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SITING SMALL WIND TURBINES

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INTRODUCTION

A recent survey (1) has indicated that improper siting has been a common cause of dissatisfaction among users of small wind turbines. That is, the user has not received the power output or machine life he expected. If poor siting decisions have been a cause of complaints in the past, such decisions will certainly be a source of user dissatisfaction in the future. Historically, wind turbines were used because they were the only option available for providing power in rural areas. Thus, the user was likely to be satisfied with whatever energy he could glean from the winds. Today, however, wind turbines must compete with other options for providing power as well as with central grid power.

Most potential purchasers will need to be reasonably certain of the cost of wind power for their particular application before they decide to buy a wind energy conversion system (WECS). Such an assessment requires an accurate knowledge of wind characteristics at the turbine site. This paper presents a procedure for choosing the best available site for a wind turbine and for estimating the pertinent wind characteristics once the site is chosen. In some cases, extensive onsite measurements may be required before an accurate analysis of turbine performance can be made.

A SITING STRATEGY FOR SMALL WIND TURBINES

A potential purchaser must consider many factors other than siting before buying a wind turbine. Among these factors are logistical and legal (e.g., zoning) constraints in addition to economic considerations. The potential user must also be aware of the available hardware and of the most viable storage or backup systems for his needs.

Purchasing a wind turbine (except, perhaps, a simple water pumper) will require more extensive analysis than is customary for most consumer purchases. Clearly, a detailed plan must be prepared in advance if the analysis is to be successful. The following outline (2) is a suggested analysis strategy. The items marked with an asterisk require a knowledge of the wind characteristics at the site; therefore, only asterisked items will be discussed in this paper.

(a) This paper is based on work performed for the U.S. Department of Energy under Contract No. EY-76-C-06-1830.

Determining Feasibility

1. Initial wind resource assessment

    a. Survey available WECS
    *b. Estimate power output
    c. Estimate power needs

2. Economic analysis

    a. Analyze cost of WECS
    b. Consider legal (and other) factors
    c. Formulate working budget

Selecting Site and System

1. Final wind resource assessment

    *a. Select candidate site(s)
    *b. Determine available power at candidate site(s)

2. Selection of WECS

    a. Estimate power needs quantitatively
    *b. Estimate power output quantitatively
    c. Choose WECS and storage/backup system

DETERMINING FEASIBILITY

The first step in deciding whether or not to purchase a wind turbine is to determine if the available turbines can meet the load requirements or can meet a sufficient fraction of these requirements to make wind energy economically viable. One way of determining feasibility is to examine current and historical wind energy use in the immediate vicinity. If applications of wind power similar to the one under consideration have been successful in the past or if wind turbines are currently in widespread use, wind will probably be a feasible source of power.

If little local history exists on wind power use, an estimate of the probable annual power output must be made for the wind turbines under consideration. The first step in this process is to estimate the mean annual wind speed. With the annual wind speed, an estimate of the average annual power output can be made. Mean annual wind speeds may be obtained from nearby wind-recording stations, such as National Weather Service stations, nuclear power plants, colleges or universities, U.S. Agricultural Extension Service or state and federal forest services. In areas of relatively flat terrain, such as the Great Plains, these wind speeds should be representative of the local values to a distance of 50 to 100 miles from the station; however, in coastal areas, locations along the coast will be windier than places a few miles inland.

In remote areas or in regions where large, local variations in wind speed can be expected, the shapes of well-exposed trees can indicate the local wind speed. Figures 1 and 2 illustrate two tree shapes that have been found to be good indicators of local wind speed. Figure 1 illustrates the Griggs-Putnam index. In Figure 2, the deformation ratio is defined. Both of these parameters quantify the degree of flagging or wind sculpturing of pine or fir trees. Deciduous trees are also shaped by the wind, but they are more difficult to "read" and have not be studied as extensively.

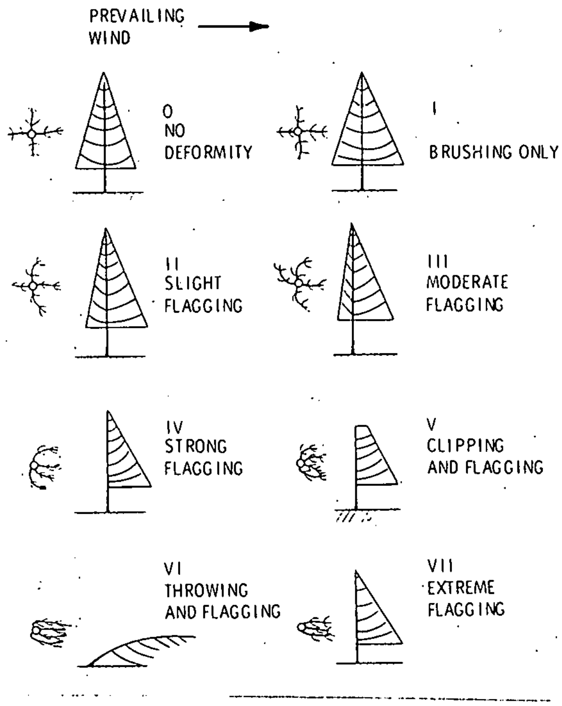


FIGURE 1. Wind Speed Rating Scale Based on the Shape of the Crown and the Degree Twigs, Branches, and Trunk are Bent (3)

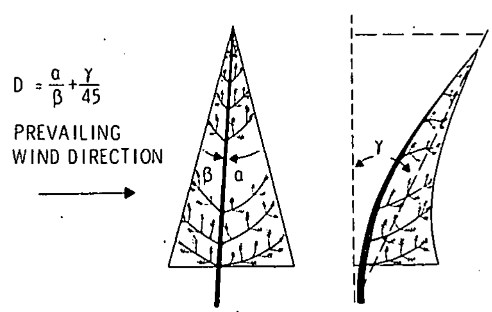


FIGURE 2. Deformation Ratio (angle a/angle b) Computed as a Measure of the Degree of Flagging (3). The Ratio α/β Lies between 1 and 5.

Tables I and II give a preliminary calibration of both the Griggs-Putnam index and the deformation ratio in terms of the annual mean wind speed. These tables are based on the work of E. W. Hewson, J. E. Wade and R. W. Baker of Oregon State University, who have been studying the effects of wind on trees for the U.S. Department of Energy (3).

TABLE I. Mean Annual Wind Speed Versus the Griggs-Putnam Index (a)

Griggs-Putnam Index (as in Figure 1)	I	II	III	IV	V
Probable Mean Annual Wind Speed Range, mph	6-10	8-12	11-15	12-19	13-22

(a) These data were prepared by E. W. Hewson, J. E. Wade, and R. W. Baker of Oregon State University.

TABLE II. Mean Annual Wind Speed Versus the Deformation Ratio (a)

Deformation Ratio (as in Figure 2)	I	II	III	IV	V	IV	VII
Probable Mean Annual Wind Speed Range, mph	4-8	7-10	10-12	12-15	14-18	15-21	16-24

(a) These data were prepared by E. W. Hewson, J. E. Wade, and R. W. Baker of Oregon State University.

The Griggs-Putnam index is the easiest indicator to use. The tree in question is simply classified by comparing its shape with Figure 1. The deformation ratio is best determined from a photograph of the tree taken perpendicular to the prevailing wind direction. Caution should be observed when using these indicators. The absence of flagged trees does not necessarily mean that the local wind speed is low because the species of trees in the vicinity may not be susceptible to flagging, the trees may be sheltered, or the trees may be exposed to strong winds that come from several directions. Secondly, the tables given here are based on data for ponderosa pine and Douglas fir only. In addition, these data were gathered at locations where the seasonal variation in wind speed is small. Thus, annual mean wind speeds derived from the above parameters should be applied cautiously. Although the parameters may aid in determining feasibility, final computations of annual power output selection of a particular wind turbine should not be based on these indicators alone.

Once the approximate mean wind speed for a site has been determined, the annual power output for a particular turbine can be estimated. Figure 3 depicts how the average annual power output is related to various turbine characteristics. This particular figure is for a modern two- or three-bladed turbine having a cut-in speed between 6 and 12 mph. It is assumed that such a turbine has a power output curve similar to that indicated in Figure 4. Figure 3 is also based on the assumption that the wind frequency distribution curve can be represented by the Rayleigh distribution (4). From Figure 3, one fact of turbine performance is clear: power output is extremely sensitive to small changes in wind speed.

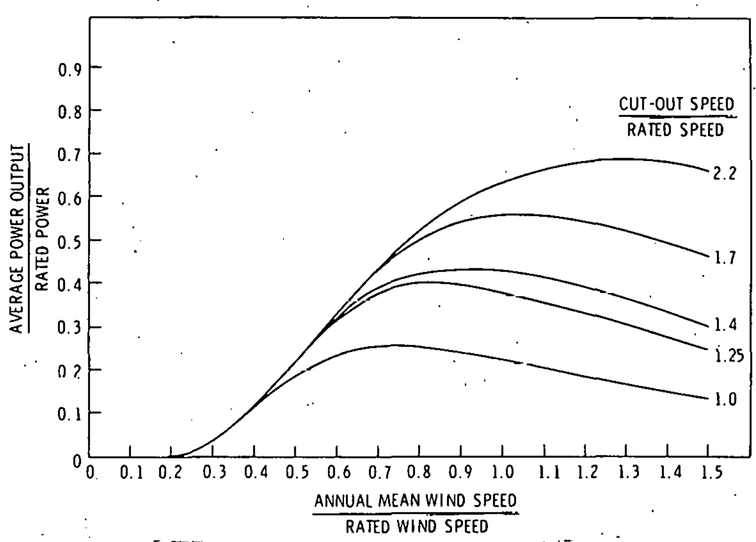


FIGURE 3. Expected Average Power Output for WECS Based on Annual Mean Wind Speed and Turbine Characteristics (4)

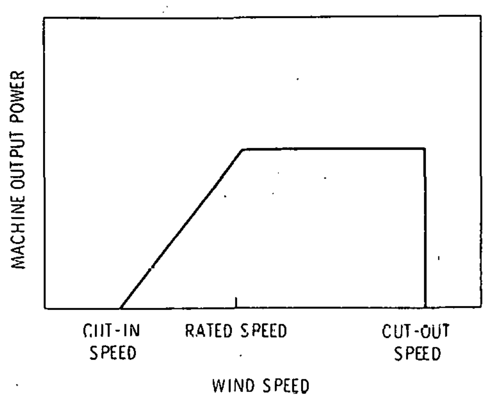


FIGURE 4. Typical Power Output Curve for a Modern Wind Turbine Generator

SELECTING A SITE

Once the feasibility of wind power has been established, the actual site for the wind turbine must be chosen. For most small WECS, the general location of the wind turbine will be fixed and must be near the point of power consumption. In other applications, the user may be able to site his turbine at any location over a fairly windy area and take advantage of terrain enhancement of the local wind speed. However, even if the location of the turbine is fairly well fixed, siting remains important. Small changes in the height of the machine above the ground or in the placement of the turbine with respect to nearby obstacles can result in significantly larger power output or in increased turbine life.

Figure 5 is a decision tree illustrating a strategy for attacking the problem of determining exactly where to place a wind turbine. As illustrated, the first step is to identify the prevailing wind directions. If the person siting the turbine has lived in the area for some time, he may instinctively know these directions. Otherwise, the prevailing wind direction can be determined from the wind summaries of nearby weather stations, from wind-flagged vegetation, or from measurements at the site.

For siting small wind turbines, two classifications of terrain should be considered: flat and complex. A very conservative definition of flat terrain can be given with the aid of Figure 6 (5). According to this definition, terrain can be considered flat if:

1) the maximum terrain relief (h) is less than 200 ft within a 2.5-mile radius of the site.

2) the machine is at least 2 h to 3 h above ground.

3) the ratio h/ℓ is less than 0.03, where ℓ is the length over which the largest terrain difference occurs.

The distance between the ground and the bottom of the rotor disk (i.e., 3 h) will seldom exceed 60 ft for most small installations. In addition, the maximum terrain relief cannot exceed 20 ft within 2.5 miles of the site in order for the terrain to be considered flat (Criterion #2). For the case of wind turbine siting, this definition of flat terrain seems overly restrictive. A more practical criterion would be to consider the terrain flat if only items 1 and 3 of above were satisfied upwind of the site.

If the local terrain is flat and the character of the surface, i.e., the surface roughness, is uniform for about one-half mile upwind of the potential site, the terrain can be considered homogeneous. In this situation, the available wind power can only be increased by increasing the height of the tower upon which the turbine is placed. A Siting Handbook for Small Wind Energy Conversion Systems (2) contains information on how much the available wind power may be increased by increasing tower height for various values of surface roughness. However, the potential WECS user must weigh the potential benefits of increasing tower height against the increased costs of a higher tower.

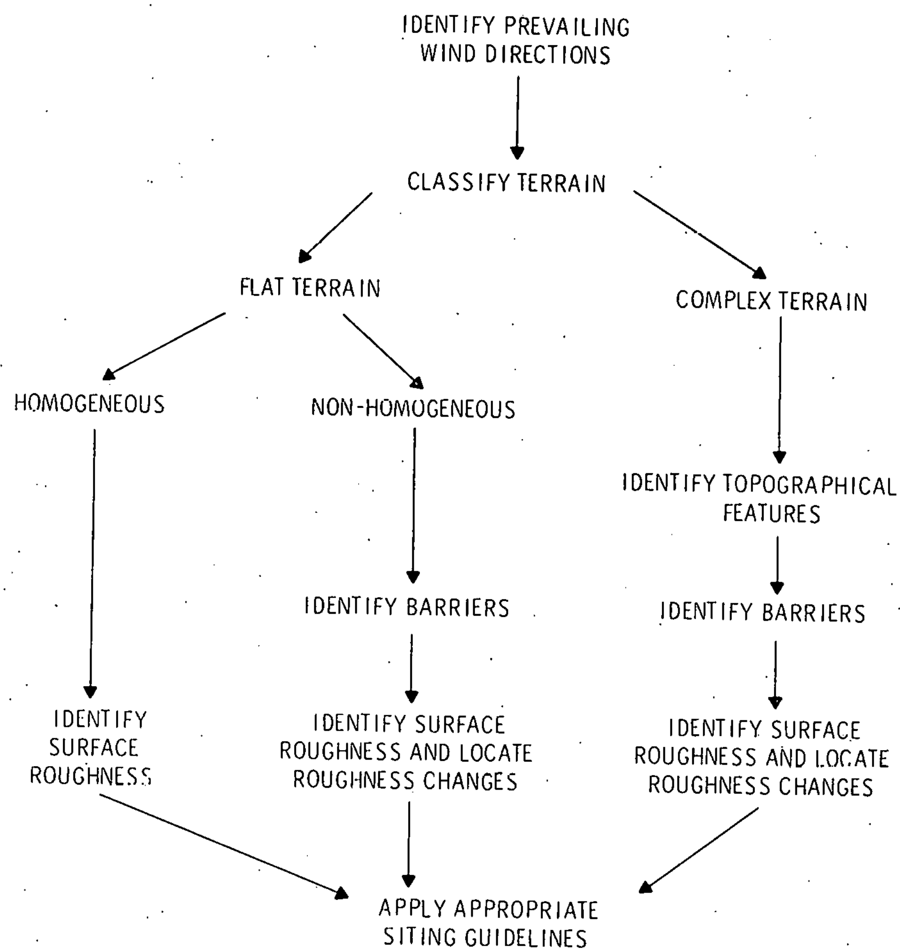
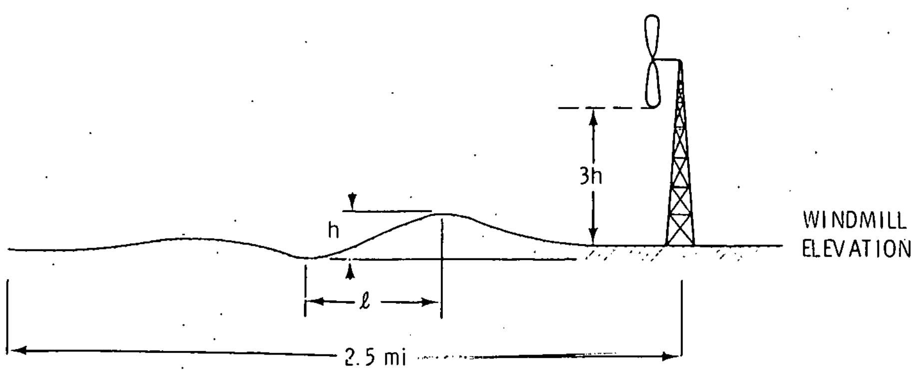


FIGURE 5. Development of a Siting Strategy Based Upon Terrain Classification



h - LARGEST DIFFERENCE OF TERRAIN

ℓ - LENGTH OVER WHICH LARGEST DIFFERENCE OF TERRAIN OCCURS

FIGURE 6. Determination of Flat Terrain (5)

If the terrain is flat but not homogeneous (i.e., there are obstacles or changes in surface roughness upwind of the site), several siting options exist:

- Choose a site that is not downwind of barriers, which are along the prevailing wind direction.
- Site enough upwind or downwind of the barriers to be outside the region of flow disturbance.
- Place the machine above the region of disturbance if a barrier cannot be avoided (see Tables III and IV and Figure 7).
- Identify significant changes in roughness and take advantage of the changes in the wind speed profile that they produce (see Figure 8).

More detailed information on the flow over barriers is contained in A Siting Handbook for Small Wind Energy Conversion Systems (2), which also contains procedures for calculating the transition heights for roughness changes. All of these guidelines, however, must be viewed as approximations. For example, in determining the optimum location for a WECS downwind of a change in roughness, it should be realized that actual transition heights vary day to day with meteorological conditions. The transition from a region of flow affected by one roughness to a region affected by another does not occur abruptly; instead, the transition occurs over several tens of feet. Nevertheless, one principle stands out: there is a greater advantage in increasing tower height in rough terrain than in smooth (see Figure 8).

Siting in hilly and mountainous (i.e., complex) terrain is more difficult than selecting a site in a flat area. Wind patterns over complex terrain are affected by interactions between the topographical features, barriers, surface roughness and the day-to-night variations in surface heating and cooling. All of these effects result in winds that may display considerable variations in speed and direction over short distances.

If possible, the effects of terrain on the wind should be used to advantage. It may be possible to find a location with considerable local wind speed enhancement. If the WECS location is fixed, the effects of terrain must be understood in order to estimate the probable effects of the terrain on the wind at the site.

In complex terrain, the mean annual wind speed diurnal variations and other features of the wind may differ considerably from those of nearby weather stations. These differences could be beneficial or detrimental to the wind-power potential.

For siting purposes, topographical features can be divided into two general classifications: elevated features and depressions. The first classification includes ridges, isolated hills or mountains and escarpments (cliffs or buttes); the second includes all depressions, such as valleys, canyons, passes, gorges and basins.

TABLE III. Wake Behavior of Variously Shaped Buildings (7)

Building Shape (Width ÷ Height)	Downwind Distances (In Terms of Building Heights) 5H Percent Speed Decrease	5H Percent Power Decrease	5H Percent Turbulence Increase	10H Percent Speed Decrease	10H Percent Power Decrease	10H Percent Turbulence Increase	20H Percent Speed Decrease	20H Percent Power Decrease	20H Percent Turbulence Increase
4	36	74	25	14	36	7	5	14	1
3	24	56	15	11	29	5	4	12	0.5
1	11	29	4	5	14	1	2	6	--
0.33	2.5	7.3	2.5	1.3	4	0.75	--	--	--
0.25	2	6	2.5	1	3	0.50	--	--	--
Height of the wake flow region (in building heights)	1.5			2.0			3.0		

TABLE IV. Available Power Loss and Turbulence Increase Downwind from Shelterbelts of Various Porosites (7)

Porosity[a] (Open Area ÷ Total Area)	Downwind Distances (In Terms of Shelterbelt Heights) 5H Percent Speed Decrease	5H Percent Power Decrease	5H Percent Turbulence Increase	10H Percent Speed Decrease	10H Percent Power Decrease	10H Percent Turbulence Increase	20H Percent Speed Decrease	20H Percent Power Decrease	20H Percent Turbulence Increase
0% (no space between trees)	40	78	18	15	39	18	3	9	15
20% (with loose foliage such as pine or broadleaf trees)	80	99	9	40	78	--	12	32	--
40% (with dense foliage such as Colorado Spruce)	70	97	34	55	90	--	20	49	--
Top of Turbulent Zone (in terms of shelterbelt height)	2.5			3.0			3.5		

(a) Determine the porosity category of the shelterbelt by estimating the percentage of open area and by associating the foliage with the example tree type.

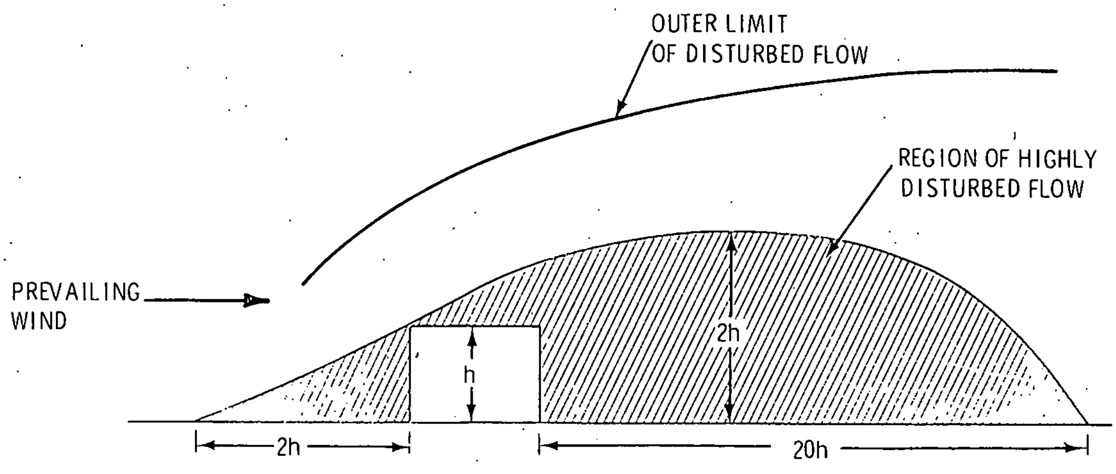


FIGURE 7. Zone of Disturbed Flow over a Small Building (5, 6)

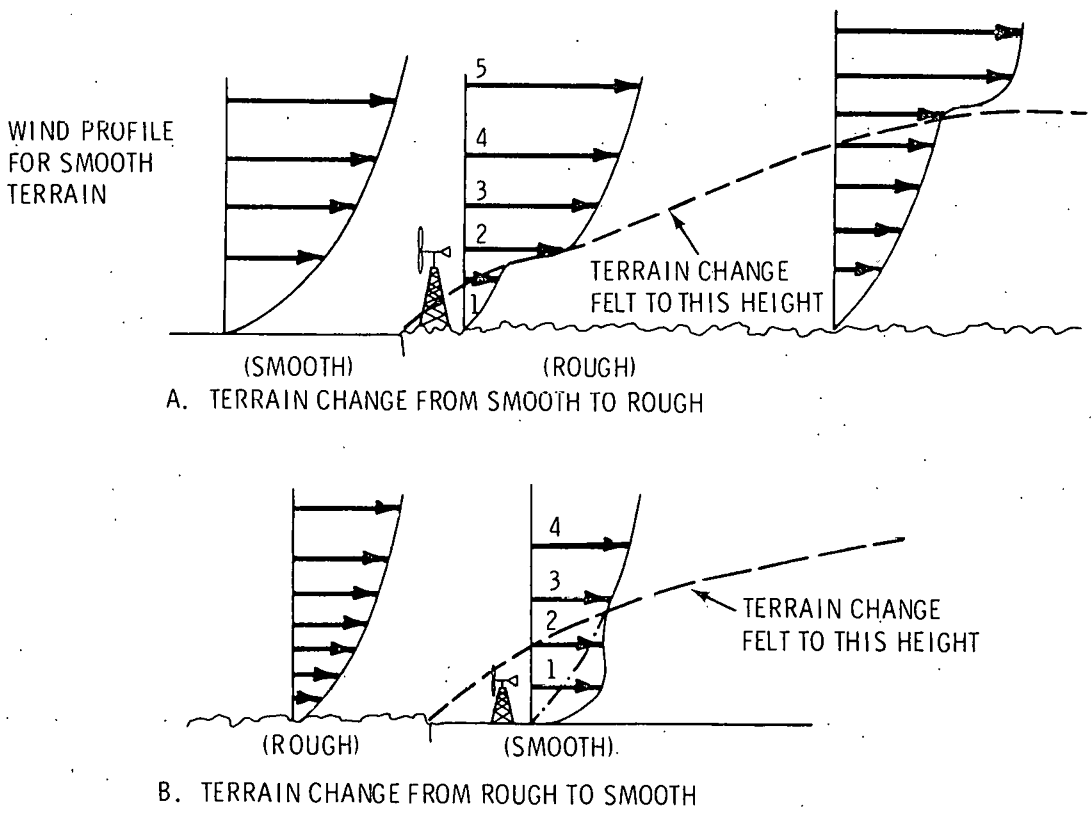


FIGURE 8. Wind Speed Profiles Near a Change in Terrain (8)

Elevated terrain features have advantages for siting:

- They act like a huge tower, raising the WECS into regions of higher wind.
- They help to avoid placing the machine where the surface winds may become uncoupled from (and much lower than) the winds at higher elevations.
- They may actually act to accelerate the flow over or around them, thereby increasing the available wind power.

However, if elevated terrain features exist upwind of the potential site, they may be detrimental, because they could either completely block the site from high winds or create hazardous turbulence or winds with severe gustiness.

Siting within depressions offers possible advantages of funneling the prevailing wind through the features and finding thermally driven circulations that could provide useful wind power. Whenever the prevailing wind blows parallel to a pass or a mountain gap, the possibility exists that the winds will be funneled through the feature and the local wind speed increased.(a) This effect may also be found in long valleys or canyons. A hypothetical example of this phenomenon is shown in Figure 9.

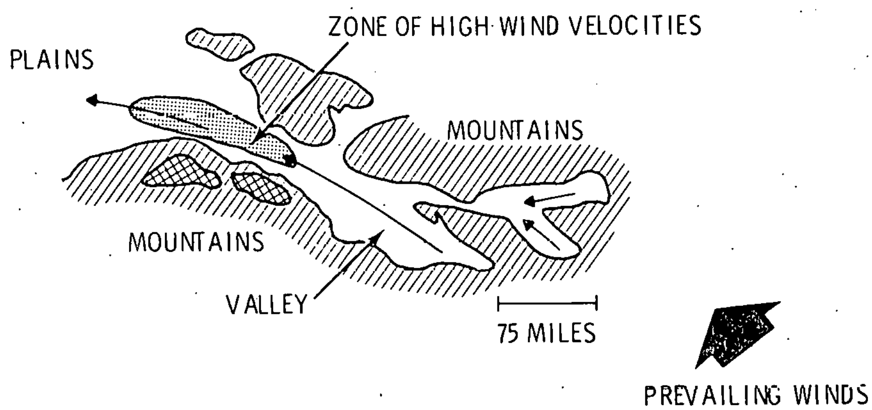


FIGURE 9. Possible WECS Sites Where Prevailing Winds are Channeled by Valleys (2)

Just as thermally driven circulations cause coastlines to be breezier than the interior, thermally driven circulations can result in winds that flow in and out of basins or up and down sloping mountain valleys. In some situations, these circulations may result in usable winds.

(a) This may not always occur. If the gap is in a relatively short ridge, the wind may blow around the ridge. Likewise, if the gap is located in a ridge that is sheltered by another ridge, no local enhancement may be observed.

A pass or gorge may be a good WECS site when a mountain range divides two distinct air masses, as is commonly observed in the summer along the West Coast of the United States. Coastal ranges divide cool, dense, marine air from warmer, less dense air in the interior, which results in strong pressure gradients across the mountains with good winds through many of the passes.

Regardless of these advantages in siting within depressions, drawbacks exist. For example,

- Small depressions may be sheltered from all winds.
- Valleys perpendicular to the prevailing wind will experience little flow.
- Depressions are more susceptible to air stagnation conditions.

As illustrated in Figure 5, the best approach to siting in complex terrain is to consider the effects of the various topographical features in descending order of size. The overall effects of the topographical features are assessed first. Then the effects of any barriers and surface roughness are considered in order to pinpoint the best site or to evaluate a predetermined site. (See A Siting Handbook for Small Wind Energy Conversion Systems (2) for more information on flow over topographical features along with pertinent siting guidelines.)

SITE ANALYSIS

For some WECS applications, the site evaluation process is completed once feasibility is established and the best site chosen. Either the user has confidence from past experience that the performance of his WECS will be satisfactory, or he is willing to accept whatever performance he gets. However, if more precise economic or performance information is needed before deciding to purchase a WECS, additional analysis of wind characteristics at the site is necessary. Table V describes three appraoches to this analysis and includes the advantages and disadvantages of each.

TABLE V. Various Approaches to Site Analysis

Method	Approach	Advantages	Disadvantages
1	Use wind data from a nearby station; determine power output characteristics.	Little time or expense required for collecting and analyzing data. If used properly, can be acceptably accurate.	Only works well in large area of flat terrain where average annual wind speeds are 10 mph or greater.
2	Make limited onsite wind measurements, establish rough correlations with nearby station, then compute power output characteristics.	If there is a high correlation between the site and the station, this method should be more accurate than first method.	Of questionable accuracy, particularly where there is seasonably modulation of wind speeds and directions.
3	Collect wind data for the site and analyze it to obtain power output characteristics.	Most accurate method. Works in all types of terrain.	Requires at least a year of data collection. Added costs of wind recorders. Data period must represent typical wind conditions.

Method 1 makes use of the same data source as the feasibility analysis -- nearby weather stations. The method however, differs from the feasibility study in that the data are analyzed in more detail. For example, the seasonal and diurnal (day-to-night) variations in wind speed may be of interest since in many applications a close match is required between power output and load if wind power is to be economically feasible. If an energy storage system is under consideration, wind return-time statistics should be examined, because these statistics are the expected or maximum observed times the wind speed may remain below a certain value, such as the machine cut-in speed. These statistics are also needed for estimating the required storage capacity.

Even though Method 1 is the simplest of the three, a good deal of work is required if a detailed performance analysis is desired. Often wind data obtained from the nearby weather station will not include wind characteristics, which are of interest in site analysis. Obtaining these characteristics may require some reworking of the data.

Method 1 can only be used for sites very near the weather station (less than 10 to 20 miles) and for high wind areas having little terrain relief and no large contrasts in terrain type. If these conditions are not met, some sort of onsite measurement program is mandated if an accurate economic analysis is required. In carrying out a measurement program, the wind-sensing equipment must be sited as carefully as the turbine. For example, if the wind turbine were placed at some elevation above the surface to avoid the wake of an obstacle, the wind sensor must be placed at this same position.

Methods 2 and 3 differ from each other primarily in the length of time that onsite measurements are made. The purpose of Method 2 is to provide a better estimate of the annual mean wind speed at the site by placing an anemometer at the site and determining the mean wind for a short period of time, for example, one to three months. The mean wind speed is determined at a nearby weather station for this same period of time. Then, the annual mean wind speed at the weather station is multiplied by the ratio of the short-term mean at the WECS site to the short-term mean of the weather station. This resultant value is assumed to be the annual average at the site. Method 2, although a traditional approach, is of questionable accuracy. The proper correction factor may not be obtained from such short-term measurements. Method 2 is recommended only for regions where the wind speed and direction is very persistent and where there is little seasonal variation.

Method 3 is the most accurate and the most involved approach, requiring extended onsite measurements. Even so, some uncertainty may exist in regard to how representative of the long-term average one year's data may be. The character of the wind, like any other meteorological phenomenon, is variable. Some years may be windier than normal; some years may be less. Clearly, the period over which the measurements are made must be reasonably representative of "typical conditions". Judging how typical the wind conditions have been over the period of measurement may require a good deal of meteorological sophistication as well as long-term residence in the area.

The major drawback to both Method 2 and 3 is the cost involved. Even a modest measurement program can be a significant fraction of the cost of a small WECS.

CONCLUSIONS

Except in situations where a WECS is the only obvious solution to a power generating problem, the decision to purchase a WECS must depend upon some level of economic and performance analysis. The purchaser must be convinced that the cost of the power generated by the WECS will be cheaper over the life of the turbine than the power generated by other alternatives, or that any greater cost would be outweighed by other considerations, such as the desirability of achieving energy independence. In some situations the cost of WECS power may have to be considerably cheaper than the alternatives, because the purchaser may prefer to pay a premium for the convenience and historical reliability of central grid power. Obviously, the behavior of the wind at the turbine site has an important bearing on the ultimate cost of the power generated. The accuracy to which these wind characteristics must be known and the resulting accuracy of the economic and performance analysis will depend upon the application of the turbine and its costs.

Proper siting procedures must attack two basic problems: finding the best or, at least, an acceptable location for the turbine within a given area, and accurately estimating the wind characteristics at the site. Locating a site is the simplest problem, because basic features of flow over obstacles and many terrain features are fairly well understood. Guidelines can be formulated that will enable a person siting a machine to avoid a disastrous choice of location. Such guidelines are given in A Siting Handbook for Small Wind Energy Conversion Systems (2).

Accurately estimating the wind characteristics at a site is more difficult. Even in the case where data from a nearby weather station can confidently be applied, there are hidden pitfalls. For example, the elevation, location, or exposure of the weather station anemometer may have changed over the period of data collection, thus affecting the mean wind speed and other wind characteristics. Although changes in anemometer location and exposure may be noted in the wind records (especially for National Weather Service data), the data user must be prepared to look for these changes. However, such a complex level of commitment applied to estimating wind characteristics may not be possessed by potential purchasers. Most WECS purchasers will need assistance in turbine siting, site evaluation and economic or performance analysis, at least until there is widespread experience iwth WECS in the purchaser's immediate vicinity.

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