the first two steps of the economic analyses, single COE computations, using successively more accurate cost estimates, are utilized to assess the economic viability of wind turbine installations. This procedure offers distinct advantages for one who wants a ballpark estimate of whether it is worthwhile to continue the siting process. It is a relatively simple procedure; it does not take long to perform; it is easily modified for varying parameters (costs, study years, etc.); and it is not expensive.

However, because of the simplicity of the first two steps, their results can often be misleading. By not being able to take into account such factors as the variable nature of the wind and wind turbine operating strategies, a simple COE analysis does not give an accurate representation of the actual displaced production costs over

the year. The only method that can properly include these factors is a generation production cost model.

Most utilities already utilize production cost modeling programs to assist in developing their generation expansion plans. For those who do not, a variety of models are available and are identified in economic analyses of generation systems done by EPRI and others.*

Basically, all production cost models match the utility system load to an economic dispatch of existing and planned generating units throughout the study period. By including such factors as unit availability, forced outage rates, maintenance requirements, heat rates at varying load levels, unit fixed and variable operation and maintenance costs and purchase and sale agreements, these models can produce an accurate estimate of production costs throughout the year. The projected wind turbine output can be appropriately modeled in these programs, and resulting production costs can be compared to the base (without wind turbine) production costs. The resultant difference is thus the production cost savings attributable to the introduction of the wind turbine. For economic viability, the carrying charges on the wind turbine plus its operating and maintenance costs should be less than (or equal to) the production savings.

*Chapter 2 cites studies of modification of production cost models to include wind turbine generation.

Appendix D

ESTIMATING INSTALLATION COSTS FOR WIND TURBINE SITING STUDIES

THE GENERAL PROBLEM

There are two basic decisions that must be made by a utility in planning for a new electric generating plant. One decision is to determine the type and size of the plant while a second, distinct decision is to determine the site where the plant will be located. These same decisions must also be made when planning for nonconventional plants such as wind turbines. Both basic planning decisions hinge on economics, and evaluating economics requires information on the installed costs of the plants.

Early in the planning process, total installed costs are based on generic estimates using typical plant layouts. These estimates are used in all preliminary feasibility studies (conceptual estimate level). The estimates are then refined as more detailed information on specific sites becomes available. At each stage in the decision process, the utility will decide on the accuracy needed in any cost estimates (budgetary or definitive estimates level). The required accuracy will dictate the scope and depth of detail needed in the information that goes into these cost estimates.

Financial matters such as economic feasibility and cash flow requirements depend on estimates of the total (absolute) costs of installing the plant at each site. Comparative evaluations of alternatives, however, can often be based on differential cost estimates. Points in the wind turbine siting process where differential cost estimates could be made are in comparing Candidate Resource Areas (where costs would be based on typical sites within the Candidate Resource Areas) or in comparing alternative sites. Differential costs are actually the total cost of an installation minus the costs common to each site; they can be calculated by identifying the items whose costs are site dependent. An example of this concept is the wind turbine itself. The basic cost, FOB the factory, will be the same regardless of the site, while the transportation of the wind turbine components to each site may vary. The cost of the final assembly can vary due to variations in labor rates, variations in the productivity of the work force, and differences in the difficulty of the erection process at different sites. Thus, even though the cost of the wind turbine and its installation is the largest single capital cost and will probably appear the same at

each site, these other factors will probably be the dominant differential costs. Other site-dependent items include site preparation and foundations. These differential costs are quite often much smaller than the large common costs and are lost in the rounding off of the total dollars. Working with differential costs, therefore, provides a degree of resolution that might be lost when working with the absolute numbers.

This appendix summarizes the types of cost estimates that should be made in each stage of the siting process. Both absolute and differential costs are considered. Estimating these costs for installing wind turbines at a site will require close interaction between the utility and the wind turbine manufacturer. Therefore, a brief survey was made of wind turbine manufacturers to obtain a gauge of their awareness of these costs and other factors important in wind turbine siting. A copy of the questionnaire and a summary of the manufacturer's response is also included in this appendix.

COST ESTIMATES FOR STAGE I

In Stage I of the wind turbine siting process, cost estimates are required for two purposes. The first purpose is to establish the minimum useful wind speed (see Section 4). This purpose requires estimates of total or absolute costs (capital plus operation and maintenance) for a typical (i.e., generic) installation. The second purpose would be to rank Candidate Resource Areas on the basis of the differentials in installation and operation and maintenance costs, if this method of ranking were preferred over the scoring procedure described in Section 4 (also see Appendix E).

Capital Costs

By Stage I of the siting process, the following information has been established:

- model of wind turbine(s) under consideration
- minimum number of wind turbines in the cluster
- in-service date of the cluster.

Since actual sites have yet to be identified, the total cost of a wind turbine installation must be estimated utilizing a typical layout of the wind turbine on a hypothetical site. Cost items that would have to be estimated in order to establish installation costs include:

- approximate estimate of installed cost of wind turbine minus cost of transportation to the site

- access roads on site
- electrical and dispatch communication equipment on site but not supplied with the wind turbine
- meteorological tower
- service building
- foundation
- site preparation
 - grading of site
 - clearing of trees, buildings, etc.
 - preparing parking lot
 - landscaping
 - installing fencing
 - installing water supply
 - installing electrical supply for meteorological tower, construction activities, service building lighting, etc.
- cost of land
- wind rights
- visitors center (if desired).

At this stage of the siting process, specific sites have not been identified; thus, the above costs can be considered common to all sites. There are other installation costs, however, that will probably show significant variation between Candidate Resource Areas. The differential costs are:

- transporting the equipment to the site
- travel time and subsistence for construction crews
- access roads to site
- typical transmission line from site to grid
- other costs, such as turbine erection costs, considered unique to a specific Candidate Resource Area.

When computing the minimum useful wind speed, typical values must be assumed for each of the variable items. The generic installed cost then becomes the common costs added to the typical differential costs plus allowances for contingencies, overheads and funds used for construction. When, on the other hand, Candidate Resource Areas are to be ranked on the basis of installation costs, the sum of the differential costs for typical sites in each Candidate Resource Area is the relevant ranking criterion.

Operation and Maintenance Costs

Wind turbine clusters will generally be installed in remote areas; thus, they will be automated or controlled remotely. The amount of operator attention will depend upon the confidence the utility has in remote analysis of the operating wind turbines.

With input from the manufacturer, the utility will be able to estimate the amount of time that utility personnel will be required to spend at the site for operation and maintenance duties. Travel time is then added to obtain labor costs for operation and maintenance.

A sample of items that could require the attendance of operation or maintenance personnel include:

- checking for damage to equipment
- checking routine operating characteristics such as vibration in components, oil levels and temperature of bearings, temperature of generator components, etc.
- performing routine normal maintenance
- inspecting components such as gear train, generator, blade, etc.
- investigating interference or other complaints.

Excluding travel time, most operation and maintenance costs will be the same for all sites.* However, for those costs that could show significant variation between Candidate Resource Areas, it is sometimes convenient to determine a capitalized equivalent of the differential operation and maintenance costs and add this to the differential capital costs when Candidate Resource Areas are ranked according to differential installation costs.

COST ESTIMATES FOR STAGES III AND IV

By this stage of the siting process the following items have been determined for a particular siting study:

- model of wind turbine(s) under consideration
- number of wind turbines in the cluster
- in-service date of the cluster

*It is assumed that the same number of turbines would be installed at all sites.

- location of potential sites
- individual characteristics of each site.

The purpose of the cost estimates at these stages is to provide the basis for ranking each site. In Stage III the basis for ranking is the probability of exceeding a break-even wind speed, defined by the average marginal production costs and the site-specific operation and maintenance costs. In Stage IV the basis for ranking is the net savings realized by the wind turbine cluster located at each prospective site. In Stage IV, these savings are determined by production cost modeling (see Appendix C).*

By these stages of the siting process, cost estimates are site-specific and are based on a specific layout of the cluster at each site. These layouts are determined by the terrain and the wind regime of each individual site; therefore, the layouts are probably not identical. The principal difference between the estimates made in Stage III and in Stage IV is in accuracy and level of detail. In Stage III, cost estimates will be site-specific, but they will be based on quick engineering estimates. In Stage IV, cost estimates will be more detailed and more accurate; they will probably be based on preliminary engineering plans for the wind turbine installation. Site specific quantities, such as length of access roads and cut and fill for grading, will be measured to provide the basis for costing. The transmission connection from each site to the utility system will be determined. Soil borings might be considered as early as Stage III to ensure that soil conditions were compatible with expected foundation loads.

The scope and level of detail required at each stage of the siting process is determined by the utility. These specifications will be defined by the accuracy desired. Typical items to be included in estimates of installed cost are:

- the best estimate (a firm price, if available) for the wind turbine delivered to the site
- the best estimate (firm price, if available) for erection or final assembly of the equipment
- access roads to and on the site

*Another way to rank Candidate Sites is to include wind turbines in the generating mix at no cost and then to determine the net costs a utility could afford to pay for the production cost savings realized (1). Sites are ranked on the basis of the differentials between these costs and the actual costs, including capitalized operation and maintenance.

- purchase and installation of equipment not supplied by wind turbine vendor
- meteorological tower(s)
- foundation - depending upon the known conditions of the soils, bed rock, etc., the utility might need borings to determine the type of foundation and thus increase the accuracy of the estimate
- electrical connection to the utility system
- site preparation based upon actual measurements:
 - grading
 - clearing
 - parking lot
 - landscaping
 - fencing
 - water supply
 - electrical supply
- cost of land based upon realtor's appraisal
- service building (if required)
- visitors' center (if desired)
- wind rights (if deemed appropriate)
- communication systems
- licensing, permits and environmental reports
- corrections for any electromagnetic interference
- public acceptance programs.

All of the costs mentioned above will be for the in-service date of the wind turbine installation. Contingency funds, overheads and allowance for funds used during construction must also be added to the installation costs if they apply.

Operation and maintenance costs will also have to be determined for each site. The estimates for operation and maintenance costs that were made in Stage I of the siting process will probably provide the base cost estimate. The site-specific operation and maintenance cost estimate will be obtained by adding the travel time differentials to the base estimate.

MANUFACTURER SURVEY

A major portion of the normal siting methodology utilized by utilities for fossil-fired generating units is applicable to wind turbine siting. However, a wind turbine consists of a single major item, from a single vendor, that requires primarily a foundation and interconnections to the electric grid and dispatch control. This is in contrast to the many components (such as the steam generator, turbine generator, and condenser), each from a separate vendor, that must be optimized and integrated into a fossil-fired generating unit by the utility. Thus the wind turbine requires a less complicated coordinating effort for design.

The utility will undoubtedly have direct communication with the wind turbine vendor. To aid the utilities in this communication, to gain insight for this project and to provide the vendors with the type of information felt necessary, a list of pertinent questions was prepared and sent to several wind turbine vendors. The list is included here since the questions are a sample of the type of information a utility might seek from manufacturers. A summary of the vendors' responses follows the list of questions.

Vendor Questionnaire

The three utility subcontractors formulated the questionnaire and sent it to the wind turbine vendors. The cover letter explained that the utilities were involved in an EPRI-funded project to develop a siting methodology for large (100 kW +) wind turbines. The methodology would address the environmental, economic and engineering factors of determining adequate sites for a single wind turbine or a cluster of wind turbines, whose output would be integrated into a utility system. A final document would contain generic guidelines for screening relatively large areas for potential sites, and parameters and a procedure for screening and ranking potential sites to identify those which should be instrumented with wind monitoring equipment to verify the wind resource. The subcontractors were to perform a trial application of the methodology as part of the project.*

The cover letter also said:

We realize that you, as a manufacturer of large wind turbines, have spent considerable time and effort in addressing many of the same issues that we are attempting to address in this project. It is our desire that you, as a manufacturer of wind turbines, be made aware of the specific issues we feel are noteworthy and to solicit input from you regarding these issues.

*This trial application is described in a separate report.

Primarily your input will be appreciated in the capital and operation and maintenance costs, safety, land requirements and other considerations to help determine site characteristics and layouts necessary to properly install wind turbine clusters. To this end, we have prepared a list of questions relating to both generic and specific issues regarding wind turbine siting. Your cooperation in responding to these questions will provide valuable input to the development of the methodology. At the same time, we hope that it provides you insight regarding the issues that utilities regard as paramount in investigating the feasibility of wind turbines for electric utility application. All answers will be considered confidential by the people working on the project and specific answers from specific suppliers will not be identified in any written document.

We realize that some of the questions are rather complex and far reaching and the answers will be speculative at this time. However, any information you can provide will be of assistance in accomplishing project objectives. For consistency in comparing costs, please use 1980 dollars for answers to economic-type questions.

General

1. Do you have a specification packet for your wind turbines and, if so, please provide a sample packet.
2. What equipment warranty or guarantee will you provide?
3. What is your assessment of public acceptance of wind turbine clusters in the more populated areas of the country? How can the manufacturer assist the utility in gaining public acceptance?
4. What is your anticipated production schedule and its resultant cost of a turnkey-installed wind turbine in 1980 dollars/kW in 5 years? 10 years?
5. Do you plan to offer a lump sum or turnkey contract and, if so, what will be your scope of supply?
6. If you do offer a lump sum or turnkey contract, how long does the quotation remain in effect?
7. What minimum set of wind data and site characteristics do you require from the utility to:
 - a) offer a proposal?
 - b) include a performance guarantee (over what period of time)?
 - c) check out and verify performance as specified?
8. What parameters must be measured on a routine basis to monitor the operation and performance of the wind turbine?
9. What information do you need in designing your machine to a specific site?
10. What training is required for utility operating and maintenance personnel?
11. Would this training normally be offered as part of the contract for the machine?

12. What is your estimate of insurance requirements?
13. What is your estimate of FAA requirements?
14. Please provide your estimate of operating and maintenance costs (both fixed and variable).

Construction Data

1. What are the forces and conditions that must be considered in the foundation design?
2. What is the cost of field construction if the wind turbine is purchased FOB at the site at this time and after several of your wind turbines have been constructed?
3. What interface provisions for remote control, such as dispatching, are provided?
4. What are the electric power requirements during construction (voltage, maximum kW)?
5. Please define the minimum quality of the access roads for transportation of equipment to the site. This includes load limits, road width, grade, turning radius, etc.
6. What is the minimum area required during construction of the wind turbine? Are there some minimum length and width requirements?

Operating Data

1. Please provide performance curves for your wind turbines.
2. What auxiliary power is required when generating?
3. What auxiliary power is required when not generating?
4. What auxiliary power is required for starting or stopping the wind turbine?
5. Assuming remote operation, what routine site observations by utility personnel do you believe are required?
6. What are the electrical characteristics of the generator, such as:
 - a) rated output?
 - b) voltage?
 - c) power factor at rated power?
 - d) short circuit ratio?

Maintenance Data

1. What is your estimate of the lifetime of the wind turbine components?
2. What is the maximum potential down time to await replacement of major components?

3. What is your projected availability of the components over the life-time of the wind turbine? This includes components made by other vendors but in your scope of supply.
4. What is your recommended routine maintenance schedule including:
 - a) frequency and duration of routine outages?
 - b) personnel requirements?
 - c) maintenance functions that are performed at ground level, in the nacelle or outside the nacelle?
5. What accommodations are provided to facilitate inspection and/or replacement of components such as generator bearings, speed increaser gears, etc.?
6. What is included in your list of spare parts and special tools? What is the cost of the package?
7. What diagnostic equipment is supplied for routine inspections?
8. Do you plan to offer maintenance as a contracted service? If so, what do you project the availability of maintenance personnel to be in the future?
9. Do you have plans to provide for an emergency maintenance service?

Safety Considerations

1. What provisions have been provided to protect the general public and utility personnel?
2. Do you have a recommended exclusion radius?
3. What provisions have been provided to protect the wind turbine?
4. What is the operating and survival tolerance for gusty winds, turbulence, storms, lightning, temperature extremes, etc.?
5. What icing detection and de-icing provisions are provided?
6. What is the maximum distance that debris could be thrown by the rotor?
7. What type of fire control system is supplied?

Site Restraints

1. What spacing is suggested between wind turbines in a cluster?
2. Please provide estimates of an expected sound spectrum, as a function of distance, from a single wind turbine and a cluster of two or three.
3. What precautions must be taken to avoid radio, TV or microwave interference?
4. What are the air quality requirements considering such things as dust, grit, sand, chemical, salt, etc.?

Other

1. Briefly state any other considerations which you consider to be pertinent to the study.

Vendor Response

The response of the vendors was fairly general and non-specific. This response was not surprising considering the infant state of the wind turbine industry. Manufacturers were also reluctant to give specific responses to a "theoretical" request. They probably would have been more specific if they had felt that an actual wind turbine purchase was imminent. Given these general observations, the results of the questionnaire are summarized below.

The manufacturers confirmed that public acceptance is an unknown, but they believed that it would be positive. This assumption can only be gauged after reliable and safe operation of several wind turbines. The aesthetic qualities of the wind turbine installation itself will do much to enhance public acceptance.

Turnkey contracts and performance guarantees will be offered as more actual operating experience is gained. Generally, up to one year's hourly data will be required from the utility for performance guarantees. This data can be supported by longer term data from nearby locations within the same general wind regime.

Normal operating and maintenance expenses are difficult to predict. "Budgetary" estimates can be 1 to 2% of the installed cost and the cost per wind turbine will decrease if the turbines are installed in clusters.

The wind turbines are being designed for a 25- to 30-year lifetime, automated operation in remote areas and emergency shutdown in case of severe weather. Reliable, safe and economical operation is the basic goal of each vendor. The vendors are ready and willing to work with each utility for specific sites so that this goal can be met and the credibility of this type of generation can be established.

REFERENCE

1. Wind Energy Systems Application to Regional Utilities. Wilmington, Mass.: JBF Scientific Corporation, 1979.

Appendix E

GENERIC COST ESTIMATES FOR WIND POWER

Source: Technical Assessment Guide. Palo Alto, Calif.:
Electric Power Research Institute, May 1982.
EPRI-T-2410-FR.

Wind power is utilized when the kinetic energy in a moving airstream (wind) is used to drive a turbine, which in turn drives an electrical generator. In a representative current horizontal-axis wind turbine design, a double-bladed rotor of 300 feet in diameter is mounted at its center to a 200-foot cylindrical tower. Rotors are made of steel or wood-fiberglass composite. A representative rating is 2.5 MW, but machines rated up to 4 MW are under development in the United States and even larger designs are being studied internationally. Typically, a machine will begin producing power at its "cut-in" wind speed, reach rated power at a somewhat higher wind speed, and continue producing rated power up through its "cutout" wind speed at which the machine shuts down for self protection. For the representative 2.5 MW wind machine, these critical design wind speeds are 14 mph, 27.5 mph, and 45 mph, respectively. The maximum survivable wind speed is 125 mph at hub height (top of tower) and the design life is 30 years. The synchronous generator for the representative machine is rated 2.5 MW, 3125 kVA, 4160 volts, 3-phase, 60 Hertz. Clustering machines at a site requires spacing equivalent to 10 to 20 rotor diameters between machines. The following list itemizes the costs anticipated for a cluster of representative wind turbines.

Exhibit App B4-23b

WIND POWER

Region: East/West Central

Unit Size--Net Electrical Output, MW	2.5
Available for Commercial Orders, Year	1985
First Commercial Service, Year	1988

Unit Capital Costs,* \$/kW (net) based on Plant Size of (number of units x unit size)	25 x 2.5
Total Plant Cost, December 1980 \$ (based on overnight construction)**	925
Total Plant Investment, January 1981 In-Service (includes AFDC)	940
Startup, Inventory, Land, December 1980 \$	30
Total Capital Requirement, January 1981 In-Service (includes AFDC)	970

Operation and Maintenance Costs,* 1981 Costs
in December 1980 \$

Fixed, \$/kW-yr	9
Incremental, mills/kWh:	-

Performance at Sea Level
Wind Speed at 200 ft
Elevation, mph

% of Rated
Output

14 or less
28-45
above 45

0
100
0 (shutdown)

Unit Availability*

Planned Outage Rate, %	5.0
Unplanned Outage Rate, %	8.0
Equivalent Unplanned Outage Rate, %	8.0
Operating Availability, %	87.4
Equivalent Availability, %	87.4
Average Daily Unavailability, ADU, %	-
Capability Ratio	1.09

Duty Cycle

Minimum Load, %

10

Preconstruction, Licensing and Design Time, Years

2

Idealized Construction Time, Years

2

Unit Life, Years

30

Technology Development Rating**

3

Design and Cost Estimate Rating**

1

* For mature plant

** See source for definition.

***Fuel displacement (typical capacity factor range: 30-40%)

Appendix F

PROCEDURES FOR WIND RESOURCE EVALUATION

Accurate but efficient evaluation of the wind resource requires an understanding of the meteorological problems of siting large wind turbines and the resource evaluation techniques that have been developed. The main meteorological problem in siting is the variability of the wind resource. The variation in the magnitude of the wind from one place to another makes it difficult to identify locations of Potential Candidate Sites. The variation of wind with time at a particular location complicates the determination of the wind resource economic value. Wind characteristics such as average wind speed, turbulence intensity, and seasonal and diurnal variations can differ significantly over seemingly short distances. Thus, 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. The high cost of making new measurements has stimulated great interest in techniques for estimating the wind energy potential of an area or site without having to initiate wind measurements everywhere.

Numerous resource evaluation techniques have been proposed. These techniques can be applied over large land areas to identify smaller areas of high wind potential, or they can be used to estimate wind behavior at a particular site. Among these techniques are:

- existing and/or supplementary wind data analysis
- topographical indicators of wind energy potential
- biological indicators of wind energy potential
- geomorphological indicators of wind energy potential
- social and cultural indicators of wind energy potential
- numerical modeling of flow over terrain
- physical modeling of flow over terrain.

The first part of this appendix provides brief descriptions of the available resource evaluation techniques. The principal features of each technique are presented; examples of how these techniques have been applied, references to studies where more details can be found, and potential pitfalls of each technique are also included.

The discussion makes it apparent that local meteorology, topography, and the size of the area being studied will determine which techniques are applicable for the various stages of the siting procedure.

A strategy for applying these techniques is necessary so that they will be used efficiently. The second part of this appendix is a guide to using the various techniques at the appropriate stages in the siting process. The problems that the meteorologist must solve at each stage are reviewed, followed by suggested courses of action for applying the siting techniques. The approach suggested at each stage emphasizes successive application of techniques in an order that will provide the most information, in the least time, and at the least expense. Thus, an action in Stage II (select Potential Candidate Sites) requiring data collection for a long period of time principally to drive a numerical model is relegated to a last-resort action. Attempts to survey a Candidate Resource Area for evidence of wind-caused geomorphological features is encouraged because those features may indicate good winds; but attempts to quantify specifics of the wind characteristics from sand dunes near a Potential Candidate Site are discouraged because the uncertainties of the technique overshadow the potential gain in information. Similarly a wind tunnel model is not suitable for modeling large Candidate Resource Areas, but can be superior to numerical models in designing a Candidate Site measurement network or laying out a cluster at the Preferred Site.

Considerable knowledge, experience, and judgment are required to apply the strategies and techniques correctly. Each technique presented in the first part of the appendix can be a powerful supplier of information, but no technique is without drawbacks. The general strategy presented in the second part has been used effectively in several different studies, but the strategy should not be accepted as dogma. It is strongly recommended that an experienced boundary-layer meteorologist be included in a site-selection team. Large utilities may have this expertise on their staff; otherwise, the relevant meteorological expertise should be found in firms that have specialized in air pollution problems in complex terrain.

TECHNIQUES FOR RESOURCE EVALUATION

A basic description and examples of the use of each resource evaluation technique are given below. Extended detail is given by Hiester and Pennell (1).

Existing and Supplementary Data Analysis

The evaluation of the wind resource in a region or at a site will always begin with examining the existing meteorological data. There are limits to the usefulness of wind data at locations separated from the measurement site by large distances or complex terrain. The numerical modeling, physical modeling, and topographical indicator techniques are used to interpolate or extrapolate wind data to other locations. However, using these techniques requires some characterization of basic wind and weather patterns. The meaning of pattern, as it is used here, is very broad. It encompasses any aspect of wind and weather behavior that may be succinctly categorized or summarized, whether the pattern describes one data station only or the simultaneous relationship among many. Once the patterns are identified, the other techniques can be applied. The result of applying the other techniques is identification of attractive high-wind areas or sites where new wind measurements are appropriate. As these new data are collected, estimating long-term statistics from short-term data becomes a problem.

These two problems in analyzing existing and supplementary wind data - characterizing wind patterns and estimating long-term significance of short-term measurements - are discussed here.

Characterizing wind patterns. 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 (discussed later in this appendix) 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. This is true if the territory is the Region of Interest, a Candidate Resource Area, a Potential Candidate Site, or a Candidate Site. In each territory there may be just one or possibly many points where data were collected.

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 needs to get to recognizing a pattern at a very flat site. More formal recognition of patterns is 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 valley winds can be cold does not matter. However, this might be a highly significant point to other kinds of models

or to the meteorologists using topographical indicators to estimate the flow behaviors at other points in the territory being analyzed.

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 F-1 provides some indication of the utility of several different single or joint frequency distributions.

Table F-1

TYPICAL FREQUENCY DISTRIBUTION PRODUCTS AND
THEIR POTENTIAL APPLICATIONS

<u>Dimensions of Frequency Distribution</u>	<u>Usefulness in Characterization of Wind Behavior or Analysis of Wind Potential</u>
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 (see section on Topographical Indicators).
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.

Table F-2 is an example of a joint wind speed-wind direction frequency distribution. This table shows that 3.0% of the winds were from the north at 6 m/s during the months of March from 1965 to 1978 at Sandberg, California. Table F-2 also shows that the most commonly occurring winds and strongest average winds were NNW or N. This may be regarded as a dominant pattern. There is a secondary peak in frequency of occurrence for SSW and S winds, which constitutes a second pattern. These directions, when interpreted in terms of the topography around Sandberg, suggest the strong regional topographic influence on the regional flow characteristics.

The right-hand column of Table F-2 contains the frequency distribution of wind speed, which is plotted in Figure F-1. The wind speed frequency distribution is fundamental information required to make energy production estimates (see Appendix B). For this application it is frequently useful to represent tabulated data with an analytical function.* The dashed curve in Figure F-1 is a Weibull distribution, which is:

$$p(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (F-1)$$

where

$p(v)$ = probability density (fraction of occurrences of wind speeds per m/s over some small interval of wind speed Δv wide)

v = wind speed

c = a scale parameter related to the mean wind speed

k = a shape parameter (defines the peak to width shape of the distribution).

By using just two numbers, c and k , a good approximation to the measured data can easily be recreated using Eq. F-1.

The Rayleigh distribution is a special case of the Weibull distribution (when $k = 2.0$) that is especially simple to use and fits many observed distributions reasonably well. That is:

*If a tabulated wind speed frequency distribution has a fair degree of resolution, representing it as an analytical function results in some loss in accuracy. However, as Appendix B shows, this loss in accuracy is small compared to the uncertainty in estimates of wind turbine energy production that are based on wind speed distribution functions.

Table F-2

JOINT FREQUENCY DISTRIBUTION, WIND DIRECTION VERSUS WIND SPEED IN PERCENT FREQUENCY OF OCCURRENCE
Sandberg, California, months of March 1965-1978

LOCATION: SANDBERG CA

(23187) FROM 650101 THROUGH 781231
ANEMOMETER HEIGHT: 9.1 METERSNO. OF VALID OBSERVATIONS: 3134
REFERENCE: ROCK TOP

MARCH

SPEED (M/SEC)	WIND DIRECTION																	TOTAL
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	CALM	
CALM	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
1	.3	.2	.1	.1	.1	.1	.1	.0	.1	.2	.1	.0	.2	.1	.1	.0	.0	1.7
2	1.0	.5	.7	.5	.3	.0	.1	.1	.2	.4	.4	.4	.2	.3	.2	.4	.0	5.7
3	1.5	.8	.7	.4	.4	.1	.1	.1	1.0	1.0	.8	.6	.7	.4	.3	.7	.0	9.5
4	1.7	.8	1.0	.6	.6	.2	.1	.2	1.4	1.1	.4	.4	.5	.3	.6	1.3	.0	11.3
5	2.6	.6	.6	.8	.9	.0	.0	.3	1.8	1.3	.6	.3	.3	.4	1.0	2.3	.0	13.8
6	3.0	.7	.6	.5	.5	.2	.1	.6	1.6	.9	.3	.0	.0	.3	.7	2.6	.0	12.5
7	2.6	.4	.4	.5	.8	.1	.0	.3	1.6	.5	.2	.0	.0	.2	.7	2.6	.0	10.9
8	2.4	.0	.2	.3	.3	.1	.0	.2	1.5	.4	.2	.0	.0	.1	.8	2.0	.0	8.6
9	2.0	.1	.2	.4	.4	.1	.0	.2	1.2	.3	.1	.0	.0	.0	.7	2.0	.0	7.7
10	1.7	.1	.1	.4	.3	.1	.0	.2	.8	.3	.0	.0	.0	.0	.6	1.6	.0	6.0
11	.9	.1	.1	.1	.2	.1	.0	.0	.5	.1	.0	.0	.0	.0	.4	1.0	.0	3.5
12	.7	.0	.1	.1	.3	.1	.0	.0	.7	.3	.0	.0	.0	.0	.4	.7	.0	3.4
13	.6	.0	.0	.1	.1	.0	.0	.0	.4	.3	.0	.0	.0	.0	.1	.5	.0	2.2
14	.3	.0	.0	.1	.1	.0	.0	.0	.2	.2	.0	.0	.0	.0	.1	.3	.0	1.2
15	.2	.0	.0	.0	.1	.0	.0	.0	.1	.1	.0	.0	.0	.0	.1	.4	.0	.9
16	.1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.2	.0	.4
17	.1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.2	.0	.3
18	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1
19	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.1	.0	.2
20	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.0	.1
21-25	.1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.2
26-30	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.0	.1
31-35	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
36-40	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
41-UP	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
TOTAL	21.8	4.2	4.7	5.0	5.3	.9	.5	2.1	13.3	7.2	3.1	1.7	2.0	2.2	6.9	19.2	.0	100.0
AV SPEED	7.1	4.5	4.9	6.0	6.6	6.5	4.3	6.3	7.2	6.0	4.4	3.2	3.3	4.4	7.5	7.9	.0	6.6

Figure F-1. Wind Speed Frequency Distributions for Sandberg, California, Months of March 1965-1978

$$p(v) = \frac{\pi v}{2 \bar{V}^2} \exp \left[-\frac{\pi v^2}{4 \bar{V}^2} \right] \quad (F-2)$$

where $\bar{V}$ = the mean wind speed. If the mean wind speed is the only information one has from a measurement location, the Rayleigh distribution provides a reasonable first approximation to the wind speed frequency distribution. The Weibull distribution of Figure F-1 is almost a Rayleigh since $k = 2.01$. There are some cases, however, where the Rayleigh distribution is not a good fit, and so it should be used with caution (1).

Another convenient way to display the information of the wind speed frequency distribution is with the cumulative probability distribution. This gives the fraction of winds that *exceeds* a given wind speed, $p(v > v_x)$. In this form, the Weibull distribution is:

$$p(v > v_x) = \exp -\left(\frac{v}{c}\right)^k \quad . \quad (F-3)$$

It is easy to convert Eq. F-3 to a linear form given by:

$$y = m x + b \quad (F-4)$$

where

$$y = \ln (-\ln[p(v > v_x)])$$

$$x = \ln v$$

$$m = \text{slope of the linear equation} = k$$

$$b = -k \ln c.$$

Using the data points for $p(v > v_x)$ and v , one can compute y and x , plot them on linear graph paper and graphically determine a good fit to Eq. F-4, thereby yielding the Weibull parameters c and k . Or, since many desk calculators (even some of the business-oriented calculators) will perform linear regressions, one could simply input x and y to those programs to determine m and b , hence c and k . Data from some stations are only available as summaries of frequency of occurrence in very broad classes like the stair-step plot in Figure F-1. Points from the stairstep plot of Figure F-1 are plotted in Figure F-2 along with the Weibull fit to them. It is seen then that an analytical function can be used to extend the usefulness of summarized, broad-class interval data.

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.

An approach often used when analyzing data from several meteorological stations is to establish a synoptic climatology. A synoptic climatology regards patterns of weather (winds, clouds, precipitation, etc.) as implicit functions of the static surface pressure distribution (2). Basic pressure pattern types are recognized through 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. Wind behavior between stations is estimated as a function of pattern type by application

Figure F-2. Cumulative Wind Speed Frequency Distribution

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.

As an example of applying synoptic climatology classifications, five basic types were used to describe the weather events in a study of wind power potential along the East and Gulf Coast states (3). The five types or, in this case, regions of the weather pattern are:

- I - in the warm sector ahead of a cold front or behind a warm front
- II - ahead of the warm front
- III - behind the cold front
- IV - under a continental high pressure center
- V - near a subtropical high pressure ridge.

As an example of the use of the synoptic classification scheme, Garstang et al. (3) summarized the analysis of wind power at J. F. Kennedy Airport in New York as a

function of these synoptic climatology types. The results showed that in winter over 80% of the wind power at JFK Airport is associated with types III and IV. Since these types will generally produce regional winds from the north through west, this is a clue to use when scanning the topography for Potential Candidate Sites, i.e., one should look for topographic features with the optimum orientation to the prevailing power-producing winds (see topographical indicators below). The study (3), which concentrated on the East and Gulf Coast states, is currently being extended to determine frequencies of each type over the Central and High Plains states.

A different use of synoptic climatology for wind prospecting in Alaska was based on six weather pattern types derived subjectively (4). The six basic patterns identified for Alaska (Figure F-3), the frequency of occurrence, and the transition probabilities from one pattern to the next (which give information on the persistence of patterns) were used as input to application of topographical indicators in a wind evaluation in Alaska (5). The importance of the patterns in Figure F-3 to topographical indicators is that the lines of constant pressure approximately describe streamlines of the large-scale wind patterns. Winds blow roughly parallel to the lines of constant pressure with low pressure to the left as one looks downwind. Significant departures from this approximation occur due to the drag of the earth's surface, which causes a component of the wind to be directed toward low pressure, due to topography, or due to rapidly changing pressure or movement of these patterns, which causes a component of the wind to be directed toward the most rapid drop in pressure.

An objective procedure for pattern recognition is known as principal components analysis (PCA), also sometimes referred to as eigenvector analysis. PCA applications to wind energy problems have concentrated on patterns among wind vectors measured throughout a region before application of numerical models (1,6,7,8). Consider wind speed and direction measurements made hourly at 10 locations for a year. The PCA technique (following the procedures of Walton et al. (6)) 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.

Figure F-3. Sea-Level Atmospheric Pressure Distributions in Millibars for Six Basic Characterizations of the Synoptic Climatology of the Gulf of Alaska (4)

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 (6) 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. (7) 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 a period as long as the data set) at any point in the region.

Estimating long-term significance of short-term measurements. After analyzing wind patterns and applying other techniques to pick out likely high wind resource sites, one may choose to instrument those sites. After a few months or a year of data collection, interpreting the climatological significance of those relatively short-term data becomes a problem. Two ways to interpret the data have been studied extensively. The first is based on a study of the natural variability of the wind measured at existing climatological stations, and assuming that the variability at the new station will be similar. The second approach, commonly known as climatological adjustment, attempts to exploit a correlation between data from the short-term station and data from a climatological station in order to correct for interannual variability exhibited at the long-term station. These two schemes are discussed here.

In the first approach, one might look at a year's data at a Candidate Site and question 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 (9,10,11, 12) with roughly the same result based on analysis of data from numerous National Weather Service sites across the United States and in Hawaii and Alaska. As a national average, the climatic mean wind speed will be within $\pm 10\%$ of a single annual mean wind speed observation with about 90% confidence; i.e., there is a 10% change that the difference between the observed annual average and the long-term average will exceed $\pm 10\%$ of the long-term mean. At any particular site the accuracy of the estimate depends on the coefficient of variation of the site annual mean speed $\sigma_a/\bar{V}$,

where $\bar{V}$ is the climatic mean and σ_a is the standard deviation of annual means. Of course, one does not know *a priori* at a new site what $\sigma/\bar{V}$ is. However, Justus et al. (10) have demonstrated how one could alter the accuracy estimate depending on one's estimate of how $\sigma_a/\bar{V}$ might differ regionally or at a particular site. They found about 10% of the 40 sites they looked at had $\sigma_a/\bar{V} \geq 0.09$ (compared to an average of 0.06), which leads to 90% certainty that the annual mean would be within $\pm 15\%$ of the climatic mean.

Similar calculations of the interannual variability of monthly means have been made. Justus et al. (10) found that $\sigma_m/\bar{V} \approx 0.11$. This implies that the climatic mean speed for a given month of the year will be within $\pm 18\%$ of a single observed monthly value of mean wind speed with 90% confidence.

A single month's wind measurement gives a biased estimate of the annual mean wind speed due to the annual variation of monthly mean speeds. For example, if winds are strongest at a site in winter, a measurement in January used to estimate an annual mean wind speed likely will be high. However, Ramsdell et al. (11) have shown that, for example, 3 months of measurements made 4 months apart for 2 years will yield an estimate of the annual mean that is as good as one full year of continuous measurements. Those results suggest that, where funds for instrumentation are limited and time pressure is not severe, information on annual mean wind speed could be obtained during preliminary resource assessments from several sites by strategically rotating one set of instruments among them.

Climatological adjustment of site data is another approach often suggested for gaining insight to the significance of onsite data. Attempts to adjust the climatic wind speed estimate using a season or year of site measurements and a comparison with nearby climatic data are possible (10,12,13) but the techniques applicability is quite limited. 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 long-term wind speed measured at the climatic station by the ratio. This essentially assumes that monthly or seasonal mean wind speeds are perfectly and linearly correlated (a correlation coefficient of $r = 1.0^*$) at all locations within an area. Typical correlation of monthly mean speeds between sites within 100 km of each other in

*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 quantities. 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.

fairly simple terrain is $r \approx 0.4$ to 0.5 ; for annual means $r \approx 0.3$ to 0.5 (10). Corotis (12) 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 reliable improvement in estimates of the climatic means (1,10,12). Furthermore the correlation of annual and monthly means between sites is a very sensitive quantity, because the interannual standard deviations are small (1,12).

Estimates of monthly mean wind speeds throughout the year can be made on the basis of adjustment of a single season's data (12). The ratio of the mean speed for each month to the climatic mean is computed for every station in a region. From these ratios an average annual cycle of ratios for the region is determined. The regional cycle multiplied by the site short-term data is used to estimate an annual cycle of winds at the site. If the correlation of daily mean winds between the site and a climatic station is estimated, some reduction in the breadth of the confidence interval around the projected annual cycle of monthly means is possible. The reduction is generally small unless the correlation exceeds $r = 0.8$. A difficulty with the technique is that there can be a significant uncertainty in the estimate of the long-term correlation between sites determined from short-term measurements (1). Also, this technique will fail in areas where the annual cycle of monthly means at the site and the climatic station are significantly out of phase. This could occur, for example, in coastal mountain areas where high elevations obtain peak average winds during winter storms but broad valleys inland of the mountain crests obtain peak winds due to summer sea-breezes.

Conclusions. Analysis of the wind resource in a region or at a specific site will always begin with a look at existing data. It is useful to prepare displays that will, at least in part, categorize the wind behavior into patterns. Once a basic characterization of meteorological behavior patterns is achieved there is a foundation upon which other techniques may be used to estimate the resource or locations of high wind resource at points where no data are available. Short-term data (e.g., from a season or a year) collected at a site can provide some estimate of the expected climatology of a site, and techniques are available to establish confidence intervals for the estimate. For sites in simple terrain, in close proximity and well-correlated to a climatic station with decades of wind measurements, some adjustment of the short-term data to achieve a better estimate of the climatic behavior at the site is theoretically possible. Some reduction of the confidence interval about the estimate is also possible. In practice, however, climatological adjustment does not generally result in improved usefulness of site data. There is no good substitute for adequate on-site measurement.

Topographical Indicators

Historically, wind machines have been sited by applying topographical indicators, which are empirical guidelines describing the general 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. Gaps, passes, and gorges in areas of frequent strong pressure gradients are one group of such indicators. Strong pressure gradients occur when large temperature gradients form across a mountain barrier. For example, coastal mountains separate marine air masses of nearly uniform temperature 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 in a storm, blow up against the mountain barrier. If the flow has insufficient kinetic energy to cross the 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.

Ridges and mountains usually provide enhanced wind resource sites. The air accelerates over the crest of small-scale hills and ridges (less than 300 m high). This is 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. Air does not necessarily accelerate so over large-scale mountains, however. 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 still often contain good resource sites because they are like tall towers that intercept the flow at higher levels where winds are usually stronger.

Some topographical features, on the other hand, are associated with low wind energy potential; among these are basins and valleys that are perpendicular to the prevailing

winds. These features tend to 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 in the basins.

The above guidelines are general and must be extended in each specific application. How to extend the guidelines and how far to trust them are complex problems requiring considerable judgment and expertise. The complexity of deciding how far to trust an interpretation of air flow over terrain is due to the complex responses of the atmosphere to varying surface conditions. Important characteristics of the earth's surface are the distribution of:

- surface elevations or topography (e.g., hills and plains)
- surface roughness (e.g., forest and prairie)
- surface temperature (e.g., land-sea temperature contrasts).

These characteristics force or modify the atmospheric flow in a way that also depends on the ambient characteristics of the flow. The most important flow characteristics are the distribution (both in the vertical and horizontal dimensions) of:

- air temperature
- pressure
- wind direction
- wind speed
- turbulence.

These flow characteristics are interrelated so that terrain variations affecting one flow characteristic affect all of them. The meteorologist must anticipate the nature of these interactions.

For example, consider the winds in the coastal hills and low mountains of northern California. The first approximation application of a topographical guideline suggests that the passes and gaps in the coastal mountains would be good wind areas, and the hills and ridges perpendicular to the onshore flow would also be good wind resource areas. In this particular case, however, the meteorologist will extend the reasoning farther. The summer sea-breeze is driven by a difference in pressure that develops between cool marine air offshore and the warming air within the planetary boundary layer (PBL) onshore. The top of the PBL is often clearly marked by a temperature inversion that forms a "lid" which traps smog beneath it or is marked by the top of the lowest fog or stratus cloud layer. The sea-breeze usually only develops when winds above the PBL are light. The thickness of the marine PBL (or the height of the temperature inversion) as it moves onshore can be as little as a few hundred

meters or as much as a couple of thousand meters. Thus, on one day the hills and mountains might rise above the PBL and be in the light winds above, or on other days be totally immersed in the PBL and the fully developed sea-breeze. The air is strongly accelerated through gaps in the coast range as the cool dense marine air flows inland along the surface, especially if the temperature inversion is strong (i.e., the "lid" atop the PBL is clamped on tightly). Therefore, even though the general weather patterns from one week to the next appear to change very little, afternoon winds at the summit of a coastal hill may change significantly with time due to differing strengths and elevations of the temperature inversion. Over the same period of time, the afternoon winds in the coastal mountain gaps may remain relatively constant. Thus the second approximation application of topographical guidelines will steer the meteorologist more toward the gaps and less toward the summits.

The meteorologist can dare to be more quantitative in some cases where better developed theory or experience is available. Vertical extrapolation of near-surface data is an example. Figure F-4 shows the diurnal variation of average wind speed at three levels over a flat terrain site in Oklahoma (14). Note that the winds increase with height and that the increase is greater at night than in the daytime. This typically occurs over flat land because daytime heating of the ground and resultant turbulent mixing (unstable conditions) tend to homogenize the winds in the vertical, whereas at night the cooling of the surface tends to separate the lower atmosphere into more or less independent layers (stable conditions). The variation of wind with height is often described by the power law, which is:

$$V(z_2) = V(z_1) \left(\frac{z_2}{z_1} \right)^\alpha \quad (F-5)$$

where

- $V(z_2)$ = wind speed at height z_2
- $V(z_1)$ = wind speed at height z_1
- α = power law coefficient.

The value of the power law coefficient is a variable that can be related to other parameters on a theoretical basis (1), or an empirical basis (15,16,17). However, Appendix B points out that the extrapolation formulas tend to work well on an average of a large number of sites but can err significantly in specific cases. The prudent course in using vertical extrapolation schemes is to estimate the range of wind

Figure F-4. Annual Average Diurnal Variations at Three Heights Above Flat Terrain in Oklahoma

behaviors that could be observed at hub height, but resist pressures to make specific predictions that are premature (relative to the importance of the decisions based on the predictions) and not warranted by available information.

Evaluation of topographical effects on wind potential is always a basic step to understanding wind resource characteristics in a Region of Interest, Candidate Resource Area, or at a Potential Candidate Site. The examples discussed above illustrate, however, that in all but 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. 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.

Succinct generalizations are useful; however, reliance upon them must be tempered.

Biological Indicators

The character of an ecological community can reveal usable information on the wind power potential of an area or site to those who know how to interpret the biological indicators. Among the many effects of wind on plant and animal communities, the permanent deformation of trees by persistent strong winds is the most useful for wind prospecting (see Figure F-5). Wind information can be obtained for various scales:

- single turbine site, where the wind has permanently deformed a single tree or shrub
- Potential Candidate (cluster) Site, where the wind has deformed a number of trees that may provide a map of average wind directions and speeds
- Candidate Resource Area, where appropriate use of satellite or aerial survey techniques may show observable effects of wind on entire plant communities (18).

Figure F-5. Deformed Trees at Pacheco Pass, California

The degree of permanent tree deformation has been calibrated against the annual mean wind speed for numerous genera of trees (19). This was accomplished by measuring 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; and 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. Figure F-6 shows a side view and a top view of conifers (Griggs-Putnam Index) and deciduous trees (Barsch Index) to demonstrate the brushing of individual twigs and branches and the shape of the tree trunk and crown. Table F-3 gives the mean wind speed and the 95% confidence limits determined (19) at each value of the appropriate index for several genera of trees.

It is best to interpret tree deformation in a local region as a relative indicator of wind speed. The relationships presented in Table F-3 should be used only as rough estimates. The 168 data points used to construct Table F-3 represent trees and measurements that span much of the United States, but calibrations can vary locally (20).

The use of trees as indicators of wind velocity is subject to a number of practical limitations that have a bearing on the method of selecting indicator trees. Of greatest concern is the tree's exposure to the wind. Trees selected as indicators must be well exposed to the prevailing winds. Seldom do trees in a forest extend far enough above the canopy to be in an air stream undisturbed by the other trees. High winds will suppress the growth of new shoots above the canopy so that smooth, evenly topped canopies are, at least, a qualitative indicator of windy areas. However, isolated trees or those in small, widely spaced groups should be favored as wind velocity indicators. All trees should be of nearly the same height if they are going to be used to compare several locations. All trees should be of the same species if they are being used to rate potential sites.

It should be emphasized that while wind-flagged trees indicate strong winds, a lack of flagging does not necessarily indicate that the wind is not strong. There may be situations where strong winds come from three or more directions, but their persistence is insufficient from any of the directions to cause noticeable deformation.

(a)

(b)

Figure F-6. Useful Qualitative Indices of Tree Deformation. The Griggs-Putnam Index (a) and the Barsch Index (b)

Table F-3

ANNUAL MEAN WIND SPEED AND 95% CONFIDENCE INTERVALS AS A FUNCTION OF
TREE DEFORMATION INDEX VALUES (19)

Genus (Popular Name)	Index	Annual Mean Wind Speed (m/s) and 95% Confidence Limits ($\pm$ m/s)							
		Index Value							
		0	1	2	3	4	5	6	7
Abies (Fir)	Griggs-Putnam	6.0 $\pm$ 2.0	6.7 $\pm$ 1.9	7.4 $\pm$ 1.8	8.1 $\pm$ 1.8	8.8 $\pm$ 1.8	9.5 $\pm$ 1.8	10.2 $\pm$ 1.9	10.9 $\pm$ 2.0
Juniperous (Juniper)	Griggs-Putnam	4.4 $\pm$ 2.1	5.0 $\pm$ 2.0	5.6 $\pm$ 1.9	6.2 $\pm$ 1.9	6.8 $\pm$ 2.0	7.4 $\pm$ 2.1	8.0 $\pm$ 2.2	8.6 $\pm$ 2.5
Picea (Spruce)	Griggs-Putnam	3.0 $\pm$ 2.8	4.2 $\pm$ 2.6	5.4 $\pm$ 2.5	6.6 $\pm$ 2.4	7.8 $\pm$ 2.5	9.0 $\pm$ 2.6	10.2 $\pm$ 2.8	11.4 $\pm$ 3.0
Pinus (Pine)	Griggs-Putnam	3.3 $\pm$ 1.9	4.0 $\pm$ 1.8	4.7 $\pm$ 1.7	5.4 $\pm$ 1.8	6.1 $\pm$ 1.8	6.8 $\pm$ 2.0	7.5 $\pm$ 2.1	8.2 $\pm$ 2.3
Pseudotsuga (Douglas Fir)	Griggs-Putnam	3.3 $\pm$ 1.7	4.1 $\pm$ 1.6	4.9 $\pm$ 1.5	5.7 $\pm$ 1.5	6.5 $\pm$ 1.5	7.3 $\pm$ 1.6	8.1 $\pm$ 1.8	8.9 $\pm$ 1.9
Acer (Maple)	Barsch	3.4 $\pm$ 1.5	4.3 $\pm$ 1.0	5.2 $\pm$ 1.4	6.1 $\pm$ 2.2	7.0 $\pm$ 3.1	7.9 $\pm$ 4.1	8.8 $\pm$ 5.1	9.7 $\pm$ 6.1
Quercus (Oak)	Barsch	3.0 $\pm$ 1.8	4.1 $\pm$ 1.7	5.2 $\pm$ 1.7	6.3 $\pm$ 1.8	7.4 $\pm$ 1.9	8.5 $\pm$ 2.1	9.6 $\pm$ 2.3	10.7 $\pm$ 2.5
Legumes (Mesquite-Locust)	Barsch	3.7 $\pm$ 1.2	4.4 $\pm$ 1.0	5.1 $\pm$ 1.0	5.8 $\pm$ 1.3	6.5 $\pm$ 1.7	7.2 $\pm$ 2.1	7.9 $\pm$ 2.5	8.6 $\pm$ 3.0
Ulmus (Elm)	Barsch	3.3 $\pm$ 1.5	4.4 $\pm$ 1.4	5.5 $\pm$ 1.4	6.6 $\pm$ 1.6	7.7 $\pm$ 2.0	8.8 $\pm$ 2.4	9.9 $\pm$ 2.9	11.0 $\pm$ 3.4

Factors not related to wind may cause a characteristic one-sided crown. The growth of two trees side by side, for example, will cause both trees to have an asymmetric crown. If one tree is removed, the other will look wind-flagged. Always look for evidence of past competition. Soil or snow creep, an occasional severe ice storm, fires, insect damage, pruning, or logging damage may all result in asymmetric crown forms that are not associated with wind. Salt damage in coastal areas may enhance the degree of deformation. Coastal trees deformed by wind may be compared to one another, but should not be compared to wind-deformed trees in noncoastal locations.

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. However, flagged trees reflect the prevailing direction of the strongest winds that may occur at one location during part of the year only. Therefore, when observing flagged trees, one should also look for the tattered appearance of winter flagged trees or the smoother bending of branches of growing-season-flagged trees (19).

Trees can also be used as indicators of destructive forces of severe wind and icing, which present severe problems for wind turbines, their support structures, and the power transmission lines from the turbines (5,19). 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.

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.

Geomorphological Indicators

Where 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. Since eolian landforms usually exist in areas where people do not live and where wind data are not likely to have been gathered, a correct interpretation of the landforms may provide useful auxiliary data to assist in wind prospecting.

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
- to indicate prevailing wind directions.

Eolian landforms are generally either deposition areas (such as sand dunes) or deflation areas. When blowing sand enters an area where either the nature or configuration of the ground or vegetation interferes with the wind, it accumulates into dunes. Sand dunes in deserts take different forms, and the mechanisms for generating them are complex and not completely understood. The type and quantity of vegetation significantly influence the development of dunes; however, active dunes that experience frequent strong winds do not allow the vegetation to persist and stabilize the dune (21). Deflation areas are erosional features, such as blowouts, scour streaks and playas. Blowouts are saucer-shaped hollows formed by wind erosion. Scour streaks are similar to blowouts, but are elongated along the direction of strongest winds. Scour streaks are usually found in dry areas of easily erodible soil; however, their occasional occurrence in nearly rock-hard surfaces is a sure indication of very high wind speeds. Playas are depressions that collect water, as well as the silt and salts transported by water, during the wet season. In the dry season, playas are dry and subject to wind erosion. The alkaline sediments blown out of the playa settle out downwind of the playa and are often visible in high-altitude photographs.

Eolian features, whether they are depositional such as sand dunes, or deflation features such as blowouts or playas, indicate substantial winds. However, these features can be created by a few wind events. For this reason, identified eolian features should be confirmed as currently active features by site visits.

Weathering processes act to reduce coarse-grained sediments to fine-grained sediments. The wind transports sediments through three general processes. Fine-grained sediments that do not settle out quickly travel in suspension. Heavy-grained sediments tumble along the surface. Intermediate-sized grains saltate, that is, airborne grains

collide with the surface, which causes the same or new grains to become airborne. The wind accelerates the grains before the next collision with the surface. Since more wind energy is required to transport larger grains than smaller grains, the rate of transport and the characteristics of the transported material should be related to the transporting wind regime.

Usually eolian landforms and transport have been studied as a function of the wind regime (22). The inverse problem of determining wind characteristics from sand particle size distributions and sand dune migration rates has also been examined (1,23). The principal difficulty with 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 saltate? If these answers are in hand before eolian features are analyzed, why carry out the analysis?

Mean wind directions and mean wind patterns in a region can be mapped on topographic maps using eolian landforms as wind direction indicators. However, the temporal nature of the geomorphological processes should be reviewed before a wind pattern is described. One must be careful to determine that eolian landforms being used to describe a wind pattern were formed at the same time and do not represent components of several wind patterns.

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 Region of Interest analysis and Candidate Resource Area evaluation 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 response 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 driving through and exploring a Candidate Resource Area should actively look for and evaluate clues provided by social and cultural indicators of wind. Some examples follow.

People do not like to live in high wind areas. If a town or home is sited in an obviously sheltered location and other conveniences such as water access or road service are less available than if the town or house were located in a less sheltered area, the area surrounding the sheltered location may be windy. Often, people grow shelterbelts on the upwind side of an area they wish to protect, if they cannot avoid windy areas.

Land use can also indicate wind characteristics. Land cannot be cultivated for long in a windy area before the land will no longer sustain crops. Therefore, in regions of mixed open rangeland and cultivated fields, the range areas are more likely to be windy. The border between crop and rangeland can also be noted on small space scales, as when cultivation exists in small protected areas or on the lee sides of small ridges but not on the windy crests of ridges.

Past use of wind power for local water pumping or small-scale electric generation may indicate a wind resource. Water pumpers were often sited down in small valleys and ravines, because those sites were nearer the water table. If there was enough wind for water pumping in these poorer sites, then the surrounding high ground is probably a viable resource area. Snow fences, used in semi-arid areas to control drifting snow, may also indicate windy areas and prevailing wind directions.

Signs along roadways often reflect wind potential. "Blowing sand" or "blowing snow" warning signs probably indicate local topographic enhancement of winds. "High winds likely" or "gusty winds likely" indicate strong turbulent winds that are probably more a hazard to avoid than a boon. State highway patrols can be a source of information on wind because of their continual concern with road conditions. Accidents where trucks carrying light bulky loads (such as mobile homes) have had their loads blown off may be considered along with the concurrent large-scale weather conditions. The extrapolation of the information contained in these roadside indicators may be extended to the surrounding off-road areas.

Wind damage to power lines, buildings, billboards, etc., can also be considered. Damage to some structures may indicate extreme wind speeds or extreme turbulence to be avoided. On the other hand, some structures may be poorly situated in locations where turbulence is particularly enhanced. In the latter case, surrounding areas could have strong but more benign wind.

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 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 Candidate Resource Area evaluation.

Use of these techniques does not and should not require a great commitment of time and effort. Instead, these techniques require an attitude of continual observance for clues of wind effects.

Numerical Modeling

A numerical model consists of a set of equations that are assumed to adequately represent the processes being studied and a procedure for solving those equations. The application of numerical models to simulating flow over terrain is discussed here.

The atmosphere, fortunately, obeys a few fundamental physical laws. Principally, these are:

- conservation of mass
- conservation of energy
- conservation of momentum.

These laws describe the fundamental relationships between the atmospheric variables of interest: winds, temperature, and pressure. Unfortunately there is no general solution to the equations (known as primitive equations) that describe those laws. A common approach is to enlist the assistance of computers to numerically achieve a solution to the fundamental 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 simpler set of equations, e.g., a set that only considers conservation of mass.

The complexity of the physics simulated in a numerical model is only part of the total complexity. A procedure for solving the equation set is necessary and considerable sophistication is involved in the choice of numerical procedure. For example, some solution procedures produce successive estimates of the variables of interest at discrete points (a grid) in space throughout the modeled territory at discrete points in time (time steps). The model can "blow up" (i.e., amplify small perturbations in the evolving solution until the resulting solution is physical nonsense) if the grid and the time steps are chosen improperly. Strategic choices of the equations used to

describe the boundary conditions at the top, bottom, and sides of the modeled territory must also be made for some models. Similarly, how to use input data to provide the initial conditions at every point on the model grid at the start of a model run is a question requiring careful thought.

The advantage of numerical modeling as a tool for wind prospecting 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 accuracy achieved in numerical solutions depends on the accuracy and the density of the input data, the amount of realism in the physics to be simulated in the model, and the skill with which the solution procedure is applied.

The primary disadvantage associated with the use of numerical models is the uncertainty in their accuracy, which is due to a 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, and the task of gathering enough data to allow the flow over a complex piece of topography to be deduced unequivocally from the data alone is impossible. 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.

Examples from several models are presented below to demonstrate typical products and accuracies obtained in model verification studies.

A primitive equation model available at the University of Virginia has been tested with applications to wind turbine siting in mind (24). The model was run in three regions: the Chesapeake Bay area, Apalachee Bay, and the south Texas coast. Figure F-7a shows model predictions for the wind power density (units of 100 W/m^2) over Chesapeake Bay, the Delmarva Peninsula and into the Atlantic for the morning of January 30, 1980. Measurements from a research aircraft flying a rectangular pattern on the same day are presented in Figure F-7b. The general pattern of the wind power field (inland minimum, coastal gradient, offshore maximum) are reproduced by the model but the model has missed on details of the magnitudes.

In an analysis of the skill of the model (24), it was argued that prediction errors must be partitioned into those due to inadequacies of the model and inadequacies of

Figure F-7. Areal Distribution of Predicted (a) and Observed (b) Wind Power Density (10^2 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 (Source (24))

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. The study concludes: "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 attempt 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 nonexistent. For example, flow from the ocean over a coastal ridge might be simulated with such a model by assuming the flow looked the same on all planes perpendicular to the coastline. Often this type of two-dimensional model is developed as a subset of a larger three-dimensional primitive equation model and used for initial tests before 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 (25,26) 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 (27). 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 (1,6,7,28-33). 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, that the conservation of mass be satisfied. 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 (7).

Objective analysis models have received the most attention for verification studies for wind energy applications (1). Figure F-8 shows contours of wind speed at 15 m above ground over Oahu, Hawaii, for a simulation of 10 m/s tradewind conditions.

Figure F-8. Wind Speed Contours at 15 m Above the Surface for Idealized Tradewind Flow Over Oahu. The freestream wind speed at 200 m was 10 m/s and the wind direction was 65°

The results are quite reasonable showing 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.

How accurate are wind speed predictions at individual stations? Figure F-9a plots calculated wind speeds against observed wind speeds from 15 wind stations on Oahu for 24 simulations. Six surface wind observations and a rawinsonde (wind sensing weather balloon flight) measurement of the vertical distribution of winds from the nearby island of Kauai constituted the input data set. If all points had fallen on the diagonal line, the predictions would have been perfect. In fact, the mean deviation from the line was 2.5 m/s (31). When the average predicted and observed speeds from the 24 simulations are plotted for each station, Figure F-9b results. It is evident that the mass consistent model generally discriminates the more windy from the less windy sites.

Table F-4 provides another perspective on numerical model accuracy and relates it to accuracy achievable through use of topographical indicators. The table shows, for an Oahu simulation using a high data density input, that of the four windiest sites predicted with the model (KL, MN, MU, and PT in Figure F-9) only one (KL) was actually observed to be in the four windiest sites (KL, KH, TT, KK). 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 62% chance that a result at least as good as the tabulated result could have been obtained through a random selection of any four of the sites. However, there is a 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 F-4 from modeling the Nevada Test Site (32) 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 F-4 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

Figure F-9. Comparison of Calculated to Observed Wind Speed for 24 Oahu Simulation Events. Plot (a) is for individual events and stations, plot (b) for averaged events at each station (31)

Table F-4

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*, 6 stations plus rawinsonde input	1 (62%)	5 (<2%)	9 (<1%)
Oahu, NOABL, rawinsonde input	1 (62%)	5 (<2%)	8 (1%)
Nevada, NOABL, 6 stations plus rawinsonde input	3 (1%)	4 (15%)	5 (67%)
Oahu, topographical indicators**	3 (1%)	6 (<1%)	8 (1%)
Nevada, topographical indicators**	2 (16%)	3 (47%)	6 (33%)

* NOABL is the name of a mass consistent objective analysis model (29).

**The rank was determined independently using topographical indicators by a recognized expert.

unfamiliar with the model verification studies, determined a rank. Evidently, a qualified meteorologist can compete fairly well with the mass consistent models, although concurrent use of both techniques is desirable.

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. Physical modeling has a very long history of use in aerodynamics, naval engineering, and structural design. In more recent years, it has been used to model atmospheric flows in air pollution studies (34). The primary reason for using physical modeling is that current numerical models are still incapable of accurately simulating many problems in fluid mechanics. A scaled model in a flow facility represents a physical analogue to the real problem in nature; and if the study is constrained to consider only those problems that can be properly posed in a flow facility, physical modeling can yield results far more accurate than those of numerical models (35). Physical modeling of atmospheric flows does require large, specialized facilities, however. Riley and Delisi (36) as well

as Hunt and Feinholz (37) provide listings of institutions that have proper facilities for modeling atmospheric flows.

The theoretical foundation of physical modeling is the principle of similarity. The principle 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 (1,38,39).

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 .

When the buoyancy forces on warm or cool parcels of air contribute to the generation of turbulence, the atmosphere at that level is said to be unstable. If buoyancy forces suppress turbulence, the atmosphere is stable. If turbulence is neither enhanced or suppressed by buoyancy forces, the stability is neutral. Atmospheric stability, which depends on the vertical variation of wind and temperature, is reflected in the Froude number. The Froude number is an important descriptor of the flow since atmospheric stability controls detailed characteristics of the turbulence structure, which in turn feeds back to affect the wind structure.

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. 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. These conditions are typical of partly cloudy to sunny days with moderate-to-high wind speeds. 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 tunnel or water flume.

Maintaining strict similarity between full-scale and laboratory flows requires that Re , Ro , and Fr have identical values for both the flows. It also requires that conditions at the boundaries of the studied region be identical. 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. If the wind direction over a large area changes rapidly with height above ground, as is often the case at night, the boundary conditions cannot be met in a wind tunnel in which the air moves only down the tunnel at all levels. The result of this inability to strictly achieve complete similarity is that there are constraints on the kinds of flows that can be physically modeled and on the interpretations of the results. Useful results can be obtained provided the neglected similarity requirement has a small influence on the resulting flow.

Even considering the limitations, physical modeling can be a useful tool in siting. Under neutral-to-mildly unstable conditions, wind tunnel modeling should give reasonably accurate information on the effects of terrain profile and roughness on wind speed distributions near the surface, on the wind profile and on turbulence (including the location of zones of probable high turbulence and reverse flow). These simulations should be superior to the capabilities of currently available numerical models even when a neutrally stratified flow is used to represent the actual conditions that are not quite neutral. The accuracy of physical models of stable flow over terrain is more uncertain. For stable flows, it is very difficult to model the approach boundary conditions since these boundary conditions can be complex and since small changes in their structure can affect the flow significantly. These boundary conditions will also seldom be known with any precision. However, very similar problems exist in the numerical modeling of stable flows over terrain, as well.

Finally, there is one problem common to all modeling techniques: How representative are a few model runs to typical conditions over the site? The wind climatology of a real section of terrain is made up of a series of highly complicated, ever-changing flows. When flow over real terrain is modeled, an attempt is made to reproduce the

actual wind climatology with a very small number of steady-state flows obtained by using highly simplified boundary conditions. These simulations of the real world can provide useful guidance, but their basic limitations must always be kept in mind.

APPLICATION OF THE SITING TECHNIQUES

The siting techniques discussed above are applied differently, or not at all, at the various stages of the siting methodology depending on the particular problem at hand. Suggestions on applying the techniques at each stage are presented here.

Stage I: Identification and Ranking of Candidate Resource Areas

This stage (see Section 4) begins with the Region of Interest and ends with one or more identified Candidate Resource Areas. The principal and recommended tool at this stage is the DOE regional wind atlas for the appropriate region (see Appendix A). The level of detail and accuracy of the atlases is consistent with the objectives of this stage.

The method described in Section 4 does recognize that there may be conditions under which one wishes to use more than the wind energy atlas. If no CRA emerges from the first pass through Stage I, an examination of the quality of the regional resource estimates is called for. Alternatively, a meteorologist with substantial local experience may not entirely agree with the analysis in DOE regional assessments. If so, application of siting techniques to enhance or modify the available resource estimates may be justified. Keep in mind, however, that in Stage I, *areas* that might contain Potential Candidate Sites are being sought, not Potential Candidate Sites.

Of the siting techniques described previously in this section, the following (in probable order of cost-effectiveness for accomplishing the objective of Stage I) may be applied:

- evaluation of existing data
- topographical indicators
- geomorphological indicators
- biological indicators
- social and cultural indicators.

Recall that these techniques were all considered in the preparation of the DOE wind energy atlases.

The study of existing data coupled with a study of the regional topography will be the primary means to identifying potential wind resource areas. If sand dunes or other geomorphological features are present in the Region of Interest (either known by utility personnel familiar with the region or observed in aerial photography), this is a very good sign. Similarly, aerial surveys of wind-deformed vegetation in a region will provide a feeling for areas that may contain Potential Candidate Sites. The difficult part, however, is converting the information from these indicators into break-even annual mean wind speed estimates (see Section 4) that are any more reliable than what is published in the DOE atlases.

Numerical modeling is not an appropriate technique at this stage. Principally this is because the cost of a numerical model study is high relative to the value of the incremental improvement in analysis that might result. Also, for a large Region of Interest ($>10^5$ km²) it does not make sense to run a model for the entire region. The resolution of the models would be too coarse to make sensible predictions of the wind resource within 150 m of the earth's surface. If the Region of Interest is small (<5000 km²), there is no technical reason why numerical models could not be used.

The use of a short-term supplementary measurement program is also not suggested. Determining sites for those measurements is tantamount to determining a Potential Candidate Site, and does not help achieve the objectives of Stage I.

Stage II: Selection of Potential Candidate Sites

Stage II (see Section 5) seeks to identify Potential Candidate Sites within the identified Candidate Resource Areas. The usable siting techniques in an approximate order of cost-effectiveness are:

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

Two optional procedures for identifying Potential Candidate Sites are described in Section 5. Option A discriminates the better wind zones from the poorer wind zones, and then identifies the Potential Candidate Sites within the better zones. Option B is applied where the wind resource is expected to be more horizontally uniform across the Candidate Resource Area. The Potential Candidate Sites are then selected from a

group of the best exposed sites identified following screening with nonmeteorological factors. The wind prospector has the most work to do under Option A.

Under Option A, the meteorologist should begin by determining the meteorological patterns that dominate winds in the Candidate Resource Area. Especially important are the wind directions. Then, topographical maps should be consulted. When the wind patterns are evaluated with respect to the topographical features, the meteorologist should be able to identify the better 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 Candidate Resource Area, 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 Candidate Resource Area, the meteorologist will clearly be somewhat confined to stay near roads (road qualities and bridge load limits should be considered) and possibly transmission lines. On this drive, 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. The mass-consistent models are probably the easiest to apply. The best results are obtained with the mass-consistent models using numerous input data stations. Obtaining these data may require a supplementary wind measurement program. Hiester and Pennell (1) describe how such a program might be run. 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 run the model first 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 case 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 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 because 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 an 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.

Stage III: Selecting Candidate Sites

Stage II (Section 6) eliminates certain Potential Candidate Sites from consideration and arrives at a list of Candidate Sites. Two meteorological issues are important:

- likelihood of exceeding break-even wind speeds
- assessment of meteorological hazards.

Likelihood of exceeding break-even wind speeds. The following siting techniques are applicable:

- evaluation of existing and/or supplementary wind data
- topographical indicators
- biological indicators
- numerical modeling.

As little as a season of data from a site might be used to determine the likelihood of exceeding the break-even wind speed if the Potential Candidate Site is in simple flat terrain and if there is a long-term data station within close proximity (less than 10 to 20 miles away). The annual cycle and confidence limits for the adjusted mean wind speeds could be estimated as described earlier in this section.

Topographical indicators would be used to judge whether the exposure of the site is sufficiently like that of a not too distant but similar site where data have been collected. Since existing data were probably collected at a height of 10 m or less, there is particular concern for the details of the terrain slope near the anemometer

which may enhance the near-surface winds but cause little enhancement near hub height. Topographical indicator information derived from numerical or wind tunnel simulations of flow over hill or bluff shapes (1) are particularly useful.

Inspection of the site for deformed vegetation may reveal trees that are sufficiently wind-deformed to justify scoring a Potential Candidate Site as *highly likely* to beat the break-even wind speed. Due to the uncertainty associated with biological indicator wind speed predictions, biological indicators will probably not be capable of discriminating the *likely* from *unlikely* sites (20). Lack of tree flagging should only be used to indicate a *highly unlikely* site if one is certain that the wind directions are constant enough that significant tree flagging should be observed at windy sites in that area.

The ability of mass consistent numerical models using the eigenvector wind pattern analysis described above makes them attractive for generating statistics on seasonal variations of site mean wind speeds. The decision to employ those models would be based on the results of the scoring of the Potential Candidate Sites before using models. If there is no clear consensus on which Potential Candidate Sites to designate as Candidate Sites, the cost of a simple modeling program such as that described by Endlich et al. (7) is justified and may help clarify the decision.

Assessment of meteorological hazards. This assessment can employ the following techniques:

- supplementary measurements
- topographical indicators
- biological indicators
- geomorphological indicators
- social and cultural indicators.

Short-term measurements from kites or kite anemometers can be used to indicate zones of persistent high turbulence. The choice of measurement locations is indicated by evaluation of topographical effects on the local flowfield, and where those effects might result in high turbulence. Wind-deformed vegetation sometimes shows evidence of persistent and dramatic average wind direction shifts associated with zones of high turbulence. Biological and social/cultural indicators would be used to assess probabilities of significant icing (as would traditional meteorological analysis methods). The presence of geomorphological indicators of high wind speed should also indicate that airborne dust and grit may be a problem. However, sand transport will

usually remain too near the ground to be a hazard. Social and cultural indicators may provide clues about the impact of dust resulting from agricultural operations.

Stage IV: Selecting Preferred Sites

The objective of Stage IV (see Section 7) is to select from the Candidate Sites those that appear most viable on the basis of hard meteorological and engineering evidence. The major meteorological concern is to make adequate measurements to fulfill this objective. The siting techniques are used to determine locations for the meteorological towers. The principal techniques to use are:

- topographical indicators
- supplementary wind measurements
- numerical modeling
- physical modeling
- biological indicators.

One meteorological tower will probably be sufficient in simple terrain. Siting the tower is then a matter mostly of convenience.

In complex terrain the initial choice of tower locations will be dictated by topography and initial estimates of cluster layout. The choice of how many towers to use at a Candidate Cluster Site will be difficult. The major concern is how much the wind resource varies from place to place over the Candidate Site. Short-term wind measurements using kite anemometers or tethered balloon systems (see Appendix H) as well as variability among wind-deformed trees may give some indication of the wind resource variability. Care is required in making these measurements to avoid confusing temporal and spatial wind variations (1). Of course, any short-term measurements only indicate whether or not significant variability exists, and do not provide any information on the precise nature of the variability. Numerical models can also help analyze the wind structure over a cluster site.

Physical modeling will give the most accurate and detailed analysis of wind resource variability over a site. As discussed previously, wind tunnel models cannot adequately cope with variations in atmospheric thermal structure over a site. Nevertheless, wind tunnel simulations could prove extremely valuable in designing the most efficient measurement network for a large cluster in complex terrain.

Since there are, as yet, no numerical models capable of predicting wind turbine wake effects in complex terrain, the layout of wind turbines in a cluster can currently be done most quantitatively using wind tunnel simulations of cluster output.

Therefore, the expense of developing a model for a particular Candidate Site to determine wind measurement locations could be shared with the modeling effort to determine the layout of wind turbines.

SUMMARY

There are wind resource evaluation problems to solve at all stages of the siting methodology. 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 appendix. These include:

- existing and/or supplementary wind data analysis
- topographical indicators of wind energy potential
- biological indicators of wind energy potential
- social and cultural indicators of wind energy potential
- numerical modeling of flow over terrain
- physical modeling of flow over terrain.

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 methodology 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 technique(s) applied produce(s) the most information toward satisfying the objectives of each stage for a given increment of cost. A suggested guideline is given in this appendix. The actual strategy used for any specific utility system will require fine tuning by the boundary layer meteorologist overseeing the wind resource evaluation efforts.

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Appendix G

METEOROLOGICAL INSTRUMENTATION

Quality in wind resource data is essential for quality in the decisions made in a wind turbine siting program. The quality of the wind data should match the quality required in their application. For most applications the wind data in the DOE wind energy atlases are sufficient to accomplish the objectives of Stage I (Section 4). The decision to select and ultimately install wind turbines at a Preferred Site clearly requires higher quality data; a data quality that is appropriate to the importance of a final siting decision.

In this appendix, measurement systems and measurement programs are discussed. First, a perspective of measurements is provided by examining the potential cost of inattention to detail and quality. Measurement system components are described followed by a discussion of measurement programs and quality assurance considerations in a measurement program. Finally, two example systems appropriate for site evaluation in Stage IV are described.

THE POTENTIAL COST OF MEASUREMENT ERRORS

Wind measurements made at a Candidate Site need to be as accurate and reliable as the current state-of-the-art allows. However, achieving that level of accuracy and reliability will require a level of diligence exceeding that required in most other meteorological measurement programs. After all, certain inaccuracies in wind measurements can go unseen in an air quality program, but there is a much more direct relationship between wind measurement error and cost when a revenue-producing wind turbine is involved.

As the reader may recall, Eq. 4-1 relates the target cost of energy to the installed cost and the annual energy production. The target cost of energy is, in effect, a crude estimate of the maximum levelized average value of wind-generated electricity. If the annual energy production is assumed, the break-even installed cost is given by:

$$IC = \frac{AEP \cdot COE - LF \cdot AOM}{FCR} \quad (G-1)$$

Under these assumptions, IC represents the maximum amount a utility could afford to pay for a given wind turbine at a given site. Assuming AEP is only a function of the site mean wind speed $\bar{V}$, a relationship between an error in the estimate of the mean site wind speed and an error in IC is possible. This relationship is

$$\delta IC = \frac{COE}{FCR} \frac{dAEP}{d\bar{V}} \delta \bar{V}$$

where

δIC = the error in break-even installed cost

$\delta \bar{V}$ = the error in site mean wind speed

$dAEP/d\bar{V}$ = rate of change of AEP with $\bar{V}$.

For the hypothetical 200 kW wind turbine shown in Figure 4-5, between 5 and 8 m/s, $\delta AEP/\delta \bar{V} \approx 150,000$ kWh/(m/s). Thus, if $FCR = 0.18$ and $COE = \$0.07/\text{kWh}$, an error of 0.5 m/s in measurement of $\bar{V}$ results in an error of the estimate of the maximum allowable installed cost for the wind turbine of about \$29,000 (or about \$145/kW). If the installed cost of that wind turbine were, say, \$1200/kW, the error in wind speed measurement translates to about 12% of the capital cost.

There are, of course, numerous sources of uncertainty in the estimates of wind turbine cluster value arising from variability in general economic conditions, improper siting of meteorological towers, methods of estimating cluster energy output, and so forth. Instrument error is one uncertainty over which choice of instruments and design of measurement program can exert some control. Clearly, the choice and design of the meteorological measurement program deserves careful consideration so that avoidable errors are not made.

MEASUREMENT SYSTEMS

A measurement system consists of sensors, recording devices, and any other peripheral or supporting equipment. Information on the specifications and uses of meteorological measurement systems can be obtained through meteorologists employed by the utility, meteorological consultants, and equipment suppliers. A good basic description of meteorological equipment is given by Moses (1), while Hiester and Pennell, Wegley et al., and Park et al. (2,3,4) discuss wind energy applications specifically. This section supplements these references by presenting brief comments on the following system components:

- sensors
- data-recording devices
- towers
- shelter
- power.

Numerous types of wind speed and direction sensors have been developed for a variety of purposes. Conventional cup and vane or propeller and vane anemometers are most appropriate for most wind energy siting purposes (2). This recommendation is based on the wealth of experience that exists with these systems in uses similar to wind turbine siting. It is also based on the accuracy and response (i.e., how quickly the sensor responds to a change in the wind) of these systems, which are matched to the requirements of wind turbine siting.

Within the field of conventional anemometry, however, there are several differences between sensors that require careful consideration. For example, anemometer rotation, which is proportional to wind speed, may be sensed by voltage generated by a small generator or by the frequency of light pulses created by a continuous light, which is interrupted by a slotted disk that rotates with the anemometer. The "chopped" light source is sensed by a photocell. When a generator is employed as the anemometer's transducer, the physical wear on generator brushes and potential subsequent change in anemometer calibration is something that must be carefully monitored. Monitoring is especially important in areas where dust or salt might enhance deterioration. However, the power consumption of a light-chopping anemometer may be a problem if local power is unavailable. Anemometer response is also a consideration. Overspeeding -- the tendency for anemometers to speed up faster than they slow down in a gusty wind -- is not as severe for lightweight, responsive instruments as it is for more rugged sensors. However, overspeeding is not a serious problem in wind turbine siting. Errors due to overspeeding are small and correctable. The improved accuracies that can be obtained by using light and responsive instruments should be carefully weighed against the better survivability (e.g., in heavy icing conditions or heavy grit, dust, or salt conditions) of the more rugged instruments. The uncertainty associated with loss of data due to measurement system failure represents a cost just as much as measurement inaccuracy.

Remote sensing has been considered as an alternative to conventional tower-based anemometry (2,5). Currently, conventional anemometry is perceived more practical and cost-effective than remote sensing. However, remote sensors using laser, acoustic wave, or radar technologies may become, in the not too distant future, a viable

alternative to multiple tower measurements or numerical and physical model analysis of cluster sites.

Tethered balloon systems that carry anemometers aloft or wind-sensing kite anemometers are applicable for making short-term measurements called for in Stages III and IV. They can be used to assist in identifying potential severe turbulence or wind shear zones, or to assess how variable the winds are from place to place. High variability across a Potential Candidate Site foretells the difficulties that lie ahead in accurately assessing the flowfield through a Candidate Site. The spatial wind variability at the site also reduces the confidence with which one might claim that winds at the Potential Candidate Site will probably exceed the break-even wind speed (Section 6). High variability across the site also can be associated with higher gustiness or turbulence.

There are several levels of sophistication in data-recording devices (2,3). The simplest are analog display or dial read-outs. The next level of sophistication includes the wind-run anemometer, which records the number of miles of wind passage in an interval between readings. Dividing the miles by the time between readings yields an average wind speed, e.g., miles per hour. With the next level of sophistication, the instrument does substantial summarizing of wind data by converting it into histograms, frequency distributions, or averages. Preprocessing data reduces costs, but exact sequential information is lost. The cost of some of these data loggers is quite reasonable. Therefore, this level of data recording sophistication may be the best choice for preliminary measurement programs (see Figure 6-1). The fourth level of data recording sophistication is a system that records time series. The time series can consist of raw wind speed and direction sequences or a sequence of partially processed data, such as hourly averages and hourly variances computed from one-per-second samples. The recording medium can be paper charts, cassette magnetic tapes, computer tapes, or magnetic disk cartridges. Data can also be telemetered from the site, via satellite or telephone line, to a user's computer.

Wind sensors are clearly most important to a wind energy siting program, but other sensors may also be needed. Direct measurement of temperature can be used in calculating air density, which can be used to refine the estimates of available wind power. The same is true for atmospheric pressure. Both temperature and pressure are easily measured to the accuracy required for computing air density; however, a meteorologist could also make reasonably good assumptions for the values of air density in the absence of these measurements.

Another measurement of potential importance is the frequency of icing conditions. Ice formation on wind turbine blades can cause a hazard to nearby personnel from ice thrown off a rotating blade. To avoid the hazard, wind turbines may be shut down during episodes of icing, but this constitutes an energy production penalty. Although measuring the rates of ice formation is very difficult, measuring the frequency of icing conditions is relatively simple. Ice detection is addressed by Hiester and Pennell (2).

Some form of tower or mast is required to support the meteorological sensors. Several practical points must be considered. The first consideration is the choice of tower height. If the measurements are preliminary (see Figure 6-1), the low cost of a 30-ft guyed steel mast is attractive (2,6). However, significant data loss can occur with masts that can be knocked down by cattle, ice loading, or vandals. Also, the accuracy of low-level wind measurements in wind turbine siting is questionable, especially in rough terrain (see Appendices B and F).

For measurements in Stage IV (Section 7), a tower extending to hub height is recommended. However, there are two possible considerations that could require a tower extending to the top of the rotor disk. The first would be possible FAA lighting requirements (once turbines are actually installed, see Section 2). The second would be if certain negotiated performance guarantee or wind turbine warranties required data representative of flow through the entire rotor disk.

Siting of the tower is another consideration. Clearly, the tower should be immersed in winds representative of the cluster site. The siting techniques discussed in Appendix F are used to achieve this. The towers should also be sited slightly to the side and upwind in the prevailing wind direction of the expected turbine site so that the tower can measure undisturbed winds for assessment of turbine performance. When considering sites for a tower, be sure to estimate the locations of the tower guy wires. On some steep ridges guy wires cannot be effectively anchored on the ridge sides. Free-standing towers are available, but they are generally quite expensive.

The mounting of sensors on the tower is also a consideration. The tower interference with wind flow can result in inaccurate measurements of the undisturbed flow. However, sensors mounted on booms extending two tower diameters out from the face or corner of the tower into the prevailing wind direction or away from the direction of the least frequent winds should minimize this uncertainty (2). The sensor booms can

be mounted on an elevator system so that sensor maintenance activities can be done without requiring a person to climb the tower.*

A final but important tower consideration is survivability in high wind and icing conditions. A tower installation contractor with local experience should be a good source of advice. Also, the record of communications towers of similar heights in the area could also be checked.

Shelter for the data logger is a necessary element of the system. The shelter could be a simple weathertight enclosure mounted at the base of the tower (beware of vandalism though). In some cases a small room (4 ft x 4 ft) is justifiable. Field checking or repair of equipment in inclement weather may be difficult or impossible without shelter.

The need for power at a measurement site depends upon the power requirements of the measurement system. If data are recorded on cassette tapes, the interval between tape changing visits will probably be less than the battery charge life so that battery level checks can easily be made on routine site service visits. Solar cells adding a trickle charge are convenient for extending the useful charge in a battery pack. For towers that are 200 ft tall or taller, the Federal Aviation Administration requires a reliable warning light system.** To achieve that reliability, AC power will be needed at the site. Since bringing AC power into a remote site can be expensive, there is a strong incentive to use 199-ft towers rather than hub-height towers (if hub height exceeds 200 ft). However, if AC power is brought in, site power requirement problems are small. Even with AC power at the site, backup power is needed for both data loggers and FAA lighting. Data logger power is conveniently obtained by using AC power to trickle charge the batteries, which actually power the measurement system. FAA lighting backup power requires a backup generator, such as a butane generator, that will start when a loss of line power is sensed.

The specifics of what measurement system components will be used for a given measurement program will vary depending on the data requirements, the hostility of the environment, the remoteness of the site, and the preferences of the individuals

* Reliability is a problem with some elevator designs. This point should be discussed with tower manufacturers and other experienced parties.

**Lightning rods extending above the tower do not add to the tower height according to FAA interpretation of existing statutes (personal communication, R. N. Swanson, Pacific Gas & Electric).

designing the measurement program. Some points to be considered in the design of a measurement program are discussed below.

MEASUREMENT PROGRAMS

The starting point for designing a measurement program is to determine what data are needed. The data requirements (data products and required accuracies) dictate the choice of measurement strategies, measurement system components, and level of quality control efforts. Data requirements or considerations at each stage of the siting method are discussed below. Additional detailed discussion of deployment of measurement systems is given by Hiester and Pennell (2).

Stage I: Identify and Rank Candidate Resource Areas

No meteorological data collection is required or suggested as part of Stage I (Section 4). If a utility were to undertake a regional resource assessment program based on new measurements to supplement the DOE atlas analyses (Appendix A), the choice of measurement locations would be tantamount to selecting a Potential Candidate Site, and would not help achieve the objectives of Stage I.

Stage II: Selection of Potential Candidate Sites

The quickest and generally most efficient execution of Stage II will not require additional wind data. However, if numerical models are to be used to help identify the better wind zones within the Candidate Resource Area (Section 5, Appendix F), supplementary measurements may be required.* The data needs are determined by the specific model to be used and should be worked out with the modeler.

Measurements to drive numerical models will likely require time series measurements of some or all of the following quantities at one or several locations throughout the Candidate Resource Area:

- 1-hr averages of wind speed and direction
- vertical wind and temperature profiles
- near-surface temperature and humidity
- surface temperature
- solar radiation
- cloud cover
- evaporation rate from the surface.

*If the strategy suggested in Appendix F is adopted where input data are assumed and model sensitivity to variations of input data is tested, it may be that no supplementary measurement program will be required.

These measurements may be needed from several key locations throughout an area. Therefore, expensive systems and tall towers are probably not cost-effective simply to drive the numerical modeling program. Considerable detail on measurement systems and their deployment to support modeling programs is given by Hiester and Pennell (2).

Stage III: Selection of Candidate Sites

Two aspects of Stage III could require meteorological data collection (Section 6, Figure 6-1):

- evaluate Potential Candidate Site meteorology
- preliminary measurement program.

One or more visits to the site are made by a meteorologist in Stage III, during which wind measurements between 10 and 200 m are made to evaluate the local meteorology. Kites, kite anemometers, or tethered balloon systems are currently the most usable systems.* The primary purpose of the measurements is to determine if potentially hazardous wind profile characteristics occur with substantial regularity.

Wind profile characteristics that are potentially hazardous and that could disqualify a site are high wind shear or even reverse flow** and persistent zones of high turbulence. The existence of these zones is easily determined with a wind-sensing kite (2). Kites will fly very erratically in the high turbulence of the reverse flow zone, but fly relatively smoothly in the quiescent stronger winds outside the flow separation zone. The occurrence and extent of flow separation varies from day to day (and also with time of day) so repeated probing of an area on many visits and at different times is necessary to adequately assess a potential hazard.

The second possible need for measurements in Stage III arises if a preliminary measurement program is elected. A preliminary measurement program is used to help reduce the size of the group of Potential Candidate Sites from which the Candidate Sites will be selected and to establish the likelihood of exceeding the break-even energy production.

* Tethered balloons can only be launched in wind speeds much less than 10 m/s at release level. This limitation restricts their use in site evaluation.

**Rugged topography often causes reverse flow (or flow separation). For example, flow upwind and over a ridge may be from west to east, but within a few tens of meters of the surface in a zone extending downwind of the ridge crest for several hundred meters, the wind may be from east to west and very turbulent.

Recall from Appendix B that there are several methods for estimating energy production. The simplest approximation requires only a measurement of the mean wind speed for the month, season, or year. That measurement is simply achieved with a wind-run anemometer. Somewhat more involved is an estimate of the energy production derived from a measured wind speed frequency distribution. There are systems available that directly accumulate the wind speed frequency distribution by month and even by time of day for little more cost than a wind-run anemometer. The added flexibility in analysis makes those systems very attractive for preliminary measurement programs. An example preliminary measurement program based on strip-chart recordings at numerous sites is described in (6), whereas (7) describes a program based on time series data recorded on cassette tapes.

Stage IV: Selection of Preferred Sites

There currently is, and probably will be for some time to come, controversy over data requirements for Stage IV (Section 7) of the siting process. Meteorological data are required to:

- estimate cluster energy production
- determine effects of cluster output on the utility system
- ensure wind characteristics are compatible with trouble-free operation of the wind turbines.

Estimating wind turbine energy production is discussed at length in Appendix B and is the primary concern of data collection. The principal decision to make is whether or not to perform a quasi-dynamic simulation of turbine output (Appendix B). If so, then time series data are needed. The data should be wind speed and direction measured at hub height and averaged over time compatible with the response time or operating strategy of the wind turbine being considered (e.g., one-minute averages). If one is not sure that a quasi-dynamic simulation will be employed, the conservative approach is to collect data that will allow the simulation to be performed later. If 60 one-minute averages have been collected but one later decides hourly averages are all that is required, it is a trivial matter to take the one-minute data and generate hourly data.

Quality Assurance. A quality assurance (QA) program must be established once the measurement strategy and system have been designed. This is especially true in Stage IV since the data collected in Stage IV will be used to make the decision to develop a cluster. The QA program encompasses calibration and maintenance procedures, data recovery goals and procedures, and data editing and validating procedures. If meteorological consultants are used to gather and reduce data for the utility, it is

still ultimately the utility's responsibility to see that the data collected conform to desired quality specifications. This is best achieved through a written QA plan, possibly prepared by the consultant but certainly agreed to by both the utility and the consultant.

A QA plan documents the procedures to be followed that should result in maintaining specified levels of data accuracy and recovery rates. Those levels can be set to any mutually agreed upon standards matched to the problem. The standards required by the Nuclear Regulatory Commission (NRC) for meteorological measurements at nuclear power plant sites (8) serve as stringent goals for a wind data collection program. The NRC guidelines specify that measurement system (i.e., sensor, cables, signal conditioner, recorder, and data reduction) errors shall not exceed $\pm 5^\circ$ in wind direction, ± 0.22 m/s (0.5 mph) or $\pm 1.0\%$ (whichever is the greater) in wind speed, and recorded time within 5 min of actual time. A valid data recovery rate of 90% is specified.

Achieving a 90% data recovery rate is a demanding accomplishment. Redundant systems may be required. A strip-chart recorder used as a backup is one simple and inexpensive approach to cover possible data logger failures. In especially hostile environments where a site may not be inspected more often than once every few weeks, one should probably choose a rugged wind sensor. This would help ensure the data recovery rate goal but may somewhat compromise the speed measurement accuracy goal due to the increased tendency for overspeed in the heavier sensors. It is not likely to be cost-effective to install redundant sensors for wind energy applications. A possible major cause of long periods of data loss is system failure shortly after a site visit that is not discovered until a subsequent visit is made. A solution to that problem is the remote telemetry of data, which allows system status to be checked at any time.

A strict QA plan will describe procedures used to initially calibrate each sensor (e.g., in a wind tunnel using a reference anemometer that has been calibrated at the National Bureau of Standards). The periodic (e.g., quarterly or semi-annual) system calibration process should also be described. This process might entail testing that the torque required to turn anemometer or vane shafts remains within specified limits, that anemometers driven at known speeds produce the expected signal, that known signals applied to the signal conditioning equipment and data loggers produce the expected recorded output, and that time is being kept properly. The documentation and correction procedures applied to components found to be out of tolerance should be described.

The calibration and maintenance procedures can be dependent upon the type of sensors used and where they are used. For example, anemometers that use generators with brushes to create a signal may deteriorate fairly quickly in environments of high dust or corrosion. To keep on top of any possible changes in the calibration of those sensors, semi-annual or quarterly calibrations are a must. However, a light-chopper type of anemometer does not suffer that form of deterioration and usually doesn't require the close calibration scrutiny that the generator-type anemometer does. If deterioration that might affect the calibration of an anemometer is suspected, the anemometer should be recalibrated before refurbishing so that corrections can be made to the data since the last previous calibration.*

The utility or its meteorological contractor may subcontract with local individuals to perform routine site services, such as changing data tapes or paper charts, checking to see that all systems are functioning, and inspecting the tower or other peripheral systems for potential problems. The subcontractor should be provided with standard procedures or checklists and logs for the routine site inspection or tape changing activities to ensure that no problems go unnoticed. For example, without a checklist someone could forget to correctly reset a data logger clock, or fail to note potentially troublesome corrosion.

Quality assurance also encompasses data reduction procedures. With the power of automated data processing available, there is a disturbing tendency for investigators to process data into digestible statistical summaries without first examining the raw data. Therefore, data reduction process should at least contain programs that check for spurious data with unreasonable values (e.g., more than three standard deviations from the mean), check for unreasonable wind shears, etc. An advantage to using strip charts for backup to the data logger is that the strip chart trace can be rapidly scanned by eye for peculiar systematic behavior that might not be apparent in automated editing programs.

EXAMPLE MEASUREMENT SYSTEMS

The configuration of two different, though state-of-the-art, site evaluation measurement systems and programs are described here. Each has strengths that the other doesn't. The fact that two different approaches have been taken simply reflects that site-evaluation measurement strategies are still developing.

*The bearings within cup anemometers are the greatest source of calibration error for either generator or light-chopper anemometers.

The first system is the Department of Energy Candidate Site Program (9). The second is the system adopted by the Pacific Gas and Electric for use at their wind turbine project sites.*

Department of Energy Candidate Site Program

Part of the U.S. Department of Energy (DOE) wind turbine research and development program is to field test prototype wind turbines on sites proposed by electric service organizations. The candidate site program** was established in March of 1976 when DOE issued an RFP to acquire, on a competitive basis, a group of candidate sites proposed by utilities interested in the field test program. Meteorological equipment was installed by DOE on the selected sites to assess the wind energy potential at the site.

As a result of the 1976 RFP, DOE selected 17 candidate sites. The NASA-Lewis Research Center (NASA/LeRC), which manages the design, construction, and installation of the turbines, initially coordinated the meteorological measurements at the candidate sites. NASA/LeRC selected Western Scientific Services, Inc. (WSSI) of Fort Collins, Colorado, as its meteorological measurement contractor. As the meteorological measurement contractor, WSSI provided services in installing and maintaining the meteorological equipment and in analyzing and publishing the data. After the 17 sites were selected, WSSI arranged for the installation of 150-ft meteorological towers and for the placement of standard cup and vane anemometers at two levels on these towers. At most sites, the sensors were installed at the 30-ft and 150-ft levels. At some sites the lower level was chosen to be 60 feet to avoid effects on the measurements as a result of nearby obstructions. At all sites, the tower was installed at a location about 100 meters from where a wind turbine would actually be located.

The towers were generally located upwind, in the prevailing wind direction, of the proposed turbine location. This arrangement would ensure that the tower would measure the free-stream wind characteristics so that the data could be used for performance evaluation of the turbine if the site were selected to receive one.

*Based on personal communications with Messrs. Warren Alton, Richard Simon, and Robert Swanson, February 13, 1981.

**The DOE candidate sites are not to be confused with the term Candidate Sites used in this report, even though there are clear similarities in the status of DOE candidate sites and Candidate Sites resulting from Stage II of the siting process.

The data from the sensors were recorded on strip-chart recorders - each sensor having its own recorder. Upon receiving the strip charts from the utilities each month, WSSI arranged to have the data reduced by hand and summarized into hourly wind speed and directions. WSSI also prepared monthly data reports.

In 1978, the Pacific Northwest Laboratory (PNL) in Richland, Washington, operated for DOE by Battelle Memorial Institute, assumed the responsibility of the program from NASA-Lewis. PNL selected as its subcontractor Environmental Systems Corporation (ESC) of Knoxville, Tennessee, to provide calibration, maintenance, and data reduction services at the candidate sites. Although at this time there were a total of 16 candidate sites (measurements were terminated at Bonneville Power Administration's Augspurger Mountain site in January 1978 because of severe winter icing conditions that caused a tower collapse), ESC was responsible for maintenance of 14. The other two sites, Kaena Point (Hawaiian Electric Company) and Boardman (Portland General Electric) were maintained by the proposing utilities.

In the fall of 1978, ESC traveled to each of the 14 sites and installed instrument elevators and ESC designed digital cassette data loggers on the towers. In some cases the strip-chart recorders were retained as backup systems. The primary system of recording wind speed and direction is presently the digital data loggers, which record instantaneous samples of each sensor every two minutes.

Of the 16 candidate sites in the original program, five were selected to receive large wind turbines for field testing. These five sites are:

Site	Turbine
Clayton, NM	MOD-OA (rated at 200 kWe)
Culebra, PR	MOD-OA
Block Island, RI	MOD-OA
Boone, NC	MOD-1 (rated at 2 MWe)
Oahu, HI	MOD-OA

Special modifications to the meteorological measurement program were made at these turbine sites. At the first three MOD-OA sites, a third level of sensors was installed on the towers at the 100-ft level (hub height). In addition, the original wind speed and wind direction sensors were replaced with more sensitive ones. This allowed for more detailed turbulence studies to be conducted at these sites.

The original MOD-OA site at Kaena Point on the island of Oahu, Hawaii, has been moved to the Kahuku area. A 150-ft free-standing tower was installed about 60 m north of

the wind turbine. The tower is equipped with three levels of sensors and a digital cassette data logger similar to those at the other MOD-OA sites.

An important feature at these sites is that turbine output parameters (alternator power output, nacelle yaw error, and wind speed and direction from the nacelle anemometer) are recorded simultaneously with the meteorological tower data. This allows detailed analysis of the turbine's performance and response to the meteorological conditions at the site.

At the Boone, North Carolina, site the tower was extended to 290 ft so that a Federal Aviation Administration (FAA) warning light could be installed (the MOD-1 blade tip is 275 ft above the ground). A third level of sensors was installed at the 275-ft level on the tower. However, arrangements were not made to record turbine output parameters on the data logger.

In the summer of 1979, DOE began selection of a second group of candidate sites. Twenty sites were selected. To carry out the installation and maintenance of the equipment at the new sites as well as to take over the operations of the previous group of candidate sites, PNL selected Engineering-Science of Arcadia, California, as a subcontractor. Meteorological measurement systems similar to the MOD-OA turbine sites were installed at the new candidate sites; that is, 150-ft towers, three levels of wind speed and wind direction sensors, and ESC data loggers. Table G-1 summarizes certain details of the DOE candidate site program system.

A goal of 90% data recovery at each site was established for the program. Achieving this has been difficult since, unlike other programs with similar goals (e.g., nuclear power plants), there are generally no backup systems at the candidate sites, and often the sensors and loggers are checked only once a week by utility personnel. In general, data recovery decreases during the winter months when severe weather hampers performance of the sensors and loggers.

Since the late fall of 1978, the following procedures have been observed to produce monthly data reports from each of the sites.*

Every two weeks a representative of the utility visits the tower site, changes the cassette tape in the data logger, and mails the data-filled cassette to PNL's

*In the summer of 1981, PNL took over the entire operation of the DOE candidate site program, including operation and maintenance functions that were previously performed by subcontractors. The text describes the program using subcontractors.

Table G-1

SUMMARY OF DOE CANDIDATE SITE PROGRAM SYSTEM ELEMENTS

<u>Item</u>	<u>Approximate Cost (\$10³)</u>	<u>Description and Comments</u>
Tower	5 + 2 to 10 Installation	Standard truss-type communications tower. Upper guy wires at 45°.
Instrument Elevators	5	
Anemometer	0.4 ea	Second candidate site group and turbine sites: fifty-slot light chopper, accuracy of $\pm 1\%$ or 0.15 mph (whichever is greater), starting threshold of 0.6 mph, range of 0-110 mph.
Wind Vane	0.4 ea	Second candidate site group and turbine sites: standard wind vane, threshold of 0.75 mph, damping ratio of 0.4.
Lightning and Grounding Kit	0.6	
Data Logger	4	Battery-powered cassette data logger, instantaneous samples at selectable intervals, usually two minutes.
Battery Pack and Charger	0.4	
Guideline Total	20-30	

subcontractor. The utility representative also visually inspects the tower and sensors, checks the performance of the logger, and fills out a site inspection form, which is also mailed to the subcontractor.

The voltage data on the cassette data tapes are then converted to engineering units and transferred to a nine-track tape. The data are then edited to note spurious values with the aid of a computer-assisted data editing program as well as by the visual inspection of a meteorologist. A final, edited nine-track tape is then prepared, and a copy mailed to PNL for use in preparation of a monthly data report.

When a monthly nine-track data tape is received at PNL, it is put into various data analysis programs, which provide summaries of pertinent wind characteristics at each candidate site. These summaries are incorporated into monthly data reports, which

are forwarded to NASA-Lewis, DOE, and each participating utility to allow an assessment of the wind energy potential at the sites. These monthly reports include such information as mean and standard deviations of wind speed and direction, joint wind speed and direction frequencies, mean hourly wind speeds, cumulative frequency distribution of wind speed, wind speed persistence, maximum gusts, turbulent intensities and power law coefficients, as well as a log of the sensor performance during the period.

The subcontractor provides routine calibration and maintenance services, as well as emergency maintenance services, at each of the sites. For example, when a utility representative reports a sensor or logger failure, the subcontractor is to proceed to the site within 72 hours to correct the problem (in some instances, the problem can be identified and corrective procedures implemented by discussing the situation with the utility representative over the telephone).

The subcontractor also performs periodic calibrations at each of the sites. Annually, calibrations include changing all sensors with precalibrated spares. Quarterly onsite calibrations of all electronics are performed. The precalibrated wind speed sensors have been calibrated in a wind tunnel. All calibrations are traceable to standards established by the National Bureau of Standards.

The DOE candidate site program provides a unique perspective on wind energy site evaluation procedures because it is the largest and longest running measurement program for large-scale wind energy applications. Several criticisms or conclusions can be drawn in hindsight based on experience gained in this program. First, instantaneous samples recorded every two minutes probably do represent an optimum sampling strategy. It is appropriate if hourly averages of wind speed and direction are desired. However, some form of short-term average (say, one or two-minute averages) is probably more appropriate for performing a quasi-dynamic time series simulation of energy production (Appendix B). Second, there is no universal measurement system. Towers, sensors, and data loggers should be chosen according to local conditions. If salt, heavy icing, or gritty conditions occur regularly, rugged systems must be chosen to ensure high data recovery rates. Fast response sensors are probably not required for most siting programs (not necessarily true of research programs) and certainly such delicate sensors can only be used effectively in relatively clean or benign environments or where there is an extraordinary commitment to site maintenance.

Pacific Gas and Electric Measurement Program

Pacific Gas and Electric (PG&E) has been involved in wind energy activities for many years. Many potential resource areas have been identified and further wind monitoring and site evaluation efforts continue at several sites. The measurement system currently used by PG&E at some of their most promising sites represents a different viewpoint and strategy than that currently used at the DOE candidate sites.

The most significant difference in the PG&E system is in the measurement strategy and the data logger. The data logger is manufactured by an experienced manufacturer of meteorological instrumentation with certain modifications made specifically at the request of PG&E. The data logger samples the wind speed and direction sensors at a high rate (0.5 Hz) and computes averages and standard deviations. The average is an average for the hour. Standard deviations of the rapidly sampled wind speed and direction are computed for different length intervals of time, namely, 30 s, 60 s, 120 s, 300 s, and for the hour, 3600 s. Thus, in one hour 120 standard deviations for 30 s intervals are computed, 60 for 60 s intervals, 30 for 120 s intervals, 12 for 300 s intervals and only one for the 3600 s interval. For each interval an hourly average standard deviation is computed and recorded on cassette tape.

The motivation for this measurement strategy is based on a relatively simple way to obtain a rough estimate of the turbulence spectrum of the winds (10). A time series trace of wind speed shows the wind speed fluctuating above and below some mean value. The fluctuations can be partitioned into some that are very rapid, some that are not so rapid, and some that are very slow oscillations. Thus, the original trace is a superposition of short-period fluctuations on longer period fluctuations. The turbulence spectrum is one way of analyzing how much of the variance of the wind speed is associated with different period fluctuations. This is potentially useful information because, for instance, a wind turbine might not respond to the very fine scale (short period) fluctuations, but may start up and shut down frequently as the turbine controls attempt to track and respond to larger (longer period) fluctuations occurring around the turbine cut-in wind speed.

Table G-2 is an example of the output from the PG&E 300-ft tower at the Solano #1 site with four levels of wind sensors, one temperature, and one dewpoint temperature. The first line presents site identification, data, and time information and unit labels. The second line offers labels for the data presented in each logical block of four lines. The third line gives the start and stop time of the data in the block and the wind data for the lowest (30-ft) level. The fourth line is the wind data for

Table G-2

EXAMPLE OUTPUT FROM PG&E SOLANO 350-FT TOWER

S01	80/12/19	00:00	20	1	0	ARCSIN(DSG=)SIGMA;WS=MPS;TDP=DEGC							
<u>TIME</u>	<u>TEMP/DP</u>	<u>AVWSP</u>	<u>SSG 1</u>	<u>SSG 2</u>	<u>SSG 3</u>	<u>SSG 4</u>	<u>SSGHR</u>	<u>WDR</u>	<u>DSG1</u>	<u>DSG2</u>	<u>DSG3</u>	<u>DSG4</u>	<u>DSGH</u>
00:00	01:00	6.17	0.52	0.60	0.67	0.75	0.87	256	983	1064	1133	1165	1346
		7.03	0.52	0.62	0.71	0.78	0.89	255	1323	1400	1454	1498	1710
TEMP	8.9	7.90	0.36	0.46	0.53	0.60	0.83	263	674	748	802	844	1124
DEWP	7.6	8.06	0.16	0.21	0.28	0.32	0.60	265	452	519	570	620	1105
01:00	02:00	6.91	0.62	0.74	0.85	0.88	0.99	259	1060	1117	1157	1200	1301
		8.03	0.52	0.67	0.77	0.84	0.98	256	1184	1259	1294	1340	1469
TEMP	8.7	9.09	0.37	0.47	0.54	0.60	0.83	263	558	654	690	715	858
DEWP	7.5	9.13	0.23	0.32	0.38	0.44	0.77	264	460	506	549	589	768
18:00	19:00	7.38	0.60	0.72	0.82	0.90	0.94	252	1028	1113	1197	1266	1422
		8.23	0.61	0.71	0.81	0.87	0.92	254	2136	2272	2377	2454	2774
TEMP	10.1	9.26	0.65	0.77	0.87	0.94	1.01	257	861	927	976	1006	1295
DEWP	8.6	10.01	0.32	0.41	0.50	0.57	0.65	257	628	689	737	776	1160

the 100-ft level. The fifth line has the hourly mean temperature and wind data for the 200-ft level. The sixth line has the mean dewpoint temperature and wind data for the 300-ft level. The data block is then repeated for successive hours.

A great deal of information is economically collected, processed, and stored in the PG&E approach. The turbulence information is certainly of use to a meteorologist in achieving a qualitative understanding of the wind behavior at a site. Whether or not the information will play an important role in quantitative calculations (e.g., in energy production simulations or in computation of gust loadings on a turbine) is not known at present.

Rugged wind sensors were used at most of the sites. The sensors were designed for reliability at some cost in performance. The manufacturer-quoted specifications claim accuracy of ± 1 mph or 2% (whichever is greater), a starting threshold of 2 mph and a range of 0 to 200 mph for the anemometer. Compared to the sensors used in the DOE program, the sensors used by PG&E are not as accurate and do not perform as well at low wind speeds. However, PG&E reasoned that for wind energy purposes the low wind speed performance is not crucial and that reliability in harsh environments is the overriding concern.

The wind direction sensor deployed by PG&E uses a potentiometer to indicate wind direction. Although this transducer is generally satisfactory, PG&E has noted times when the potentiometer has gotten dirty, which causes a noisy signal. A noisy signal can lead to erroneous calculations of standard deviations of wind direction. The above problem is one disadvantage of a system that does substantial computing before recording pieces of processed data; it may be difficult to recognize bad data.

A check on the overall performance and suitability of the PG&E strategy will be possible based on measurements being made at their MOD-2 wind turbine site. On the 350-ft tower at that site are two completely independent data systems, but with sensors of each system at the same level. One system uses a data logger with the rugged wind sensors. The second system records data in a time series format using more sensitive wind sensors. In addition, the more sensitive wind direction sensor does not use a potentiometer and will not have the potential signal noise problem of the other system. The long-term experience gained at the MOD-2 site will clearly indicate whether more rugged systems really require less maintenance and whether economics in preprocessing of data at a Candidate Site are worth the loss in data analysis flexibility.

The Solano #1 site requires lighting on the 300-ft tower. To achieve reliability in the lighting, AC power was brought in to the tower. Approximately two miles of line were required at a cost of approximately \$10,000. If the line power fails, a butane generator takes over to maintain tower lighting. Also, in the event of power failure, a signal is relayed through the PG&E microwave communications system, which has a relay link near the site. The availability of AC power allows a bank of strip-chart recorders to be run as backup to the data loggers.

Several PG&E sites are maintained with towers less than 200 ft high, thus not requiring tower lighting. These remote sites are powered only by batteries that are charged by a solar cell panel mounted on the tower. No strip chart backup to the cassette data logging system is used at the remote sites. Table G-3 summarizes the PG&E system at a typical remote site.

Table G-3
SUMMARY OF TYPICAL PG&E REMOTE MEASUREMENT SYSTEM

<u>Item</u>	<u>Approximate Cost (\$10³)</u>	<u>Description and Comments</u>
Tower	5 + 2 to 10 Installation	Standard truss-type communications tower. Upper guy wires at 45°.
Wind Sensors	1.9	Rugged cup and vane anemometer system. Wind speed: 40 slot light chopper, accuracy of ±2% or 1 mph (whichever is greater), starting threshold of 2 mph, range 0-200 mph. Wind direction: threshold of 2 mph, damping ratio of 0.2,* accuracy ±3°.
Data Logger	5.5	Battery-operated data processor. Processed data recorded on cassette tape.
Solar Panel	0.5	6 W Solar Panel
Miscellaneous	0.5	
Guideline Total	15-25	

*All direction sensors will have damping ratios of 0.4 by January 1982.

The towers are typically visited every week for tape changing, battery level checks, and overall system check. Once tapes are returned to the laboratory and translated to computer compatible tape, a series of editing programs similar to those of the DOE candidate site program are executed to search for suspicious data. Every six months the sensors are changed out completely with refurbished sensors. Although wind tunnel calibrations are not routinely performed, PG&E randomly samples about 20% of their sites and performs an end-to-end check on the wind sensors to verify that anemometers driven at a known rate produce the properly recorded signal.

A final but strongly stated measurement philosophy is in the choice of tower heights. Much of the area under investigation for wind energy by PG&E is in quite hilly terrain. The percentage speedup of wind as it passes over hills (Appendix F) is usually greatest near the surface of the hilltop, and the speedup usually decreases with height. The details of the speedup are difficult if not impossible to predict reliably. The meteorologists at PG&E strongly favor the use of 100- to 200-ft towers (rather than 30-ft preliminary measurements) as early in the site evaluation process as possible. This philosophy has not yet been fully implemented in their measurement program, in part due to capital costs and in part due to the uncertainty of the extent of the role that private wind energy developers will play in supply of wind energy to the PG&E system.

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Appendix H

GLOSSARY

Boundary Layer - See Planetary Boundary Layer.

Boundary Conditions - The treatment or specification of the values of variables of interest (e.g., wind speed and direction or temperature) at the upper, lower, or lateral boundaries of a numerical or physical model domain.

Candidate Resource Area - A subdivision of the Region of Interest that has a wind resource strong enough to be economically viable.

Candidate Site - The Potential Candidate Sites considered to be most favorable for wind turbine installation.

Certainty Rating - The degree of certainty with which a wind power class can be specified in a region. Certainty ratings are discussed in Appendix A and Chapter 4.

Cluster - A group of any number of wind turbines sited within a sufficiently close proximity that they may be considered, for most purposes, as a single power producing unit; also called a WECS farm.

Confidence Rating - See Certainty Rating.

Control Strategy - The algorithm of the wind turbine microprocessor that takes wind data and wind turbine status or performance data to determine what, if any, changes in machine operation should be initiated (e.g., startup, shutdown, yaw maneuver, pitch control). See Appendix B.

Cut-In - The wind speed at which the wind turbine control system initiates startup procedures.

Cutout - The wind speed at which the wind turbine control system initiates shutdown procedures.

Digitized Data - Weather data, usually time series, that have been placed on magnetic tape or computer cards for use in a computer.

Flagged Tree - A tree, deformed by the wind, with characteristic crown asymmetry. The use of flagged trees to indicate areas of good wind resource is discussed in Appendix G.

Horizontal-Axis Wind Turbine - A wind turbine in which the rotor rotates about an axis that is horizontal and parallel to the wind. The axis is at hub height above ground.

Hub Height - The height above ground of the axis of a horizontal-axis wind turbine. It is frequently assumed that hub-height winds may be used to construct an adequate representation of the winds affecting the entire wind turbine. For a vertical axis wind turbine, such a height would be midway between the top and bottom of the rotor.

Icing - The buildup of ice on turbine or anemometer blades. Icing is a meteorological hazard and is discussed in Chapter 2.

Large-Scale Terrain - Defined for this document to be terrain in which the vertical relief is either a significant fraction of the boundary layer depth or exceeds the boundary layer depth.

Mean Wind - The definition varies with context. If no averaging interval is specified, such as annual mean wind, the reference is probably indicative of an averaging interval just long enough to filter out the turbulence in the wind, e.g., 15 min to 1 hr.

Mesoscale - A scale of atmospheric motions that are smaller than synoptic scale but larger than microscale; i.e., horizontal scales between 1 km and hundreds of km. Mesoscale meteorology is especially difficult because the mesoscale flow interacts with the synoptic scale and the microscale in ways that are poorly understood.

Microscale - The scale of motions in the atmosphere associated with turbulence; i.e., scales smaller than about 1 km.

MOD-0 - The first wind turbine developed in the DOE program. With a rotor diameter of 125 ft, it can produce 100 kW of power in an 18-mph wind. It has been reconfigured numerous times for testing of new wind turbine design concepts.

MOD-0A - A wind turbine of similar dimensions as the MOD-0, however, it can generate 200 kW of power in winds above 18 mph.

MOD-1 - The first megawatt-scale wind turbine developed in the DOE program. With a rotor diameter of 200 ft, it can generate 2 MW of power in a 26-mph wind.

MOD-2 - A DOE-developed wind turbine that can generate 2.5 MW of power in a 27-mph wind. The MOD-2 has a 300-ft-dia rotor with hub height at 200 ft.

Numerical Modeling - The forecasting or diagnosis of the behavior of atmospheric motions by the numerical solution of the governing fundamental equations of hydrodynamics or some simplified equation set, subject to observed initial and/or boundary conditions. Numerical modeling is discussed in Chapter 5 and Appendix G.

Objective Analysis - Analysis of the flowfield from a few observations where the relation of flow variables at separate points in space or time is constrained to satisfy governing equations, which may or may not include all relevant physics. This is opposed to a subjective analysis where the individual performing the analysis relies, as best he can, on his understanding of all of the governing physics to guide his interpretation of flow features between observations.

Planetary Boundary Layer (PBL) - A layer of the atmosphere near the ground where the friction of interaction of winds and the surface causes turbulence and wind shear. The planetary boundary layer is typically 1 to 2 km deep, although it can be as little as a hundred meters deep.

Potential Candidate Site - A plot of land in the Candidate Resource Area where the installation of wind turbines would be practical from an engineering standpoint.

Preferred Candidate Site - Those candidate sites that after onsite verification of the magnitude of the wind resource, and analysis of engineering, economic, and environmental factors show the greatest potential as wind turbine sites.

Physical Modeling - The attempt to measure solutions to a small-scale flow, e.g., in a wind tunnel or a water towing tank, so that the measured solutions may be applied to full-scale flow features. Physical modeling requires strict attention to preserving dynamical, kinematic and geometrical similarity between model and full-scale flow. The technique is described in Chapter 5 and Appendix F.

Power Law - A description of the variation of wind speed with height used extensively in the engineering community where the ratio of wind speeds at two heights is equal to the ratio of the two heights raised to some power. The power law is discussed in Appendix B and Appendix F.

Probability Density Function (PDF) - A function that yields information on the probability of observing a random variable between any given values of that variable.

Profile - A graphic representation of the variation of one property, such as wind speed or temperature, with respect to another property such as height above ground or position.

Rated Wind Speed - The wind speed at which the power output of a wind turbine reaches its rated value.

Rawinsonde - A weather balloon system with the additional capability of evaluating wind speed and direction aloft by means of tracking by radar or radio direction finder.

Rayleigh Distribution - A unimodal, one-parameter probability density function described by:

$$p(x) = \frac{\pi x}{2\bar{x}^2} \exp\left[-\pi x^2/4 \bar{x}^2\right]$$

where $\bar{x}$ is the average value of the variate x . The Rayleigh distribution is frequently used to describe the distribution of wind speed.

Rotor Disk - The area swept by the blades of the wind turbine.

Region of Interest - A large land area in which a utility is looking for wind turbine sites.

Roughness Length - A parameter (z_0) used to describe the texture of the earth's surface and its effects upon the wind profile. The roughness length is not really an applicable parameter for nonflat terrain; however, the texture of nonflat terrain is, for comparison, often described in terms of a roughness length.

Shutdown - The procedure whereby a wind turbine returns to parked standby status. Shutdown procedures may be initiated by wind speeds exceeding cutout, by wind speeds dropping below cut-in before startup is complete, by power output falling below a prescribed value, or by excessive changes in wind speed or wind direction.

Site - Property upon which one or more wind turbines could be located.

Small-Scale Terrain - Defined for this document to mean nonflat terrain in which the vertical relief is a small fraction (<10%) of the boundary layer depth.

Startup - The procedure whereby a wind turbine starts from parked standby status, is made operationally ready, achieves synchronization with the grid and begins to satisfy load. Startup requires several minutes.

Summarized Data - Weather observations condensed into various formats, such as monthly average wind speeds, diurnal variations in wind speed, or frequency distributions of wind speed and direction (see Appendix F).

Synoptic Scale - The scale of migratory high- and low-pressure weather systems with wavelengths of 1000-2500 km. A reference to synoptic-scale winds refers to winds due to the pressure gradient of the synoptic-scale waves. There may be mesoscale wind systems superimposed upon the synoptic-scale windfield.

Terrain Classification Code - A system for identifying types of terrain, used in the DOE wind resource assessments. The terrain classification code is described in detail in Chapter 4.

Turbulence - Motion of fluids in which local velocities and pressures fluctuate irregularly in a random manner. Additionally, three-dimensional turbulence, usually known just as turbulence, is distinguished from other random flows in the atmosphere by the cascade of kinetic energy of the disturbance to smaller and smaller scales caused by the stretching and amplification of vorticity.

Turbulence Intensity - A statistic to convey the magnitude of turbulence kinetic energy of a component of a flow. Turbulence intensity of the longitudinal wind component as expressed by wind engineers is where σ_u is the standard deviation of the velocity fluctuations of the wind parallel to the mean wind $\bar{u}$.

$$\frac{\sigma_u}{\bar{u}}$$

Unsummarized Data - Original weather observations, often still on paper charts or observation forms.

Wake - The region downstream of a body immersed in a fluid in which the effects of the body on the fluid's motion are concentrated.

Weibull Distribution - A unimodal probability density function depending on two parameters; a scale factor and a shape factor. The Weibull distribution is given by

$$p(x) = \left(\frac{k}{C}\right) \left(\frac{x}{C}\right)^{k-1} \exp\left[-(x/C)^k\right]$$

where C is the scale factor, related to the mean value of x ($\bar{x}$) by

$$\bar{x} = C \Gamma(1 + 1/k)$$

where Γ is the gamma function of k is the shape factor which is related to the variance of x

$$\sigma_x^2$$

by

$$\sigma_x^2 = C^2 \left\{ \Gamma(1 + 2/k) - [\Gamma(1 + 1/k)]^2 \right\}$$

The Rayleigh distribution is a special case of the Weibull distribution where $k = 2$.

Wind Power Density - A gauge of potential wind resource. Wind power density incorporates in a single number the combined effect of the distribution of wind speeds and the dependence of the power density on air density and on the cube of the wind speed. Wind power density was broken into classes in the DOE wind resource assessments. Definitions of the wind power density classes are given in Appendix A.

Wind Profile - See Profile.

Wind Shear - The local variation or gradient of the wind vector or any of its components in a given direction. Unless otherwise stated, wind shear refers to the vertical shear of the horizontal winds.

Wind Zone - A geographical area with reasonably homogeneous wind resources.

WTG - Wind turbine generator. A machine that converts energy in the wind into electric power.

Yaw - The rotation or movement of a horizontal axis about a vertical axis.