11333

INDUSTRY AND ENERGY DEPARTMENT WORKING PAPER
ENERGY SERIES PAPER No. 45

Guidelines for Assessing Wind Energy Potential

Reprinted September 1991
(Originally Published in August 1986)

The World Bank Industry and Energy Department, PRE

Guidelines for Assessing Wind Energy Potential

Prepared for
the World Bank

by

Rene Moreno
The World Bank

Reprinted September 1991
(Originally published August 1986)

The World Bank
1818 H. Street, N.W.
Washington, D.C. 20433
U.S.A.

ABSTRACT

This paper provides an overview of the characteristics and issues related to the exploitation of wind energy. It provides guidelines for assessing the wind energy resource base and the economic potential of specific wind energy activites. It can serve as a primer for those with little or no familiarity with the technology and help those with more experience working on wind energy activites avoid pitfalls in the implementation and evaluation of those wind energy activites.

The paper was originally published in August 1986 as Energy Department Paper No. 34 of the former Energy Department. It is being reprinted in the IEN Energy Series as a reference for World Bank energy staff.

TABLE OF CONTENTS

CHAPTER 1. THE WIND ENERGY POTENTIAL

INTRODUCTION

1.1 Wind is an important energy source. It has been estimated that 1% of the daily wind energy available on earth is equivalent to the present annual world total energy consumption. The world's wind energy resource is highly dispersed and prevalent mostly at sites where it is difficult to harness for example, at seas and high altitudes or in the form of storms and hurricanes (See Appendix 4). Nevertheless, it is available in many accessible sites and is becoming increasingly competitive with other conventional energy sources. A 1982 study carried out under the auspices of the EEC found that within the EEC countries alone there were suitable sites for wind turbines to generate 4 million MWh of electricity per year. As wind energy technologies are continuing to mature, performance is becoming more and more reliable while at the same time costs continue to decline. It is not difficult to find instances, even at today's relatively low oil based energy prices, where wind would be the least cost energy alternative.

1.2 Primarily as a consequence of the disruptions in the energy market experienced in the 1970's, the focus on wind as a potential alternative form of energy has sharpened. In many developing countries interest in development of the domestic wind energy resource is increasing. The presence of wind energy installations in developing countries as free-standing activities or as components of other energy activities is becoming more wide spread. It has therefore become necessary for people who are responsible for management of their country's energy sector or utility companies to be acquainted with the wind energy technology as an alternative for meeting certain energy needs and for those directly involved with wind energy projects to have a source of reference on issues relating to the technology and its economics.

1.3 The purpose of this wind energy note is to provide that kind of information and reference in a compact and easily accessible form. It provides information on several aspects of importance to wind energy development. Areas covered include wind structure characteristics, wind measurement and site selection, basics of aerodynamics, design characteristics, performance and field testing, economics, storage, system integration, and environmental aspects.

1.4 Thus, it will serve several functions. It will provide information on the above topics for those seeking to familiarize themselves with certain aspects or concepts related to the technology. It will also discuss the economic characteristics which usually surround the technology. And finally, it will serve as a check list reference for the actual implementation of wind energy activities to reduce the chances of pitfalls. Thus, it will be a useful companion for anyone who will be dealing with wind energy. It will certainly not make a wind energy expert out of the reader, but it will hopefully provide an overview of the principles to allow one to have a better understanding of the technology, the economics and the issues at hand.

BACKGROUND

1.5 Wind as a potential energy source was recognized as far back as 200 B.C. Anthropological finds suggest that wind was captured through primitive windmills to drive machines used to grind grain. Eventually, the jib sail type horizontal axis windmill was designed and can still be seen today in many parts of the Mediterranean (e.g. Greece). Around the 1300's the Dutch began using windmills for draining water from their lakes to support their land filling activities. Today, the principal uses for wind energy are in electricity generation and water pumping.

1.6 Particularly in its application to generate electricity, wind energy has experienced tremendous growth in the past few years. In the early 1900's windmills were being used for pumping water and to some extent for generating electricity in remote areas in the United States, Northern Europe, and some other places. With the development of oil based grid electrification which in the 1940's offered power prices several times lower than those of existing wind machines, wind systems could no longer compete and were driven out of the electricity generation market. But the onset of the 1974 oil crisis and related huge increases in oil prices reversed this trend, prompting another look at wind energy as a serious generating alternative -- not only from the strategic energy independence perspective, but also from the purely economic one.

1.7 Traditionally, wind energy has been used primarily to pump water for human or cattle consumption or for irrigation. The extent of these uses grew gradually, reached a plateau, and in the last few decades started a decline. Today windmills for water pumping are found primarily in Australia and some developing countries. Recently, interest in wind pumping in developing countries has been regaining strength. There are instances (e.g. Cape Verde) where wind pumping is by far the most cost effective alternative for pumping water. It can be expected that wind pumping will experience some growth in the years ahead.

1.8 The use of wind energy to drive electricity generators has in recent years experienced a phenomenal increase. Since 1981, wind turbines have been used to generate electricity competitively. They can be found primarily in the U.S. and Europe but also in the Caribbean, Guam and to some lesser extent in other developing countries where they are often used for charging batteries for various end uses such as minor electrification of remote communities, telecommunications, and military and maritime uses. Thousands of wind turbines of various sizes have been installed in North America and Europe as part of wind farms-- a cluster of wind generators jointly generating electricity which is usually fed into the main power grid. The total installed capacity in the U.S. alone has been estimated at over 1000 MW. This compares with a typical nuclear power plant which has a capacity of 1000 MW and that of a typical coal fired plant which has a capacity of about 500 MW. In other words, in the past four years the development of wind electric generation in the U.S. has been equivalent to the construction of a typical nuclear power plant. Considering that it takes about eight to nine years to build a nuclear power plant, this development is remarkable indeed. While special tax incentives for wind farm projects in California and elsewhere have been major contributing factors to this development, the significance of what can be achieved in wind energy in a relatively short time and the importance of the commercial motivation in many instances remain.

Wind Energy Systems

1.9 As mentioned above, windmills, also referred to as WECS (Wind Energy Conversion Systems), extract energy from the wind to meet two fundamental needs: water pumping and electricity generation. The operating principle of both are similar. Wind energy is captured through a rotor or turbine which through its rotational movement drives either a water pump or an electricity generator. The horizontal axis WECS is the most commonly known having a propeller type rotor, composed of a varying number of blades, which is positioned perpendicular to the wind direction. This is the type commonly seen as pumping devices in developing countries and rural areas of developed countries. The unit consists of a tower on which the rotor is attached to the nacelle housing the gear unit. In the case of an electricity generating WECS, the nacelle also normally houses the generator unit. The horizontal axis machine usually has a rotor vane to keep the rotor pointing into the wind to extract maximum power. In large wind generators, this is achieved by means of a wind sensor and computer mechanism which turns the nacelle as appropriate to keep the rotor pointing into the wind. Wind pumps commonly also have a side vane, perpendicular to the rotor vane, whose function is to push the rotor out of the wind and reduce the rotor rotation speed when wind speeds rise to levels which threaten the safe operation of the machine. Although most horizontal axis machines are of the upwind type, where the rotor hub faces into the wind, there are also down wind machines where the reverse is the case.

1.10 In addition to the horizontal axis machines, there are also WECS known as vertical axis machines. These consist of a rotating shaft which is positioned vertically to the ground with the blades generally having a curved shape running from the top of the shaft to the bottom, somewhat like an egg beater (see Chapter 3 Figure 3.1). They have the advantage that the gear and generator units are located at ground level which facilitates installation as well as maintenance. In addition, because of its design the rotor is always facing properly into the wind regardless of the direction of the wind, so that no mechanism (like a vane) is needed to keep the windmill pointed into the wind. Nevertheless, so far, relatively few vertical axis machines have been installed. Because of their greater cost (particularly in smaller models) their use has been limited practically exclusively to electricity generation although theoretically there is no reason why they could not be used for pumping water. The number of manufacturers producing this type of WECS is increasing but there is no clear indication at the moment that its use will expand rapidly in the future.

CHAPTER 2. WIND STRUCTURE, MEASUREMENT, AND SITE SELECTION

Main Characteristics

2.1 Winds result because the areas closer to the earth's equator receive more solar energy than the areas closer to the two polar regions. This difference produces large scale convection currents in the atmosphere which we know as wind. Estimates suggest that about 1% of the solar energy reaching the earth is converted into wind energy. And as noted earlier, about 1% of the daily wind energy is equivalent to the world total annual energy consumption.

2.2 Wind has some well known characteristics, of which the principal one is its variability. There are two basic types of variations: average wind speed variations between locations and over time. The variability between locations can be divided into two distinct components: differences in wind regimes between sites and differences in wind speeds at different heights for any particular site. The variability of windspeed over a particular time (e.g. three years) generally increases as the unit measurement period per observation decreases. It is probably intuitive to most people that the distribution of average daily windspeeds for any particular site (over three years say) would have a greater variance than that of average monthly or yearly wind speeds. In other words there is a tendency for average wind speeds, and thus available wind energy, to be more predictable over longer cycles (e.g. on a yearly basis) than shorter ones (such as from day to day). This characteristic makes wind as a source of energy more acceptable in situations where short run variability in energy output would not be catastrophic; i.e. where the total energy output from the wind system over, say a year, must have a rather high level of predictability, but where output variability from day to day does not matter too much.

2.3 For example, wind pumping for irrigation could be appropriate where the crops involved were not too sensitive to occasionally not being irrigated on those unpredictable days (sometimes a few in a row) when wind speeds were too low to pump any water. Crops for which daily uninterrupted irrigation is essential are in general much less likely candidates for irrigation by windmills than crops for which the periodic absence of water for some time would not be catastrophic. Clearly, provision of water storage tanks (or batteries) does reduce the variability factor. However, storage systems always increase the cost of the overall water provision (electricity generation) system and in so doing will decrease its economic attractiveness. Deciding whether or not to include storage in a particular use of wind energy (for both pumping and electricity generation) and how much of it to include is a task involving careful analysis (see Chapter 5).

2.4 Besides its variability over time and from site to site as mentioned above, the wind speed generally also tends to increase with altitude, at most sites. This happens for the principal reason that as altitude increases, the influence of surface roughness created by geographic structures (hills, trees, etc) and man-made ones (houses, buildings, etc.) becomes less in reducing wind speeds. This, however, is not always the case. Some sites have, at times, negative shear; wind speeds would become less at greater heights. This would happen because of combined meteorological and terrain effects (e.g. mountain passes). Wind fluctuations, over short periods, which are common at surface levels also occur at greater heights and the intensity of these fluctuations is about the same at different heights (for any particular site).

2.5 For purposes of study and analysis, the atmosphere has been divided into three altitude segments having distinct wind characteristics. The lowest stratum, usually ranging from the ground to between 50 and 100 meters above ground is known as the region of constant shearing stress. That is, the influence on the wind speed due to the surface roughness is constant. The next region is that between the lowest stratum and about 500 to 1000 meters above ground. This area is known as the region of transition having variable shearing stress. And finally, above 1000 meters, wind movements become similar to that of a fluid with zero viscosity not affected at all by surface characteristics.

Wind Measurement

2.6 Knowledge of the wind regime is crucial to the implementation of any type of wind energy system. The principal descriptive parameter of a wind regime is the annual average windspeed. It is usually given in meters per second (m/s) or miles per hour (mph) but is sometimes also provided in terms of watts per m^2 and, as such, is referred to as the power density.1/ Appendix 1 shows the conversion between various wind speed units as well as power density. As was discussed above the variable nature of windspeed makes it unpredictable over short periods but over longer periods its average becomes more stable. Wind resource measurement, also known as anemometry, concerns itself with quantifying the amount, variability and other characteristics of the wind. It is commonly carried out at most airports world wide as part of aviation needs. Some of the more industrialized countries carry out a more expanded program of anemometry as part of their weather forecasting and measurement program. On the basis of this world wide wind information, a wind energy atlas (Appendix 4) has been prepared but is generally not considered detailed enough for use in wind applications and because of the questionable measurement techniques used in many countries, can be of limited reliability.

2.7 With the increasing interest in wind energy, the need for wind data has gone beyond its aviation and weather forecasting needs. As will be shown later, because of the cube relationship which exists between the power in the wind and the wind speed (see footnote 1/, below), small differences in wind speed can have significant effects on the total power available. It is therefore important that good wind

---

1/ A rule of thumb for converting from wind speed (v) in meters per second to power density (PD) in watts per m^2 is: $PD = 0.62 \times v^3$

measurement be carried out by qualified meteorological specialists. Therefore, in many cases it is now necessary to set up wind monitoring and measurement stations at sites which have been identified as having potential for wind energy programs. Such accurate wind information is crucial for making proper site selection, system design, and investment decisions. The variable nature of wind makes extended periods of measurement necessary. As the period of measurement is extended, the certainty of the wind characteristics so observed, for example average wind speed increases. Before any wind energy system can be seriously contemplated good wind regime data must be available. "Good" here includes not only the accuracy and range of data collected (speed, air density etc.), but also the length of time over which measurements are made. There is no absolute number for what would be an adequate period of wind monitoring and measurement. In theory it would be as long as possible, because the longer the time the greater the confidence of the estimates so obtained. But in any case it should be long enough to include enough data from each season. In other words, a one year period is a bare minimum. Five years would be highly desirable, although if data for two full years is available, that could generally be sufficient to have a reasonable certainty of the distribution. Confidence of wind regime measurements can be increased by comparing the results one has obtained for a particular site with existing information for nearby sites. Studies have also shown that wind regimes tend to be more stable where average wind speeds are greater.

2.8 It happens some times that wind data is available for a site which is a candidate for a wind energy application. However, wind measurement for the site may have been carried out at a height which is not relevant for the application in question. For example, the height at which the wind measurement was carried out may have been too high or too low compared to the height of the windmill which is to be installed. In such circumstances, it would be possible to estimate tne corresponding average wind speed at the different height from the data available using what is known as the Log Law which is discussed in the following section.

The Log Relationship

2.9 Wind speed measurements from 10 feet height may be available for a site which is of interest for some wind energy application for which the hub height of the windmill would be 25 feet. In such a case, the available wind speed information would not be relevant and it would seem arduous and expensive (money wise and in terms of time) to have to remeasure the wind profile at the required height (25 ft.).

2.10 It has been found that there is a generally consistent relationship between average wind speeds at different heights which can be described mathematically by what is known as the Log Relationship: The average wind speeds at different heights are related to each other in proportion to the natural logarithms of their respective heights divided by a constant. The relationship is expressed as:

$$\frac{V(h2)}{V(h1)} = \frac{\ln(h2/R)}{\ln(h1/R)}$$

where V(x) represents the average wind speed at height x, h1 and h2 are the two respective heights in meters, and R is a surface roughness constant. Some R values for typical roughness situation are given in Appendix 2.

Example:

2.11 Suppose measurements for a particular site taken at 10 feet (i.e. 3 meters) high indicate an average wind speed of 5.9 m/s. And suppose that for some wind application being considered for that site we need wind measurements at 25 feet (or 7.5 meters). Letting h1 be 3, h2 be 7.5, and V(h1) be 5.9 and assuming that we know that the roughness index (R) for that particular site is say 0.1, we find from the equation above that V(h2) or alternatively the estimated average wind speed at 25 ft. height would be 7.5 m/s. That's considerably higher than the 5.9 m/s at 10 feet height.

The Power Relationship

2.12 The Power Relationship is functionally similar to the Log Relationship although mathematically different. Since it is sometimes used and referred to in wind energy literature it is here presented for reference and familiarization. Using similar notation as was used above, the Power Law can be used to estimate average wind speed V(h2) at height h2 from information on average wind speed V(h1) at height h1 as follows:

$$\frac{V(h2)}{V(h1)} = \left(\frac{h2}{h1}\right)^{a}$$

where,

a is a surface constant, which is generally taken to be 1/7, which corresponds to an R of 0.005 (open area, cut grass).

Instruments

2.13 Wind speed measuring instruments are known as anemometers. They generally keep track of two principal components of the wind: the wind speed and direction. In addition, proper monitoring also requires that measurements of the air temperature and the atmospheric pressure be taken since this information is also important in determining the energy content in the wind and the appropriateness of the equipment being considered. Air density is not affected very much by the common fluctuations in barometric pressure. So this variable is really used only when analyzing details. The existing anemometers have come a long way from those used in the middle ages. [1]

---

[1] For a detailed discussion of instrumentations and measurement procedures see "Standard Procedures for Meteorological Measurements at a Potential Wind Turbine Site", AWAE, May 1986.

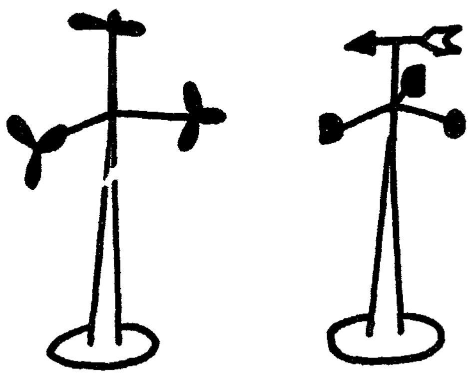
2.14 The first known anemometer was a swinging plate type instrument which was described in literature found dating back to the 1450's. By hanging a plate with some string from a horizontal rod, the intensity of the wind speed was measured by the extent to which the angle of the plate deviated from the perfectly perpendicular position it took on during still wind conditions. These types of anemometers are known as pressure type anemometers since they rely on the pressure of the wind against the surface of the plate in positioning the plate in a static position away from its perpendicular position.

2.15 Today the most common type anemometer is a rotational device known as a cup anemometer (See Figure 2.1 below). It consists of three cups made of light weight material which are equidistantly attached with spokes to a rotating center rod. The speed of rotation varies with the magnitude of the wind speed. It is known as a "drag" device because its rotation is caused by the drag of the cups against the wind. Usually a little arrow, with a vane at its end, rotating freely around its center (like a compass needle) attached to the top of the tower holding the cup anemometer, provides information on the direction of the wind.

2.16 Another increasingly popular type of anemometer is the propeller type. This anemometer is simply a very small two or three blade propeller, calibrated such that the r.p.m corresponds to specific wind speeds. This anemometer is known as a "lift" device because it relies on the rational "lift" caused by the wind on the propellers to measure the wind speed. By using two propellers held fixed at perpendicular angle to each other (see Figure 2.1 below), one can simultaneously measure the wind speed and direction using vector analysis. By including a third propeller positioned vertically relative to the other two, vertical wind movements can also be measured.

<u>Figure 2.1</u>

Anemometers



It should be noted that the effect of variations in air density (due to temperature and/or pressure conditions) are accounted for differently in lift devices (e.g. propeller anemometers) and drag devices (e.g. cup anemomaters).

2.17 Anemometers generally consist of several components each of which has a distinct function:

Sensor	for example the cup or the propeller
Transducer	e.g. a generator (to measure speed) or potentiometer (to measure direction); i.e. that which translates what you are measuring (e.g. wind speed) into something detectable by a recording instrument (a.c. voltage or frequency, d.c. voltage, or pulses which are counted);
Data Processor	that which collects the signals (e.g. computer or tape recorder).

2.18 Anemometers vary in terms of their specifications and also reliability. Whenever an anemometer is being installed, it should be calibrated against a reliable benchmark anemometer. Calibration errors are notoriously present in all anemometers regardless of price category. There are several elements of an anemometer which describe its functional characteristics:

Resolution - smallest change in what is being measured which is detectable by the instrument.

Error - the difference between the measurement given by the instrument and the actual value.

Accuracy - the degree to which the variable being measured is measurable.

Sensitivity - defined as the ratio of the output to input signals.

Response speed - quickness with which the instrument can detect a change in the intensity of what is being measured.

Repeatability - how closely the indicated measurements resemble each other under identical repetitive sequences of the variable being measured.

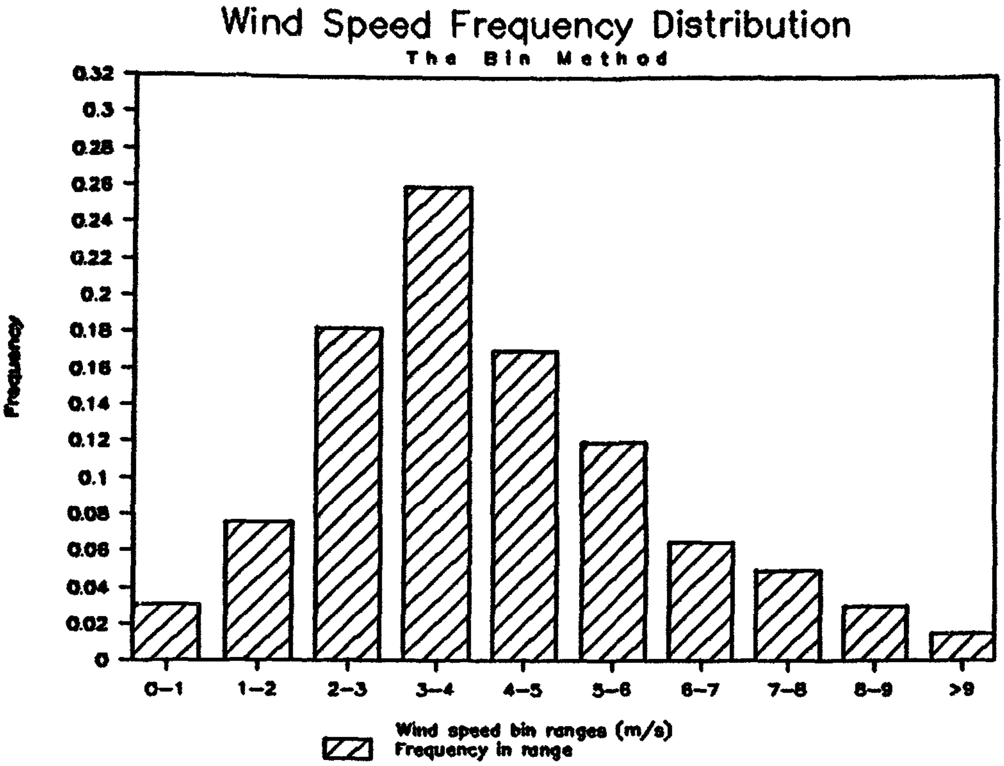
Reliability - the probability that the instrument will work to its defined limits.

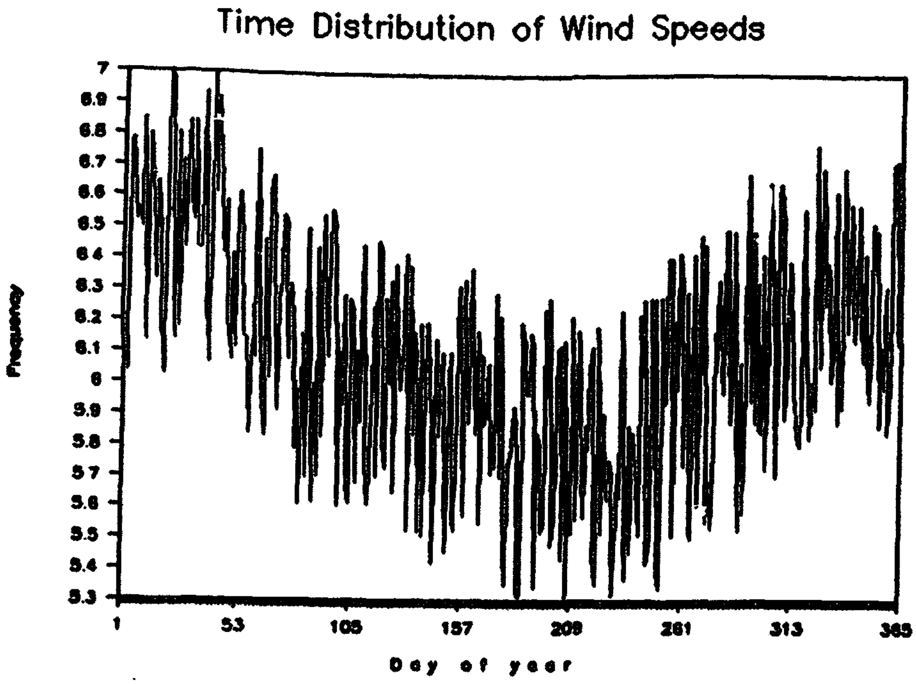
2.19 Besides the errors commonly associated with the specifications above, there are also other errors which result during wind measurements of which one should be aware. First, there is the already mentioned problem of calibration. This is very important because with improper calibration all, not just some, of the readings will be inaccurate. Besides, as mentioned above, inaccurate calibration has been found to be pervasive in all anemometers. Some need to be calibrated more often than others, but all need to be monitored periodically for calibration errors. Some other errors which have commonly been observed include: the effect of the tower shadow on inferred wind speeds as well as that of the site shelter (that is, the effect of the tower and shelter in blocking some wind passage, thereby biasing the reading downward), missing data (that is, some observations are lost because of malfunctions in the data recording mechanism, biasing the observation), and forgetting to log calms (which would occur mostly in manual recording systems and which can cause significant upward biases in average wind speed estimates).

2.20 Anemometers commonly indicate wind speed and direction on a voltage meter type gauge. The older types, used for monitoring wind statistics over time, record the wind statistics by tracing a chart as is commonly seen on barometers. More advanced ones, which are becoming increasingly popular in measuring wind conditions for wind energy activities, also include a computer which not only registers the data coming in, but simultaneously averages the information over a specified period (usually 10 minutes) and then stores the average in memory for later use in distributional analysis and charting. The choice of 10 minutes as the common averaging period is just a convention. Shorter or longer periods may be appropriate under particular circumstances. The advantage of the 10 minute period is that it is usually long enough to smooth out certain turbulence in measurement which is generally not significant for windmill applications. At the same time it is short enough to register the dramatic changes which occur due to storms or other high wind situations which usually tend to last 5 to 30 minutes. Clearly, the ideal averaging period for any situation is the longest one which still permits one to capture the type of oscillations in the wind pattern which are deemed relevant for the application in question. The 10 minute averaging period has been found to offer that for most wind energy activities.

Windspeed Frequency Distributions

2.21 Thus, with a 10 minute averaging period one would have 6 observations per hour, 144 observations per day, and 52560 observations per year; more than sufficient to allow one to obtain a good plot of the distribution of wind speeds for the year. To facilitate presentation of the distribution of wind speed data, one commonly resorts to what is known as the bin method. Here, the 52560 yearly observations would be sorted into predefined range categories of wind speeds (or "bins"). For example, the bins may comprise the following ranges: 0-1 m/s, 1-2 m/s, 2-3 m/s, etc. up to 20+ m/s. The observations are then sorted into the corresponding bin and a frequency distribution is obtained. For example, 3% of the observations may lie in the 0-1 m/s bin and 15% in the 3-4 m/s bin, etc. As an example, a bar graph as the one below may be obtained. Note that such a bin distribution provides information on the percentage of occurrences for which the 10 minute average wind speed lay within respective bin ranges. But it does not provide information about when the average wind speeds occurred; i.e. it does not give the profile of the time distribution of wind speeds. That would require a chart as that below, following the bar graph.


Wind Speed Frequency Distribution
The Bin Method
Frequency
0.32
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
>9
Wind speed bin ranges (m/s)
▨ Frequency in range


Time Distribution of Wind Speeds
Frequency
7
6.9
6.8
6.7
6.6
6.5
6.4
6.3
6.2
6.1
6
5.9
5.8
5.7
5.6
5.5
5.4
5.3
1
53
105
157
209
261
313
365
Day of year

Wind speed distribution (Weibull, Rayleigh)

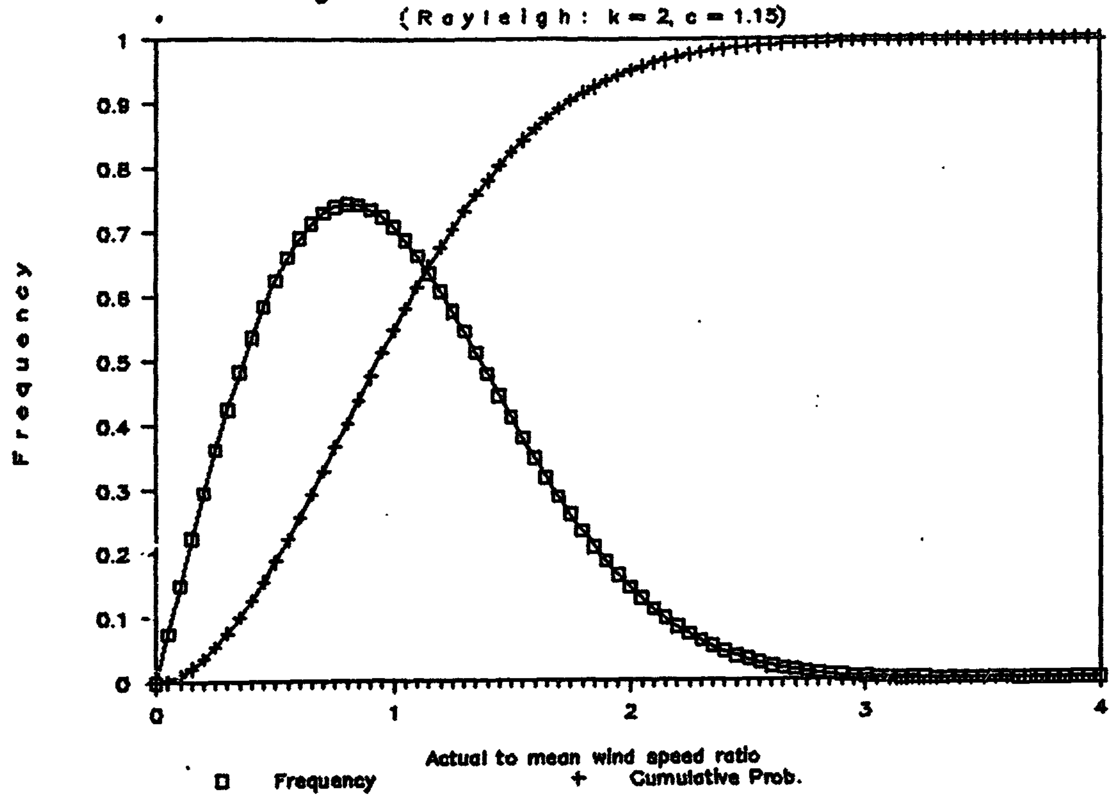
2.22 One of the characteristics of wind is that its speed at any one moment cannot be estimated based on its speed some moment earlier; that is, wind follows a basically random pattern from one moment to the next. Nevertheless, measured over longer periods of time, windspeeds tend to display a generally predictable frequency distribution. The Weibull distribution has been found to conform well to the distribution of observed wind speeds. This distribution is defined as:

$$P(v) = \left(\frac{k}{c}\right) \cdot \left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right)$$

where: v is the ratio of any wind speed to the mean wind speed, c is the site parameter (a typical value would be between 1.15 and 1.18), and k is the shape parameter (typical values: 1.7 to 2.5; for k=2, the Weibull distribution becomes the Rayleigh distribution).

2.23 Figure 2.2 below shows the shape of the Weibull distribution. As can be seen, it is bell shaped but contrary to a normal distribution, it is not symmetric around its mean. It has a lower boundary of zero but, at least theoretically, no upper boundary. The probability of any wind speed greater than v approaches zero as v increases.

Figure 2.2: Weibull Distribution



2.24 Thus, given that we know that wind profiles tend to follow the Weibull distribution and more specifically the Rayleigh distribution (i.e. $k=2$), we can extrapolate estimates for the frequency distribution of wind speeds for a particular site once we know the annual average wind speed for that site. This is a very useful "trick" because it often happens that reliable information on average wind speeds over considerable periods of time already exist for sites where (or sites near to where) wind energy programs are being contemplated. By using the Weibull distribution as an approximation, one can obtain pretty reliable estimates of the actual wind distribution based simply on the average wind speed information and some knowledge about the surface roughness. But even without this latter information, one can use a value of c equal to 1.15 and k equal to 2 and still have a reasonable approximation to the actual wind speed distribution. While this method may be valuable in a situation where little wind data exist and a decision needs to be made quickly on the potential for wind power, it is in no way a substitute for actual wind speed and frequency distribution data. Ideally, one would compliment the estimates based on the Weibull or Rayleigh distribution with some actual measurements.

Turbulence

2.25 Another characteristic of wind is the presence of turbulence. There are many definitions of turbulence but the most common one is to define turbulence as a wind speed deviation relative to the average wind speed for a particular averaging period. Thus, the length of the averaging period, that is the measurement period (e.g. 10 minutes) for which we are calculating the average wind speed, is significant in defining turbulence. Another way to define turbulence is: any wind speed change which lasts less than the averaging period. Thus assume we are taking 10 minute averages to plot our yearly wind speed distribution, then turbulence is defined as the deviations of the instantaneous wind speeds from the mean over that ten minute period. In other words it is a measure of the variance of the distribution of instantaneous wind speeds around their mean.

2.26 Turbulence is measured as the ratio of the root mean square of the instantaneous wind speeds to the average wind speed. Thus, turbulence is mathematically defined as:

$$T=\frac{RMS(V_t)}{v}$$

where,

v is the average wind speed, $RMS(V_t)$ is the root mean square of the wind speeds V_t over the averaging period t.

2.27 It has been found that turbulence generally decreases at greater heights. Information on turbulence is important because some WECS may have less tolerance to a high frequency of wind speed oscillations. Each time the wind speed decreases and increases again significantly, additional stress on the rotor and the pumping and/or generating system could result. Measurement of turbulence is therefore desirable and turbulence data should be analyzed before deciding on the appropriateness of the wind condition for WECS. Some anemometers are less responsive to turbulence than others, i.e. they have a lower response speed. This is because some anemometers are made to be more robust so that they minimize the error of overestimating the wind speed when wind speeds are decreasing. Anemometers which are very light and responsive to upsurges in the wind speed (high response speed) will also have the tendency to continue indicating a high wind speed for some instant after the wind speed drops. In other words, there exists a certain tradeoff in that greater anemometer responsiveness to turbulence tends to also result in overestimation errors on downward trends. The particular type of anemometer chosen will generally depend on budgetary considerations. Light weight devices are generally preferable for the applications in question.

Costs of Wind Measurement

2.28 As with most equipment, cost will vary depending on several factors including quality (sensitivity, accuracy, longevity, etc.), options included, and data logging techniques (automated versus manual). Nevertheless, some feel for the magnitudes can be given. A good anemometer alone can cost about US$200. But comprehensive monitoring systems including base, tower, meters, and sophisticated computerized logging equipment, can cost about US$2,000. As mentioned earlier, it is often desirable to monitor besides the wind speed also the pattern of temperature, barometric pressure, and humidity. Temperature is important because in colder climates icing can cause problems and reduce the aerodynamic characteristics of the blades. The barometric pressure in turn is important because air density also affects the relationship between power and windspeed of a particular wind machine (as will be seen in Chapter 3). Therefore, the more complete systems will include components which measure these factors also. It is important to note that often the largest share of costs in wind measurement pertain to the collection and analysis of the data and not the equipment itself. Also, unless proper programs and plans are worked out to timely and accurately collect the information and analyze it, investments in wind measurement stations may be a waste of time and money. These programs will vary considerably from country to country and from one specific situation to another; size of country or area being an obvious factor. Their format and size will also depend on information already existing about wind regimes in the area or country in question. Consequently, their costs will vary considerably due to all these factors. In the end, the only way to obtain a reasonable estimate of the cost of an overall wind measurement program is to solicit estimates from expert consultants.

Site selection - Electric Power Generation

2.29 Proper site selection is crucial to a wind energy project's success. And since wind measurement is an integral part of the site selection process proper wind measurement is crucial. Often candidate sites are chosen based on notions that the wind regime is probably favorable there. Such notions can turn out to be costly. Choose a suboptimal site and failure is next to guaranteed. Site selection is generally not as important for small isolated wind pumps as for large wind turbine programs (e.g. wind farms). However, even in the case of small individual wind pumps, information on the wind regime for the areas where wind pumps are to be installed is needed to accurately indicate the expected profile of water output for prospective farmers or village water supply authorities. As discussed later, this is particularly important to assess the storage requirements and the overall economics.

2.30 The process of site selection usually begins with a definition of the regions where the wind application appears to have potential. For electric power generating WECS, this means windy areas where there is a local need for power or windy areas where there is no particular local need for power but where good opportunities exist to feed the national electric grid for power consumption elsewhere. Within any region, some evidence must exist, be it circumstantial or actual measurements from nearby existing weather stations, about what the wind regime can be expected to be like at several prime spots. Topography must be kept in mind when selecting such spots because it has been found that e.g. passages between hills etc. can have dramatically higher wind speeds. From this information, a set of prime candidate sites must be selected. Using this set, the more detailed site selection process can begin.

2.31 First, development costs at each site within the set must be estimated, as well as the potential benefit of the wind system to be installed. Costs at different sites may vary because of different terrain characteristics, distance from the grid, transmission or transport costs or even varying labor costs across areas. The benefit may vary because of different wind regimes, different degrees of congruency between peak power demands and peak wind speeds, or different values for the power output. On the basis of such preliminary benefit/cost ratio considerations, some refinement of the set of candidate sites should be possible. For each of the sites within this refined set then, wind measurements must be made over a long enough period as discussed above (para 2.7). Having done so, sites must then be ranked on the basis of predicted benefit/cost ratios. In-depth economic analysis for the best sites should then dictate whether or not the wind systems should be installed there.

2.32 There are some important points which one should always keep in mind when beginning a site selection process. Always determine what the complete available wind information set for the sites under consideration comprises at the outset; i.e. be sure that all existing information which may be of some use in the initial stages of site selection has been gathered and used to make the initial set of candidate sites. Such information should include that from possible nearby meteorological stations, university weather monitoring activities, forestry characteristics, upper atmosphere wind data, topography, even interviewing local villagers, etc.

2.33 The type of wind data which ideally would be available to determine the desirability of a particular site include:

- average wind speed
- frequency distribution
- height scaling factor (roughness index)
- directional distribution
- distribution of windspeeds over time
- turbulence
- extremes
- surrounding topography

2.34 More often then not most of this information will not be available for long enough periods or even for short periods. One will always have to do the best possible with the available information. And finally, the more extensive and costly the wind energy program proposed, the more scrutiny in site selection and economic analysis will be necessary. In cases where large investments are proposed, it would be desirable to actually field test the performance of one or two wind machines for some time at the selected site before proceeding with full scale implementation. This is so because, although generally power output will simply be a function of wind speed, there are cases where specific characteristics of the air or locale can have disastrous consequences and yet not be obvious at the outset. For example, air containing certain dust particles with high salt content can cause erosion and damage much of the gear mechanism and/or reduce the smoothness of many turning parts. This would only become apparent after a few months of use and would not be obvious from simple wind measurement activities.

Site Selection - Wind Pumps

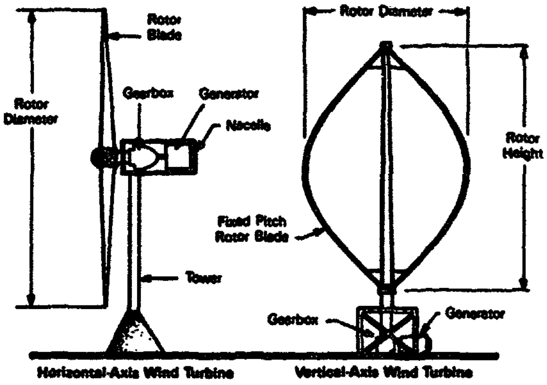
2.35 The process of site selection for wind pumps is somewhat different than that for wind electric generators. Although both favor the windier sites, wind pumps can generally be competitive at lower wind speeds than electric WECS. However, in the case of wind pumps, the power must be used locally. Consequently, sites with potential for wind pumps include only those where favorable wind conditions prevail at the site where the water is needed. Also, in order to reduce the need for storage, and thus the overall cost of the system, it is helpful if the wind regime patterns closely resemble the water demand pattern. In other words, in the case of site selection for wind pumps, one must first identify sites where there is a need for water and then determine whether sufficient wind is available where and when it is needed.

CHAPTER 3. PRINCIPLES OF WINDMILL AERODYNAMICS

Lift, Drag, and Power

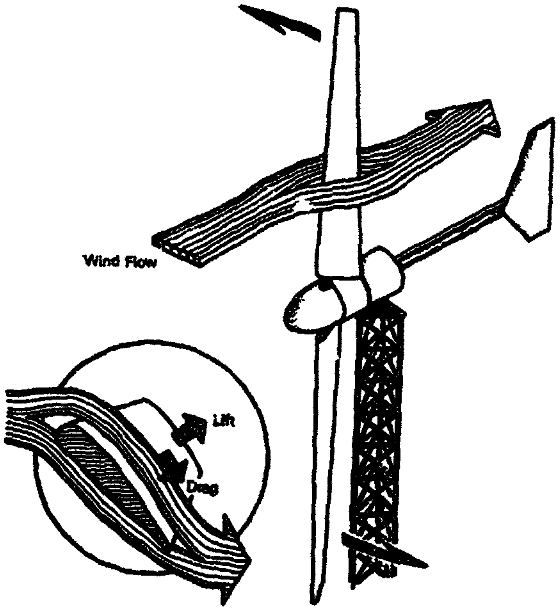
3.1 Windmills, be it to pump water or generate electricity, are devices which convert the kinetic energy in the wind into mechanical movement. They are also known as Wind Energy Conversion Systems, or WECS. There are basically two types of WECS: Horizontal axis and Vertical axis machines. See Figure 3.1 below for a schematic representation of typical examples of the two types of WECS. The principle of operation of both are the same. The extraction of power from the wind is accomplished through the interaction of the wind and the rotor blades which are attached to the hub (the blade/hub combination is also known as the turbine or rotor). The aerodynamic principle of wind turbine rotation is similar to that which causes airplanes to fly and is also known as the Bernouilli principle.

Figure. 3.1 Horizontal and Vertical Axis Machines



3.2 According to this principle, air flowing over the top of a wing or rotor blade, because of its curvature, will travel a longer path over the same length of time than the air flowing over the bottom. This causes the air pressure above the wing or blade to be lower than that at the bottom. This difference in air pressure creates an upward force known as lift (see figure 3.2 below). In a windmill, the blade is attached to the hub and consequently an upward lift force on the blade is converted into a rotational movement around the hub. As the blades rotate in a plane perpendicular to the direction of the wind, another force comes into play. This is the force of the wind flowing thru the area between the blades impeding the tendency of the blades to rotate. This force is known as drag, since it is a force which in fact works against the lift force. Clearly the higher the lift-to-drag force ratio the greater the rotational force obtained. Therefore, a major objective in the design of windmills is to obtain as high a lift-to-drag ratio as possible.

Figure 3.2. Aerodynamic Principles



3.3 The number of blades on a wind turbine affects the amount of power that can be extracted from the wind. Theoretically, a one-bladed rotor provides the potential for the highest possible aerodynamic efficiency. With each additional blade, the maximum achieveable aerodynamic efficiency decreases. This is due to drag effects which increase with additional blades. In addition, the number of blades affects other aspects of the aerodynamic relationship between the wind and the turbine such as the wind speed at which the turbine would begin rotating (cut-in wind speed) or that at which it would reach its rated (maximum) power output (rated wind speed). Two and three bladed rotors represent the best trade-offs of aerodynamic performance, balance, stabality and system cost. They are also the most popular ones.

3.4 The power available in the wind depends on the wind speed. That power can be theoretically described as:

$$P = (1/2)rAV^3 \quad \text{(Watts)}$$

where,

r is the air density (about 1.25 kg per cubic meter), A is the rotor swept area (in meters squared), and V is the wind speed (in meters per second).

3.5 This is the maximum theoretically available power in the air. Notice that this available power is proportional to the cube of the wind speed. This explains the importance (stressed earlier in Chapter 2) of having good information on the wind regime before undertaking a wind energy activity; a small variation in wind speed can result in a significant variation in available power. For example, overestimating the wind speed by 20% will result in actual power output which is only 58% of that expected. Alternatively, a 20% increase in windspeed will increase available power by almost 80%.

3.6 The formula above gives the power available in the air at any particular wind speed. However, because of inefficiencies in converting the wind energy into useful mechanical energy, an additional term must be included in the equation above to describe the actual power supplied by a WECS at any particular wind speed: the power coefficient (c). Thus the power output from a windmill can be represented as:

$$P=(1/2)crAV^3$$

where,

c is the power coefficient also known as rotor efficiency, which will vary for different windmills and also to some extent with windspeed for any particular wind machine. A good modern wind turbine should be able to yield a peak value for c of about 0.4. Using this value and r=1.25 yields a power function as:

$$P=0.25AV^3$$

Thus under conditions of, say, 5 m/s we would obtain a power output of 31.25 Watts per square meter of rotor area.

3.7 To verify the above relationship between power, rotor area, and wind speed, information on rated output, rated wind speed, and rotor diameter for 35 wind electric generators were extracted from the "Catalogue of Wind Machines" (1983). This data has been summarized in Appendix 3 and was fitted linearly through the multiple regression technique as follows:

The power equation $P=0.25Av^3$ can be rewritten as:

$$P= \frac{0.25x3.1417}{4} d^2 v^3$$

or $$P=0.196\ d^2v^3$$

or $$\frac{P}{.196} = d^2v^3$$

where d is the rotor diameter.

Taking natural logarithms (ln) on both sides we have,

$$\ln\left(\frac{P}{.196}\right) = 2\ \ln\ (d) + 3\ \ln(v)$$

Now, by fitting the above mentioned data to each other in an equation of this form, we obtain,

$$\ln\left(\frac{P}{.196}\right) = \underset{(25.1)}{1.88\ \ln(d)} + \underset{(42.1)}{3.13\ \ln(v)}$$

$$R^2 = 0.941 \qquad F=263 \qquad N=35$$

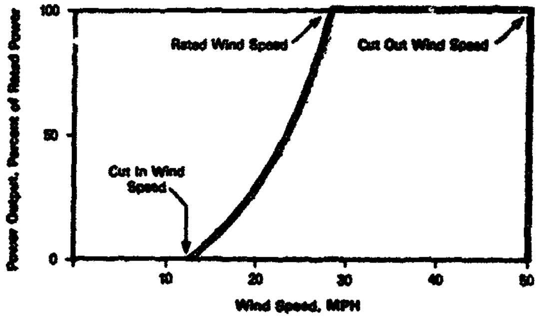
where the figures in parentheses beneath the regression coefficients are the t-statistics of significance.

3.8 From the estimated equation we can see that indeed the relationship between power and rotor area (or diameter) and wind speed for this set of WECS is significant and that the coefficients for d and v come close to the theoretical ones.

Rated power output

3.9 When wind speeds are low, the wind machine will stand idle. As wind speeds rise to what is known as the "cut-in" wind speed, the machine will begin operating. The cube relationship which exists between power and wind speed means that power output increases at an accelerating rate as the wind speed increases up to a point where the rated output is approaching (see Figure 3.3 below). The rated output is usually the maximum output of the wind machine. It is the power output which the machine produces when it is operating at the rated wind speed. Wind speeds above the rated wind speed generally do not produce greater power output levels.

Figure 3.3. Power Curve



Design Characteristics

3.10 WECS are designed to get as much power out of the wind as possible and to convert this power as efficiently as possible into mechanical power. The WECS tower is usually constructed from steel while the rotor is usually constructed from laminated wood, stainless steel, aluminum, or fiberglass. As noted above, one of the design objectives is to obtain as high a lift-to-drag ratio as possible. But there are other design characteristics which are important also. One is the 'cut-in' wind speed. In areas where wind speeds tend to be low, a low cut-in windspeed would be desirable. The reason that is not necessarily the case in all instances is that because of the mechanics of gear systems, a wind pump with a low cut-in wind speed will tend to have a lower pump efficiency at higher windspeeds than a wind pump with a higher cut-in wind speed. In other words, pumps with low cut-in wind speeds have the advantage that water can be pumped even at low wind speeds; but they have the disadvantage that they do not produce much water output at high wind speeds. An equally sized windmill with a higher cut-in wind speed would not be able to pump water at low wind speeds but would produce greater volumes than the low cut-in wind speed pump would at locations with higher wind speeds. The particular type of WECS for any application will depend on the particulars of the wind regime and power requirements for the site in question.

3.11 Another design characteristic of wind machines is their rated wind speed. As noted above, that is the wind speed at which the rated (maximum) power is obtained. Wind speeds greater than the rated wind speed would not produce more power output. Not only will power not increase further with increases in the wind speed, but as the wind speed continues to increase beyond the rated wind speed it would eventually reach a point where it could cause structural damage to the machine. The design of most wind machines therefore includes a braking mechanism (disk brakes, blade tips which pitch, or full span pitch control) which will slow the turbine rotation down when wind speeds reach such dangerously high levels, and at some point the mechanism may shut the machine off completely. The windspeed at which this occurs is called the 'cut-out' windspeed. In windpumps, this is commonly achieved by the working of side vanes in turning the rotor out of the wind. In large wind generators a more elaborate gear mechanism will put resistance on the rotor shaft and turn the blade angles, slowing down its rotation or simply reduce the power output at greater rotation speeds.

3.12 Because of the above, it is important that machines be properly matched to the wind conditions at the site where they will be used. Thus, a machine with a higher rated power output for the same cost as another lower rated one is not necessarily more desirable. This is so because the machine with a higher rated output may also require a higher wind speed to obtain the rated output. Thus, if the average wind speed at the site in question is considerably below the higher rated wind speed for this machine, more power may actually be obtained at those wind speeds from the machine with a lower power rating and lower rated wind speed. On average, wind turbines operating at an average annual windspeed of 7 m/s will have an output capacity of about 36 % of rated output over the year; at 10 m/s average annual windspeed, about 50 % of rated output. This ratio, between actual output and rated output, is known as the capacity factor. An annual capacity factor of about 30% to 35% is considered a typical goal for a wind turbine. The actual capacity factor for wind farms in the California Altamont Pass for 1985 was about 20%. Clearly, the capacity factor will be affected by actual wind characteristics and the actual in-field performance of the machine.

CHAPTER 4. PERFORMANCE TESTING AND SYSTEM EFFICIENCY

Introduction

4.1 Performance testing is important because it provides the basis for making predictions of the output and reliability that can be expected from a wind machine. It also serves as a means to compare different machines. There are basically two reasons for carrying out a performance test: the manufacturer may want to establish the performance of a new design or the user may want to verify whether the specifications provided by the manufacturer are indeed as stated in order to have a good estimate of expected power output in a specific use environment. Since there are many aspects of performance testing that can importantly affect the inferences made, it is necessary to understand the techniques used and the recommended ways to go about it.

Power Performance

4.2 The primary focus of a WECS testing exercise is to infer the relationship between wind speed and power output. In the case of windpumps, the ultimate relationship sought by a user is that between wind speed and hydraulic energy output; in other words, the volume of water pumped from a particular depth per unit time. This quantity is sometimes presented in terms of m^4 per hour or day. This represents the volume x head product; i.e. the volume of water (m^3) lifted over a certain height (m). In the case of a wind electric generator, the relationship measured is that between wind speed and electric energy output; i.e. the kWh obtained per unit time for various wind speeds. Once the instantaneous power output to windspeed relationship has been established, one can use this relationship to estimate the total annual energy output which can be expected at any average annual wind speed, by using the Rayleigh distribution as explained in Chapter 2. Table 4.1 below shows such an extrapolation using information available for actual in-field performance testing over the wind speed range from 4 m/s to 6 m/s.

Table 4.1: Output at Different Windspeeds [1/]

Rated Output (kW)	Rated Wind Speed (m/s)	Annual MWh at various annual average wind speeds (m/s) 4	5	6	7	8	10	11	12	14	17
1.8	11	2.9	4.2	6.0	6.9	7.6	9.0	9.7	10.4	11.5	12.6
4	11	6.0	8.5	12.3	14.6	16.4	19.9	21.5	23.1	25.5	28.1
10	11	16.3	22.4	31.5	36.4	41.3	49.7	53.7	57.6	63.7	70.1
65	12	81.2	124.0	187.9	220.2	247.6	299.2	325.0	349.2	383.7	437.0
200	14	182.7	300.8	476.8	566.4	650.0	805.3	882.9	1002.3	1074.0	1239.0
2500	14	2833.5	4423.8	6796.1	8123.1	9251.0	11374.2	12435.8	13431.0	15142.0	16809.0
185	17	121.9	163.8	226.2	318.3	433.5	548.6	679.1	794.3	909.5	993.9

[1/] A 0.9 availability factor is assumed throughout.

The table shows the estimated electric power output for different wind generators at various average annual wind speeds based on actual in-field performance tests. Annual output figures are obtained by using the Rayleigh distribution on the average annual wind speeds to obtain actual output estimates. 1/

System Efficiency

4.3 Another parameter of interest in performance testing is efficiency. The overall efficiency of a system (also known as system efficiency) is determined jointly by the turbine efficiency and the pump or electric generator efficiency (also known as the sub-system efficiency). The ratio of the actual useful power obtained from a wind system to the total power in the air as defined earlier in Chapter 3, gives the overall system efficiency. It represents, the percentage of the power available in the air which the machine was able to capture and convert into useful power (quantified as kW electricity or water pumped). Thus, the system efficiency can be defined as:

$$\text{System Efficiency} = \frac{\text{Useful Power}}{(1/2)crAv^3}$$

Then, the sub-system efficiency can be defined as:
Sub-system efficiency = System efficiency/Turbine efficiency.

where the turbine efficiency is defined as the proportion of the power in the air (as defined above) which the turbine captures and converts into mechanical power (to drive a pump or electric generator).

4.4 Turbine efficiencies of about 30% are common. With a pump efficiency of 40% one would obtain an overall windpump system efficiency of about 12%. With an electric generator efficiency of about 85%, which is common, one would obtain an overall wind electricity generator efficiency of about 25%. Some larger wind generators can have turbine efficiency of 40% yielding on overall system efficiency of 35%.

Performance measurement procedures

4.5 The primary objective of a performance measurement activity is to obtain as realistic as possible an estimate of the true power curve. There are performance test standards (e.g. from the International Energy Agency and from the American Wind Energy Association) which aim to standardize the tests for performance specification, to make this information more reliable and comparable between wind machines. One of

---

1/ Note: This is necessary because of the nonlinearity of the relationship between power output and wind speed. The total output over a year under varying windspeed conditions with an annual average wind speed of, say 6m/s, will be different from the output over the same period under constant wind speed conditions of 6m/s.

the crucial distinctions between in-field performance testing and analytical modeling or laboratory tests is that in the former the relationship between power output and wind speed which is obtained is based on actual in-field conditions, under the natural conditions of the atmosphere. Ideally, a performance test would be carried out at the site where the ultimate activity would be carried out; for example, at the site where an electricity wind farm project is being contemplated. That way, any particulars of the environment (e.g. air salinity, dust particles etc.) or user characteristics which could have detrimental effects would be discovered in the test results if the test period was made sufficiently long.

4.6 Besides obtaining an estimate of the power curve, long-term in-field (and at proposed site) performance measurement has other objectives. These include learning about: (i) how the system carries the wind stresses; i.e. fatigue characteristics, (ii) ease of operation in actual field conditions, (iii) atmospheric influences on equipment performance and longevity, (iv) anything about its operation which was unexpected, (v) actual degree of matching of the machine to the application in question; (vi) visual, sound and other potential impact (see Chapter 8) characteristics, and (vii) the overall cost of the final product for which wind power was used, i.e. cost of water or electricity obtained by means of the wind machine. More specifically, testing allows one to obtain a good estimate of the actual operation and maintenance costs, which are important for properly carrying out the financial and economic analyses, even though at a smaller scale than the ultimate project in its full scope.

4.7 There are several difficulties which commonly arise during performance testing. The principle ones are summarized here:

- Inaccuracies in measurement because of instrument calibration;
- Wind measurement cannot take place at hub but must be several feet away to minimize interference effects from turbine and will therefore not necessarily be the actual wind speed at hub;
- Breakdown of monitoring equipment, so that data will exclude certain periods.

Monitoring Systems

4.8 It is customary to connect an automatic monitoring system to a WECS which is being tested, similar to systems used to catalogue data from wind measurement as discussed in Chapter 2. The monitoring system generally will collect information on wind speed, wind direction, temperature, barometric pressure, and power output. In the case of a windpump, output would be measured in terms of the volume of water pumped per unit time; the depth of the water table would then also need to be monitored. In the case of a wind generator, output would be measured in terms of electric energy (kWh) generated. An automatic monitoring system generally will record data collected over certain averaging intervals on a medium such as a magnetic tape or in computer memory. This information is then transferred periodically, every 2 to 6 months onto a computer which then performs the necessary calculations and tabulations. The more modern monitoring systems include a small hand held computer which immediately tabulates the information collected and maintains relevant averages and other parameters. The cost for a system like that will vary of course with size and sophistication, some good ones can already be obtained for less than $2000. Clearly, depending on need, much larger and more sophisticated systems can be installed. In the case of the California wind farms some very elaborate and sophisticated monitoring systems can be found.

Conclusion

4.9 Having collected all the relevant information, and if the information can be deemed reliable, one should then be in a position to use a least-squares or other (non-linear) fitting technique to obtain an estimated power curve. With this power curve, one can infer the efficiency of the system at any windspeed by dividing output at that wind speed, as predicted by the power curve, by the corresponding power in the air at that wind speed (and air pressure) as defined above.

4.10 In the case of wind generators, the power output was given in units of watts as was the power in the air. Thus, the efficiency can readily be calculated as the ratio of the two. However, in the case of water pumped, the output (volume-depth; i.e. m^4) would have to be converted into watts. This would be done as follows:

Let: V be the volume (m^3) of water pumped per unit time.
H be the height over which V is pumped in meters.

Then the energy required would be $E = \frac{VH}{367}$ kWh

4.11 In other words, to pump 1 m^4 in an hour would require a pumping power of 2.72 watts. Also, by using a Rayleigh distribution, one can estimate the available energy from the wind machine over a year given an established annual average wind speed for a particular site. Using this information and the cost for the wind system (purchase, transport, installation, and maintenance) one can obtain an estimate for the annualized cost and subsequently a projected unit output cost of power from the system. This estimate can then be compared to alternative power systems to establish which offers the least cost alternative. Generally, average wind speeds of at least 3 m/s would be needed for wind pumping to have a competitive chance; 5 m/s for wind generators. Chapter 5 will discuss the economics of wind systems and will go further into the details of this type of analysis.

CHAPTER 5. ECONOMIC EVALUATION OF STAND-ALONE SYSTEMS

Introduction

5.1 The applications of wind power, for the purpose of economic evaluation, can be grouped into two categories: stand-alone systems and grid connected systems. Several aspects and economic considerations for these two categories differ considerably. They will therefore be treated separately. This chapter will discuss the economics of stand-alone systems.

5.2 In situations where the wind machine output has a constant value regardless of the time of day at which it occurs, the analysis reduces to the simple question of which system can provide the additionally needed output at least cost. Since we would be considering the introduction of a wind system, the way to go about this is to first establish the least cost alternative among all the other technologies available. For example, for an electric generating system, fuel oil generators may be the least cost alternative against which the wind alternative must be compared. Then, all one needs to do is obtain a unit cost of output using a wind machine and compare it to the least cost 'non-wind' alternative. But as mentioned above this approach would be applicable only in the case where the value of output remains constant over time and is known to exceed costs and thus where the merit of the output has been already established. This is generally so for isolated water pumping needs or stand-alone wind electric generators for which more detailed methodologies are provided in the next sections. Having thus established the least cost alternative in these instances, one may still need to estimate a value (constant) for the output if a rate of return analysis is desired. For some guidance on benefit estimation see the references provided in para 6.8. In the case of grid connected wind turbines, the value of the output, as it varies betweem peak and off-peak times, must be considered also within the economic analysis. Because of its importance, this aspect is discussed separately in greater detail in Chapter 6.

5.3 Before site specific performance testing begins and also before the economic evaluation begins, the required size of the wind machine for the application in question should be established. This is usually done by a method known as the critical output level analysis. It involves reviewing for each month of the year the ratio of required output to the historical average monthly windspeeds. The month for which this average is the greatest would be the 'critical month' since as long as the wind machine is sized to meet this output to wind speed relationship, it will also be able to meet the output for the other months. On this basis, the proper machine size for the job in question can be selected. Then, if possible, performance testing for the selected wind machine should be carried out to determine with as great a certainty as possible the actual parameters (such as expected output, costs, etc.) to be used in the economic analysis. One should know whether or not the wind system operates with the efficiency and other end results claimed by the manufacturer. Ideally one should also know something about the expected life of the machine, reliability, that is the percentage of time it will be available for normal operation, and its ability to withhold stresses caused by the wind on the turbine and the tower. Estimates for the installation, overhead, maintenance and operation costs should also be available.

5.4 Whether or not a particular wind machine performed well under the tests, and in fact may appear to be technically the best wind machine available for a particular power requirement, is not sufficient basis for concluding that it should be installed. Clearly, good engineering performance is a necessary condition for a successful operation of a wind system. But to be a worthwhile investment, the economics of the activity must be favorable. Thus, it is not the quality of the engineering performance alone that ultimately matters but the overall cost performance including reliability of supply. A comparison must be made between the cost of power using the wind machine and the cost of other available alternative methods of pumping or electricity generation. Only if the wind alternative can be shown to offer the least cost way of doing so at the same or higher level of engineering reliability, and at the same time to provide an acceptable rate of return on the investment, can the wind system be said to be a justifiable investment. There are times when the benefits of a particular activity cannot be quantified, as for example in the case of providing drinking water for a remote village as part of a rural development program. In such cases, the decision to provide water has been made and within the economic analysis the activity can be considered as exogenously determined. Thus, there will be no need to establish the adequacy of the rate of return in justifying the investment. Only a least cost analysis will be required to determine the best technological choice (be it wind, diesel or other).

Least Cost Analysis

5.5 To be able to determine which is the least cost alternative available for a particular task (pumping or electricity generation) one has to first obtain a measure of cost based on a common denominator for each of the alternatives available. This task is complicated by several factors which are summarized below:

(i) Cost profiles are different for different technologies. For example, diesel systems tend to be characterized by lower front end (investment) costs than wind systems, but to have higher operating costs (fuel) in later years.

(ii) Predictability of output is different. With diesel systems, output can generally be obtained on demand. Wind systems are subject to the erraticism of the wind. Clearly, storage systems could be added to reduce this fluctuation which would affect the cost.

(iii) Other uncertainties can play a role. For example, availability of diesel may be erratic at certain locations. Or, given the existing experience with wind systems, their use may be considered riskier, and knowledge of their true operation and maintenance costs uncertain. These factors in principle affect the economic evaluation on an actuarial basis and should be considered.

5.6 There are straightforward discounting analysis methods to deal with (i) above. And as long as one assigns probability distributions for the various variables discussed in (ii) and (iii) one could incorporate them into the analysis and obtain the expected cost per unit output for each system together with their variances or expected risk factor. One can then make the decision on the basis of individual cost and risk taking preferences.

Wind Pumps - Cost and Economics

5.7 The following paragraphs show the methodology for evaluating the cost per unit water pumped with a wind pump. Assume a wind pump system has an installed cost of C[1/], and that it has an estimated yearly overhead, operation and maintenance cost of OM. Assume also that given the known wind regime, it is expected to pump on average w m^3 of water per day or 365w m^3 per year from a given depth. But because need and supply of water pumped don't always coincide, assume that only 75% of the water pumped will in fact be useful (i.e. because it occurs at a time when it's needed). Then, the useful amount of water pumped in a year would be 0.75 x 365w. Finally, assume that the windpump has an expected life of t years under the existing operation and maintenance arrangements. Then the cost per unit of water pumped can be obtained by amortizing the costs of the wind pump system to a yearly basis and dividing that yearly cost figure by the yearly quantity of useful water. To amortize the costs a discount rate is needed. In this example, the discount rate is denoted by r. Note that since in the analysis the maintenance cost is kept constant at OM, the analysis is implicitly being carried out in constant values, net of inflation. Therefore, the discount rate r in effect represents a "real" rather than a "nominal" discount rate.

Thus, the amortized total yearly cost (ATC) of the wind system is:

$$ATC = \frac{Cr(1+r)t}{(1+r)^t - 1} + OM$$

Where C, r,t, and OM are defined as above.

Dividing this annualized cost by the volume of useful water pumped yields a unit cost of water pumped with a windmill (UCWM) at that particular site. It is represented in equational form as:

[1/] Note that in the case of the presence of a storage device, C would include the cost for that device.

$$UCWM = \frac{ATC}{(0.75)(365)w}$$

UCWM will be a figure in units of C divided by the unit of w. In other words, if C is in US$ and w is in m^3, then UCWM will be in US$ per m^3.

5.8 Now, we would be in a position to evaluate whether or not a wind pump is the least cost alternative. Having obtained similar amortized costs for the other technologies available,[1] a simple comparison of these costs will show which of the technologies can pump water for the least cost. Note however that when the total amount of water needed is less than the capacity of the smallest unit of a particular technology, only the volume of actual useful water pumped should be used in the denominator of UCWM above and not the total capacity of water that can be pumped. This is important because there are several known applications where because of the small amounts of water needed, a small windpump will produce the needed water less costly than the smallest available diesel pump, even though on a per total capacity volume basis (useful plus non-useful), the diesel pump would have been less costly. Similarly, it is important that, to the extent possible, the "down-time" for each system being compared be properly accounted for so that the estimated unit costs obtained reflect the true expected overall output cost for the various systems.

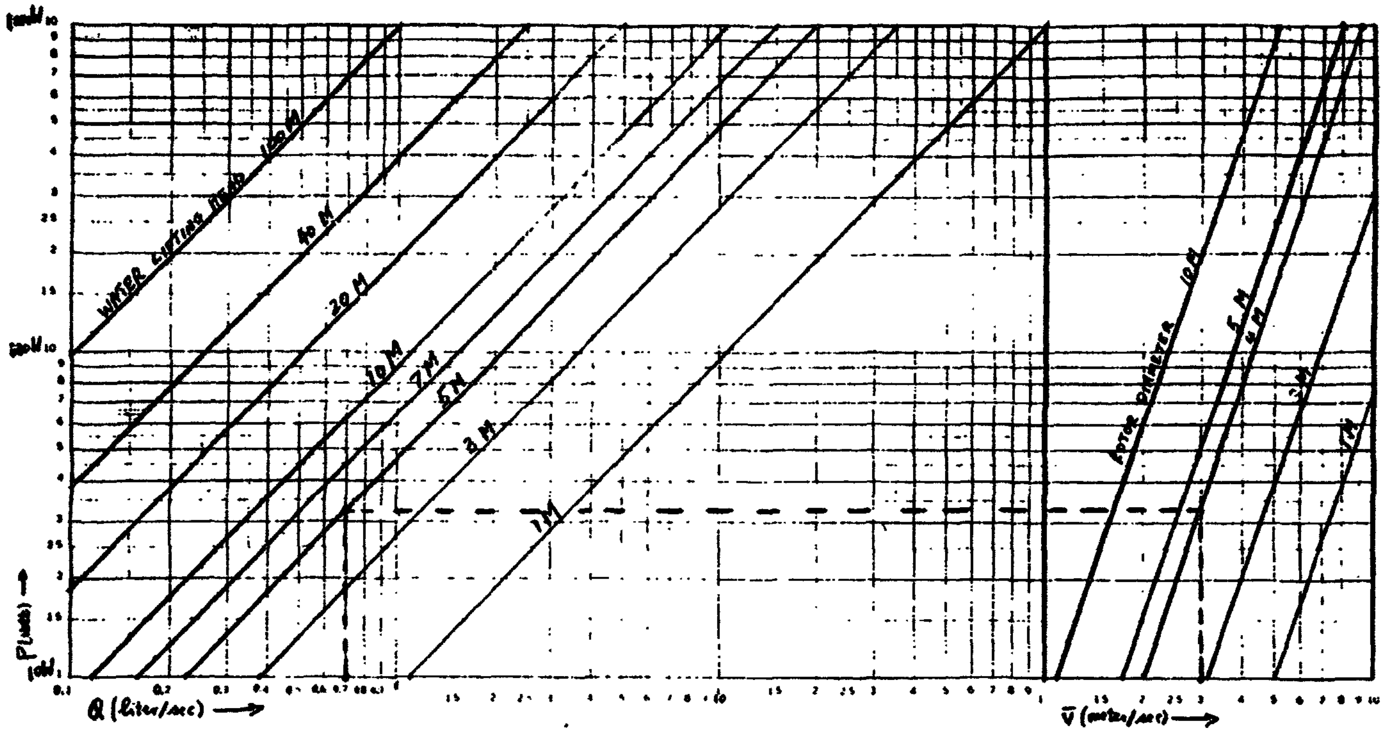
5.9 Because there are little or no known economies of scale in the size of wind pumps the relationship between total annual cost and volume of water pumped from a certain depth and for a particular average wind speed is linear. It is common practice to measure the capacity of wind pumps in terms of the amount of water that can be pumped per unit time, from a given depth and under a certain wind condition, per square meter of rotor area (alternatively, the rotor area can also be defined in terms of rotor diameter). Figure 5.1 on the next page allows one to determine roughly what one can expect in terms of water output from a windmill given the average wind speed, the rotor diameter, and the water table depth. Alternatively, given the required output, water table depth, and average windspeed, the wind machine size (in terms of rotor diameter) can be determined. This graph is based on information on wind pump performance for many wind pumps.

5.10 To see how it could be used, assume we had a location with average annual wind speeds of 3 m/s where we were considering the use of a wind pump to pump water from a depth of 5 meters. Assume we needed 60 m^3 per day which is equivalent to 0.7 liter per second. Then using Figure 5.1 we can see that the required wind pump rotor diameter to do so would be about 4 m - this would correspond to a rotor area of about 12.5 m^2. On the basis of a wind pump cost of about US$250 per m^2 (see below), this would mean that a wind pump of about US$3125 would be required to do the job. Now amortizing this cost over 10 years at a discount rate of

---

[1] It is important to stress that these costs should also be derived from actual in field performance data, as would the costs for the wind pumps, rather than on manufacturer's specifications.

Figure 5.1



10% would yield an annual cost of about US$ 510. Adding an assumed operating and maintenance cost of 5% of the capital cost[1] (i.e. about US$ 155 per year) would result in US$665 total per year cost to pump 21900 m^3. Thus the cost per m^3 of water pumped would be about 3 cents.

5.11 This methodology can be applied to any combination of average wind speed, pumping head, and cost assumptions. It has been used to estimate the unit cost of pumped water for various combinations of lifting head, windspeed, and wind pump cost. The results are presented in Appendix 5. By representing the cost of water in terms of a common denominator ($ per m^3) it facilitates cost comparisons with other pumping techniques. It is important to note that the cost per m^3 should include all costs of getting the wind pump to produce the water; that is, installation, start-up and, as appropriate, storage costs should be included. This would be the proper figure with which to compare the unit water cost of the alternative pumping technologies for which all costs should also properly have been included in this calculation. Appendix 5 has been constructed for a pumping volume of 60 m^3 per day. However, since water costs are given on a per volume basis, the unit cost would be

---

[1] Data on actual O & M costs for wind pumps are scarce, but based on information which is available, 5% is considered a reasonable "guesstimate."

the same for any volume because of the basically constant returns to scale mentioned earlier.

5.12 The spectrum of costs (\$100 - \$600) per m^2 of rotor area (installed) shown in Appendix 5 is realistic. Some "modern" designs developed for use and manufacture in developing countries using local material can be quite low cost (such as e.g. the CWD and Kijito models), while heavy steel type windmills such as the well known Aermotor (also known as the 'American' type), can be costly. However, it is uncommon to find cases close to either side of this spectrum. Some wind pumps with rotor and rating specifications are summarized in Appendix 6. For purposes of initial analysis and identification of wind pump potential, an installed cost assumption of about \$250 per m^2 would be very reasonable, even somewhat conservative, particularly in the case of developing countries, where often many, if not all, parts of the windmill can be constructed locally at lower costs. It is also clear from the above graph (figure 5.1) and Appendix 5 that the cost of water is proportional to the pump head and cost per m^2 of rotor area and is inversely proportional to the cube of the wind speed. In fact, what should become clear from the exercise and results above is that the cost per m^3 of water pumped can be represented more generally in terms of the following equations:

$$\text{Rotor Area} = \frac{QH}{0.8808v^3} \qquad (m^2)$$

$$\text{Windpump Cost} = \frac{cQH}{0.8808v^3} \qquad (\text{e.g } \$)$$

$$\text{Unit Water Cost} = \frac{\text{(Annual Amortized Windpump Cost) + (Annual O\&M Cost)}}{\text{Annual volume of water pumped}}$$

$$\text{Unit Water cost} = \frac{acH}{321.5v^3} + \frac{M}{365Q} \qquad (\$/m3)$$

Where: Q is average useful volume pumped per day (m^3/day)
H is pumping head (m)
v is average annual wind speed (m/s)
c is windmill installed unit cost in terms of rotor area (\$/m^2 rotor area)
M is annual operation and maintenance cost (\$/year)
a is the amortization factor.

5.13 Thus whenever we have an area with favorable wind conditions, where there appears to be a strong need for water, we can estimate the cost of water using the above equations and compare this with the corresponding costs for alternative pumping techniques available to determine whether wind pumping would be the least cost alternative. For purposes of comparison, it has been estimated that using diesel pumps to pump 60 m^3 of water per day from 5 meters deep would cost about 3.5 cents per m^3 assuming a diesel cost of US\$0.40 per liter. Thus, diesel pumping, at a diesel cost of \$0.40/liter, would be more costly than wind pumping where windspeeds average at least 3 m/s (see para 5.10).

However, to pump 60 m^3 per day from 15 meters deep the cost with a diesel pump would be about 5 cents per m^3 compared to about 9 cents for a windpump. Then again, at average wind speeds of 5 m/s, the cost of water with a windpump would be less than 2 cents per m^3. Note that when comparisons are being made, the total product must be similar. That is, one must make the necessary adjustments to the windpump system so that it provides the required reliability of delivery as would the diesel pump. This often means providing storage tanks or other back-up systems. If storage is essential and becomes part of the wind pump system, its additional cost must be included in the "Windpump Cost" above.

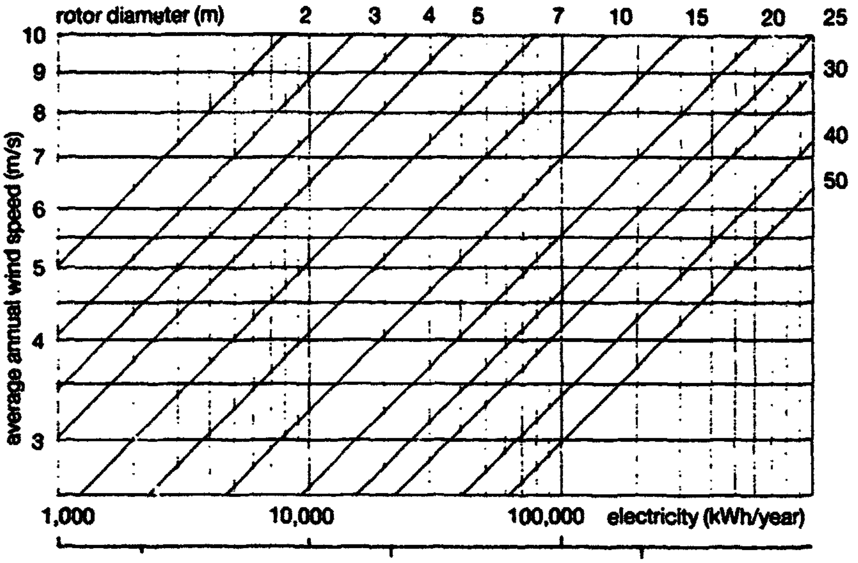
5.14 Storage tanks vary in cost. However, within the framework of limited experience, a cost of about \$50 per m^3 is commonly used in preliminary analyses. As mentioned earlier, this cost would have to be included in the unit water cost for windpumps, after amortizing it properly. Storage tanks are considered to have long lives (25 years is often used). The actual size of the storage tank for any particular use will depend on the characteristics of the wind at the location as well as the water demand characteristics. In cases where the demand patterns closely follow that of the wind regime, less storage will generally be required, all else being equal. Similarly, for applications where the need for reliability of water supply is greater, storage requirements will be greater.

5.15 There are generally two principal functions of a wind pump storage tank. These are: (i) to create a buffer to smooth out the output variations due to short term fluctuations of the wind thereby increasing the reliability of the water flow and (ii) to catch and store the water which is pumped at times when the water is not used but the wind pump is operating (e.g. at night). Generally, a storage capacity of between 75% and 100% of the daily water output will be sufficient to cover these two requirements. In the case of a 60 m^3 per day requirement, a storage capacity of about 45 to 60 m^3 would be sufficient amounting to about \$2000 to \$3000. But amortized over 25 years at 10% discount, this cost would add only 1 to 1.5 cents per m^3 to the total cost of the water pumped.

Wind Generators - Costs and Economics

5.16 Figure 5.2 on the next page shows the relationship between annual electricity output required, average annual windspeed, and corresponding wind generator rotor diameter. It can be inferred from this graph that it is based on an overall system efficiency of about 35%. It provides a quick back-of-the-envelope estimate of the size of a wind generator required to meet a particular annual energy need under certain wind conditions. Once the proper size of the wind generator has been determined more exactly by juxtaposition of load factor, wind regime and machine characteristics, its economic competitiveness can be evaluated.

FIGURE 5.2



5.17 The methodology for evaluating the competitiveness of wind generators relative to other electricity generating technologies in stand-alone situations is similar to that for wind pumps. First one must amortize the costs (equipment, installation storage or back-up), and then add in the annual recurrent costs (operation and maintenance etc.) and divide this annual cost figure by the annual energy supplied by the wind generator to obtain a cost per kWh. One can then compare this unit cost of wind generated electricity with that of the alternatives available. As before, it is important to note that it is the effective useful energy that matters and that this type of analysis is applicable only when the value of output is constant and the merit of the output has been already established. When the value of output is not constant, this approach would be inappropriate, and a more extensive economic analysis, taking into consideration long-term marginal cost and actual value of output, would need to be carried out (see Chapter 6).

5.18 In tables 5.4 through 5.8 below an analysis is made of how wind generators would perform cost-wise under various annual average windspeed conditions based on cost figures obtained from the US experience. The wind generators are the same ones for which the power output to wind relationship was given in Table 4.1 of Chapter 4. That table is reproduced here as table 5.4 for easy reference. The capital and O&M cost estimates used are based mainly on the California wind farms experience. Costs are amortized and then divided by estimated annual electric output (assuming 100% useful) for various average annual wind speeds. These output figures for the various average wind speeds are obtained by using the Rayleigh distribution for windspeed and the corresponding power curve for the various wind generators, adjusted by a 0.9 availability factor. Thus the cost for wind generated electricity is expressed in terms of US$ per kWh, for each wind machine, under various wind regimes. One can then quickly compare these costs with the long run amortized marginal cost for any other technology which could provide the required electricity at the site in question. If the unit cost of wind electricity is less, wind generators will provide the least cost alternative.

5.19 Thus, for example, with average wind speeds of 7 m/s, any wind machine with a capacity greater than 4kW (except for the 2.5 MW machine) would produce power for less than $0.10 per kWh for the assumptions and information contained in tables 5.4 to 5.8. It is important to emphasize that the cost figures shown in Tables 5.5 and 5.8 do not include possibly required storage facility, since it is impossible to generalize cost estimates for such requirements. However, the important point is that the methodology and analytical steps would remain the same as that shown above. As in the case of water pumping, any required storage costs to provide a wind system capable of serving as an equivalent alternative to the more conventional competing system would need to be included as part of the wind system capital cost (and similarly, installation cost) before beginning the excerise of amortization and conversion to a cost per kWh. Thus, where applicable, these same calculation steps would produce a cost per kWh which includes the required storage.

Table 5.4: Output at Different Windspeeds

Rated Output (kW)	Annual MWh at various annual average wind speeds (m/s) 4	5	6	7	8	10	11	12	14	17
1.8 1)	2.9	4.2	6.0	6.9	7.6	9.0	9.7	10.4	11.5	12.6
4 1)	6.0	8.5	12.3	14.6	16.4	19.9	21.5	23.1	25.5	28.1
10 1)	16.3	22.4	31.5	36.4	41.3	49.7	53.7	57.6	63.7	70.1
65 1)	81.2	124.0	187.9	220.2	247.6	299.2	325.0	349.2	393.7	437.0
200 1)	182.7	300.8	476.8	566.4	650.0	805.3	882.9	1002.3	1074.0	1239.0
2500 1)	2833.5	4423.8	6796.1	8123.1	9251.0	11374.2	12435.8	13431.0	15142.0	16809.0
185 2)	121.9	163.8	226.2	318.3	433.5	548.6	679.1	794.3	909.5	993.9

Table 5.5: Capital Costs

Rated Output (kW)	Installed costs 3) ($)	($/kW)	Other costs $/kW Contingency	(10% cont., 2% start-up) 1) Start	Total Installed Costs ($)	Total Installed Costs ($/kW)
1.8	5800	3222 1)	322	64	6496	3609
4	8100	2025 1)	203	41	9072	2268
10	16000	1600 1)	160	32	17920	1792
65	85000	1308 1)	131	26	95200	1465
200	250000	1250 1)	125	25	280000	1400
2500	7000000	2800 1)	280	56	7840000	3136
185	162000	876 2)	88	18	181440	981

Table 5.6: Wind Power Costs ($/kWh) (inclusive of start-up, O&M costs (US$0.015/kWh), & contingencies).

Rated Output (kW)	Wind system power costs ($/kWh) at different average annual windspeeds (m/s) 4) 4	5	6	7	8	10	11	12	14	17
1.8	0.30	0.22	0.16	0.14	0.13	0.11	0.10	0.10	0.09	0.08
4	0.21	0.16	0.11	0.10	0.09	0.07	0.07	0.07	0.06	0.06
10	0.16	0.12	0.09	0.08	0.07	0.06	0.06	0.06	0.05	0.05
65	0.17	0.12	0.08	0.07	0.07	0.06	0.05	0.05	0.05	0.04
200	0.22	0.14	0.09	0.08	0.07	0.06	0.06	0.05	0.05	0.04
2500	0.38	0.25	0.17	0.14	0.13	0.11	0.10	0.09	0.08	0.08
185	0.21	0.16	0.12	0.09	0.07	0.06	0.05	0.05	0.04	0.04

Table 5.7: Sensitivity analysis for 65 kW WECS

Percent Change in Capital Costs	Wind system power costs ($/kWh) at different average annual windspeeds (m/s) 4)									
	4	5	6	7	8	10	11	12	14	17
-75%	0.05	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02
-50%	0.09	0.07	0.05	0.04	0.04	0.04	0.03	0.03	0.03	0.03
-25%	0.13	0.09	0.06	0.06	0.05	0.05	0.04	0.04	0.04	0.04
-10%	0.15	0.11	0.07	0.07	0.06	0.05	0.05	0.05	0.04	0.04
0%	0.17	0.12	0.08	0.07	0.07	0.06	0.05	0.05	0.05	0.04
10%	0.18	0.13	0.09	0.08	0.07	0.06	0.06	0.05	0.05	0.05
25%	0.21	0.14	0.10	0.09	0.08	0.07	0.06	0.06	0.05	0.05
50%	0.25	0.17	0.11	0.10	0.09	0.08	0.07	0.07	0.06	0.06
75%	0.28	0.19	0.13	0.11	0.10	0.09	0.08	0.08	0.07	0.07

Table 5.8: Sensitivity analysis for 200 kW WECS

Percent Change in Capital Costs	Wind system power costs ($/kWh) at different average annual windspeeds (m/s) 4)									
	4	5	6	7	8	10	11	12	14	17
-75%	0.07	0.05	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
-50%	0.12	0.08	0.05	0.05	0.04	0.04	0.04	0.03	0.03	0.03
-25%	0.17	0.11	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.04
-10%	0.20	0.13	0.08	0.07	0.07	0.06	0.05	0.05	0.05	0.04
0%	0.22	0.14	0.09	0.08	0.07	0.06	0.06	0.05	0.05	0.04
10%	0.24	0.15	0.10	0.09	0.08	0.07	0.06	0.06	0.05	0.05
25%	0.27	0.17	0.11	0.10	0.09	0.07	0.07	0.06	0.06	0.05
50%	0.32	0.20	0.13	0.11	0.10	0.08	0.08	0.07	0.07	0.06
75%	0.37	0.23	0.15	0.13	0.11	0.09	0.09	0.08	0.07	0.07

Notes:

1) "Foreign Applications and Export Potential for Wind Energy Systems"
Solar Energy Research Institute, U.S. DOE December 1982

2) VAWTPOWER. Inc. Rio Rancho, NM (Vertical axis machine)

3) Cost figures have been adjusted to conform to more recent information obtained and summarized in internal memos: J. Fish (Feb. 4, 1985), R. Dosik (Dec. 21, 1985)

4) Includes US$ 0.015 per kWh operation and maintenance cost

5) A .9 availability factor has been applied to the annual output values.

5.20 Furthermore, whenever such cost comparisons between competing energy sources are made, only the costs which are not identically incurred by all alternatives should be included as part of the total cost to be amortized for each of the technologies being compared. Thus, for example, certain transmission costs and overhead costs may in some cases be incurred regardless of the type of generator technology (wind, fuel, etc.) being used. These costs, in those cases, would then not be included in the analysis since they are identical for all technologies. Other costs (e.g., storage costs for wind machines) might very specifically apply to one technology but not the other. These costs would have to be included in the amortization calculation and economic comparison.

5.21 Finally, it is worth mentioning that depending on the objectives of the analysis, different prices (for costs and benefits) should be used. If it is financial performance one is studying then market (or financial) prices with all taxes and subsidies included should be used. If instead, one wants to analyze the implications for national economic efficiency in terms of optimal resource utilization, the prices used in the analysis should be the "economic" or "shadow" prices.

5.22 In the tables above, the total representative financial costs, as well as the corresponding cost per kWh, for the various wind generators are given. These costs are based on consolidated information obtained through existing literature as well as direct contact with manufacturers and users. Clearly, there are site specific characteristic in every case (transport, installation, soil characteristics, storage requirements, scale of operation, infrastructure etc.) which can cause the actual costs per kWh to deviate significantly from those given above. Those costs are only meant to be representative of what one can expect on average; to give an initial indication of the approximate magnitude and expected cost of wind generated power under various wind regimes. Also, it is important to recognize that technological advances and cost reductions are being continuously introduced so that the cost estimates above should be updated periodically. To see how sensitive costs per kWh would be to changes in capital cost assumptions, tables 5.7 and 5.8 give the sensitivity analysis for the 65KW and 200 kW machines; two of the more popular sized wind generators. For example, in the case of the 200 kW machine it can be seen that at 6 m/s wind speeds, a 25% reduction in capital costs would bring down the cost of power from the base cost of $0.09 to $0.07 per kWh. 1/

5.23 A note about the capital cost per kW which is often used as a guide when comparing different WECS is necessary. The machine total cost to rated power output ratios can be a misleading guide to relative costs unless the windspeed at which the power has been rated is taken into account. For example, a machine with a greater cost per kW than another may in fact be preferable because it may also have a lower rated

---

1/ This is not an unrealistic case since the most recent estimates indicate that by the end of 1985 capital costs had been reduced some 25% below the levels shown in Table 5.5.

windspeed so that at the relatively low wind speeds prevalent at the site where it would be used, it would in fact yield more power than the other lower cost per kW machine but with a higher rated windspeed. It is also important to note that when one evaluates the financial and economic attractiveness of wind generated electricity, the benefit due to the wind system should be properly defined. For example, because of the variable nature of connected wind generated electricity, the wind system might still require as back-up the conventional fuel burning system. Thus, the savings due to the wind system, i.e. the benefit, will consist only of the fuel savings when the wind machine is operated and will not include savings due to the diversion of any capital investments in the conventional system. At the margin, this aspect becomes more and more important as the magnitude of wind generated electricity increases relative to the total power generated. As long as the wind generated electricity is only a small proportion of the total power production (say less than 10%), the wind system could under favorable wind regimes comfortably replace conventional capacity. The benefit of the wind generator would then also include savings in conventional system capacity. This aspect is discussed further in Chapter 6.

5.24 It has been thought at some point that there would be considerable economies of scale in very large (2.5 MW type) wind generators. However, as the analysis above shows, that is not the case. In fact, costs per kW and kWh are high. This is due to the fact that these machines are generally in an experimental stage and are being produced on small scale with correspondingly high production costs. In addition, many of their components need to be custom made at very high cost. It is possible that if production scale increases the expected economy of scale will be realized for these larger machines.

Storage

5.25 The problem of storage for the output of wind electric generators is somewhat different than for wind pumps. Although the objectives in both cases are basically the same -- to smooth out the flow of the output and to capture the wind power at times when the output is not in use -- there are differences worth noting.

5.26 When wind generators are linked with the main grid, there is no need for storage as such, except in so far as it would be required to maintain a constant power supply in view of the short term fluctuations in the wind speed. Since, at least so far, most wind generators have been part of a grid system, storage has not commonly been required.

5.27 However, in those applications where wind generators constitute a stand-alone power system (e.g. isolated villages, remote telecommunication equipment, etc.), storage is essential. And given the high costs of electricity storage devices, optimum storage capacity choice is crucial in maximizing the actual benefit to cost ratio of the system. The table below summarizes costs for some storage devices for stand-alone systems.

Table 5.10 Stand-Alone Energy Storage Systems

Storage System	Energy Density kWh/liter	Storage time[1/] (hours)	Cost	
			$/kWh	$/kW
Diesel fuel	10	-	0.15	
Sensible heat	0.1	1-15	13.46	75.00
Hydrogen gas (200 bar)	1	-	82.23	300.00
Flywheel	0.1	0.1	134.55	300.00
Lead/acid battery	0.05	5	149.50	315.00
Nickel/cadmium battery	0.1	3	448.50	315.00
Silver/zinc battery	0.1	0.1	2990.00	315.00
Micro pumped	0.00003	0.01	3737.50	172.50

[1/] Storage time = Storage capacity (kWh) divided by stored output (kW).

5.28 The actual size, (i.e. capacity) of a storage device for any particular stand alone application will depend primarily on the pattern of the wind regime, both short-term as well as seasonal, the degree of correspondence of this wind pattern to the power demand cycle, and the degree of reliability desired in power availability. Incorporating these factors into the design of an optimum storage capacity involves sophisticated statistical and risk analysis techniques, the details of which are beyond the scope of this report. However, it is important to recognize that such an analysis needs to be carried out by experts in this field.

CHAPTER 6. ECONOMIC EVALUATION OF GRID CONNECTED SYSTEMS

Introduction

6.1 Recently there has been increasing interest in having electricity generated by WECS fed into national main grids. When done, this usually takes the form of a cluster of wind turbines jointly producing electricity (a wind farm) which is then fed into the main grid. The most commonly used WECS for such integration with the main grid has been in the 60 kW to 300 kW range, while some utility companies have experimented with the larger, MW type machines. In California, wind farms have been largely carried out by private firms or a consortium of private investors. In some developing countries utility companies are becoming increasingly interested in the possibility of having some of their power generated by wind turbines. In many of these countries, governments often own, regulate, or participate in the activities of the utility companies. Thus, they tend to see wind power as a significant and realistic opportunity to reduce oil import dependence and at the same time to provide electricity in a cost effective way. Another major attraction of wind power to utility companies is that it allows capacity expansion to take place in small increments rather than large investments at a time when future demands for power are uncertain.

6.2 One problem or rather concern with WECS connected to main grids is the integration of an energy source which is more variable than the existing one thereby increasing the overall power output variability. True, in many countries, the unreliability of power supply and frequency of power outages are greater than the variability which would be introduced due to a wind turbine. But these are usually due to transmission problems or generator or transformer breakdowns etc. which would continue to exist with or without the introduction of WECS. These variabilities however, are not due to erratic fuel supply, as is the case with WECS where one would be relying on an uncertain "fuel", namely the wind. This would thus add an additional fluctuation factor.

6.3 There are three major types of output fluctuations related to WECS. These involve momentary, daily, and seasonal fluctuations. The momentary fluctuation involves small power output fluctuations in individual wind machines. However, when combined as part of a windfarm, the cumulative impact of this type of fluctuation from the numerous machines tends to cancel. Daily output fluctuations occur because of the changes in average wind speeds which generally take place over a 24 hour cycle. It may happen, however, as in the case of California, that this output fluctuation closely matches the pattern of system demand, making it ideal to meet some of the peak load. In such a situation, the value of the output would be greater because of the specific time it occurs and consequently the (expensive) alternative it is displacing. This is discussed further below. Finally, the seasonal power output fluctuation is similar to the daily fluctuation except that the changes occur because of changes in average daily wind speeds as the seasons change. Again, in favorable circumstances, these fluctuations might coincide with seasonal demand fluctuations giving wind power an additional advantage.

6.4 It is therefore important for utility planners, who are considering the introduction of wind generators, to carefully evaluate what proportion of the power supply could comfortably be permitted to have this fluctuation within the overall network and to what extent the wind pattern favorably coincides with power demand. In so doing one must consider the level of certainty in power availability that one wants to maintain, the potential fuel savings due to the wind generator, and the potential capital investment in future plant that can be deferred as a consequence.

Economics

6.5 The approach discussed in Chapter 5 for analyzing the economics of stand-alone wind generators is not appropriate for wind systems connected to the main grid. Analyses as summarized by Tables 5.6 through 5.8 would still provide an initial estimate of the expected average cost of wind power under various conditions and to that effect would be useful as a preliminary screening device when compared with existing average costs. However, due to the variable nature of wind power and the typically diverse value of power between peak and off-peak times characteristic of grid systems, the impact and economics of wind power will be determined not so much by average cost considerations but rather long-term marginal cost and wind power time-delivery distribution characteristics. This and other aspects relating to the economics of grid connected wind power systems are discussed below.

6.6 When evaluating the potential economic value of integrating wind generators into a utility's power generation facility, four major factors need to be considered:

1) All the costs which are directly a consequence of operating the windgenerators, including the loss of efficiency in the fuel burning plant if it has to be operating at below capacity when wind turbines are in use;

2) The fuel savings resulting from running the wind generator;

3) Savings in terms of deferred capacity expansion;

4) Long term savings resulting from re-optimizing the proportion of the different plant capacity types within the total system capacity

6.7 Where the consequence of using wind power is to reduce the capacity utilization of existing plants, these plants may need to be operated at lower efficiencies. Costs due to this factor could be calculated directly in terms of the higher cost per kWh generated by those plants when the wind turbine is in use. This incremental cost should be properly added to all other costs attributable to the wind turbine.

6.8 Another way of looking at the economic analysis proposed above is to compare the overall system's long-run marginal cost of meeting a specific load using only conventional structures with the long-run marginal cost to meet that same load using wind generators to meet part of the power demand. 1/ But, looking at the cost side alone is not always sufficient in all situations. For example, the overall power supply systems being compared (with and without wind power) may not be identical as in the scenario just discussed above. And, since energy supplied at the time of system peak typically has a much higher value than energy supplied at off-peak periods, the value of a particular wind power system under identical wind regimes may vary depending on the degree of congruity of the wind regimes with the load pattern. Therefore, to properly evaluate the economic attractiveness of a particular wind power system proposed for integration with the main grid, the true economic value of the power produced should be known and taken into account in the analysis. 2/ This should be done by considering the specific "time slices" at which the wind power would be available. The value of the output for each of these "slices" would be determined by the corresponding long-run marginal cost of producing that power with conventional systems. If when discounted to the present, the total value of the output produced by the wind power system thus calculated is greater than the present value of its costs, the wind power system would be economically justified.

6.9 There is an other consideration which further complicates the analysis. It is that all power is not created equal; not only because of the different time of day, and consequently, different value with which it may be created but also because of location. The "deeper" into the system, i.e., the closer to the point of use, the power is produced, the higher its value. Properly, this aspect would also have to be considered in the analysis. 3/

6.10 Wind power can in certain instances serve to displace conventional capacity. The extent to which it may do so will depend on the variability of the wind regime and the level of power firmness desired to meet load requirements. As discussed in the previous chapter, it is difficult to quantify monetarily the cost of the variability introduced by the wind machines. One way to do so is to include in the cost a provision for a storage system to provide with the wind turbine the same kind of supply reliability as alternative systems would have. Another method would be, as discussed above, to treat wind generators purely as fuel savers and not to attribute any conventional capacity savings to them. But it is quite conceivable that because of power consumption patterns, wind regime characteristics, composition of plant capacity, and other factors, the addition of a wind turbine would permit conventional capacity substitution without significantly introducing

---

1/ See "Guidelines for Marginal Cost Analysis of Power Systems," Energy Department Paper No. 18, EGY Library, World Bank, 1984

2/ See "Economic Benefits of Power Supply", Energy Department Paper No. 25, EGY Library, World Bank, September 1985.

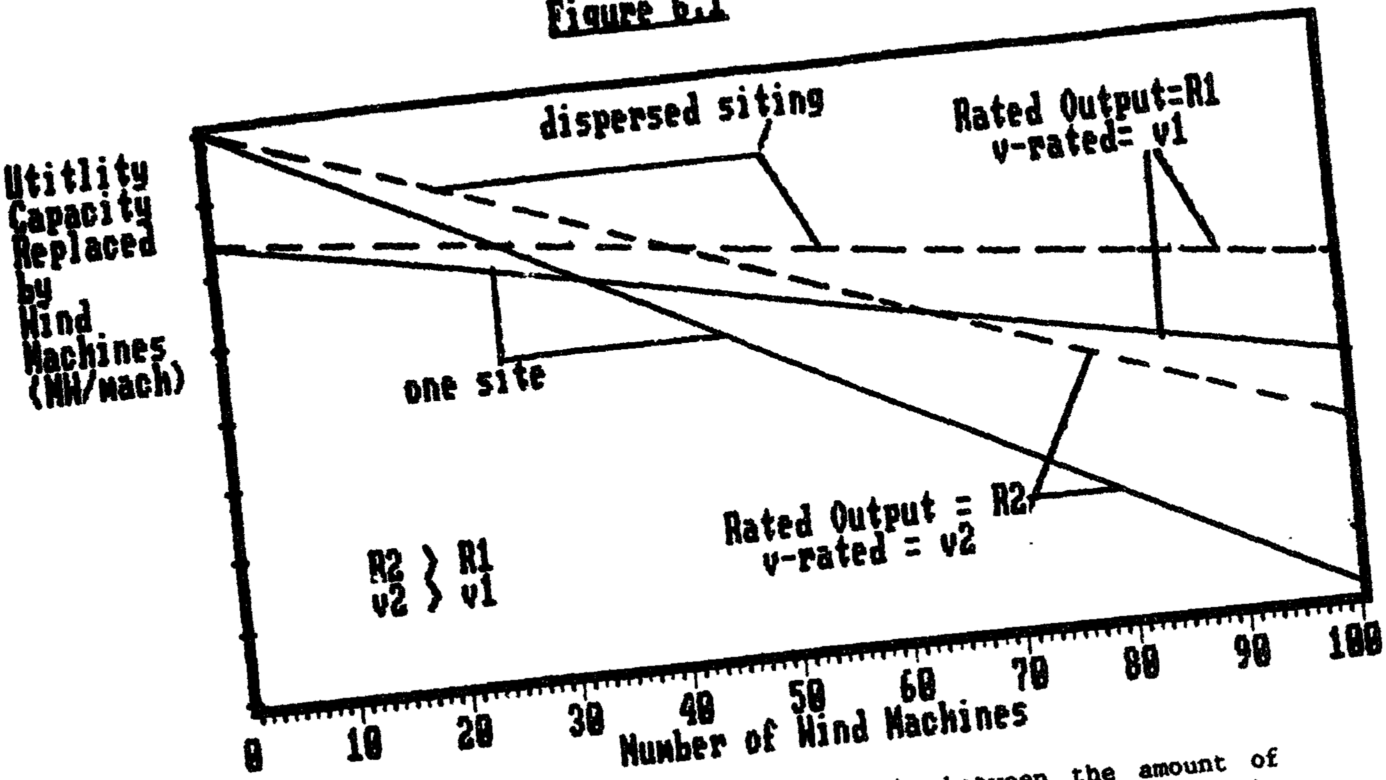
3/ See "Small Hydroelectric Components in Irrigation and Water Supply Projects," Energy Policy and Advisory Division, Energy Department, The World Bank, July 1985.

greater variability so that no additional costs would be associated with this factor. Based on experience thus far and extrapolations carried out, it is generally accepted that as long as wind power capacity remains below about 10% of total capacity, problems related to variability and unpredictability remain insignificant. This 10% level can thus be thought of as a safe, upper boundary at present which may at a later date be revised upward on the basis of newly acquired experience.

6.11 The extent to which WECS can free the need for conventional capacity will depend on two primary factors. These are: i) the amount of wind power capacity already installed, and ii) the rated output of the individual wind machines being installed. As the size of the installed wind power capacity increases relative to total system capacity, the significance of the above mentioned variability factor increases and therefore additional wind power will be less able to serve as a substitute for conventional capacity, since this conventional capacity will increasingly be needed as back-up to maintain a specific level of supply reliability. The power rating of wind machines also affects the extent to which they can displace conventional capacity (see figure 6.1 on next page). When the first machine is introduced, the one with a higher rating will displace more of the conventional utility than a machine with a low power rating. As more machines are introduced, the marginal displacement impact of the higher rated power machines will decline more rapidly than for the lower rated machines because with continued introduction of the higher rated machines the overall share of capacity consisting of wind machines increases more rapidly, augmenting the above mentioned variability factor at a more rapid pace. In addition, machines which have higher ratings generally also have correspondingly higher rated wind speeds and will therefore also generally have greater output variability than wind machines with lower power ratings and rated wind speeds. This is because machines with lower rated power and windspeeds generally operate closer to their rated output; an area where the power curve is flatter, reflecting less variability in output.

6.12 Thus, the extent to which a wind machine can displace conventional capacity will be inversely related to the variability of its power supply which in turn, ceteris paribus, is generally a function of its rated output. In addition to these factors, the pattern of siting of wind machines can also affect their ability in replacing conventional capacity. The more dispersed the wind machines are among different sites with uncorrelated windspeeds, the less the expected variance from their joint total output, and therefore, the greater their ability to replace conventional capacity. The figure below summarizes these aspects.

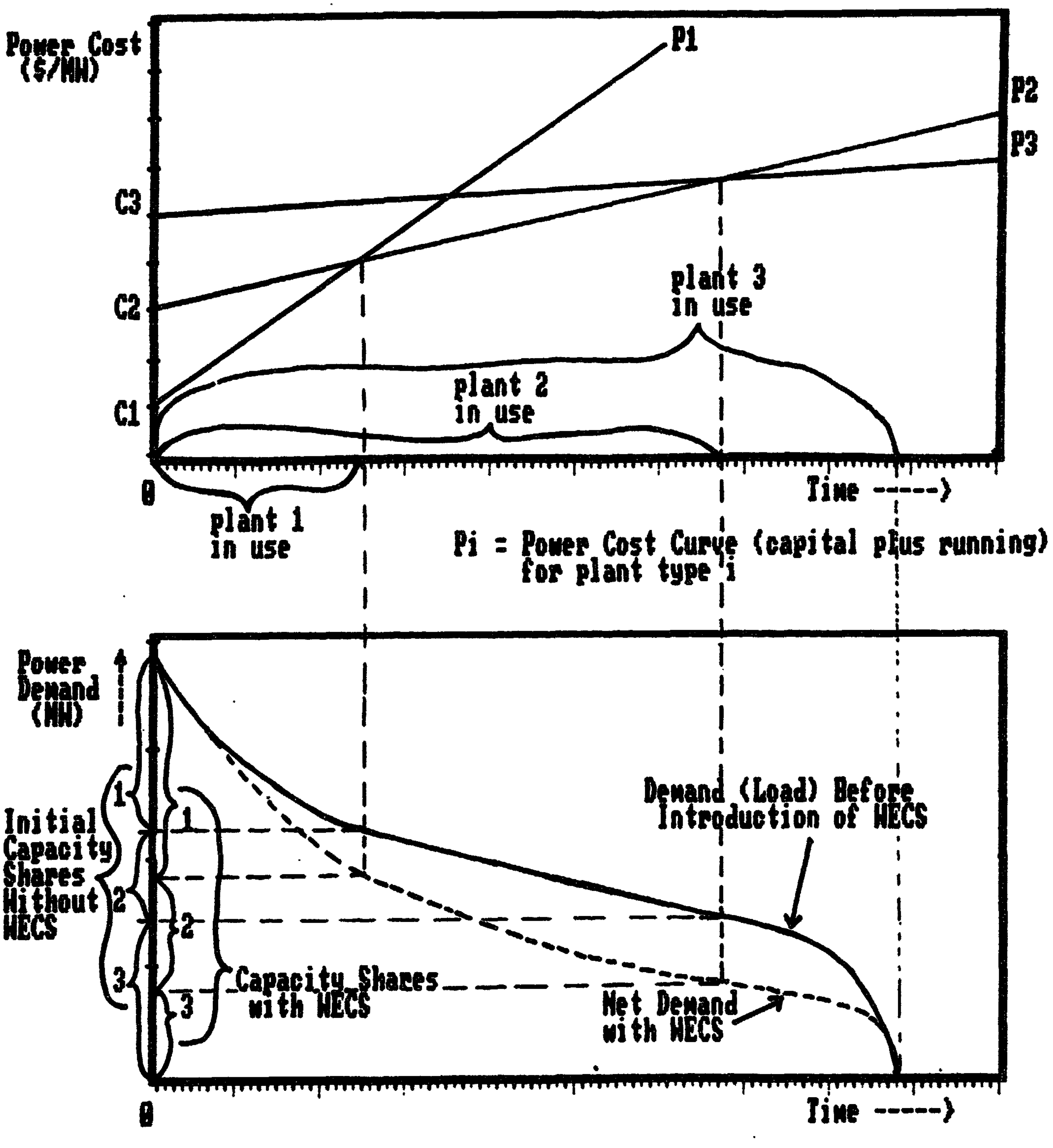
Figure 6.1



6.13 Figure 6.1 shows the relationship between the amount of existing plant capacity which can be substituted per wind machine and the number of wind machines already introduced. It shows clearly a declining marginal deferment of conventional capacity per wind machine introduced as the number of wind machines increases and correspondingly the total capacity in terms of wind power increases. The two solid lines show the hypothetical, but representative, relationship for wind machines which differ in rated output. As can be seen, the conventional capacity credit due to the higher rated machine declines more rapidly with the introduction of more wind capacity than for the lower rated machine. The dotted lines show this relationship in the case where the machines are dispersed between various sites. As can be seen in the graph, everything else being equal, wind penetration can be greater with a dispersed distribution of wind machines since the variabilities due to wind pattern become less.

6.14 Finally, the introduction of WECS into a conventional electric power supply system has an additional benefit. This benefit results from a re-optimization of sub-system plant types. A typical electric utility comprises various types of power generating plants. For example, it is likely to have some power generated by means of low capital cost plants that use high cost fuels, such as for example gas turbines. It will also have some power generated by more capital intensive type plants which use less expensive fuels such as for example hydro and nuclear. Now, as wind power is introduced into this utility, cost minimization strategies will dictate a change in the relative sizes of these plants away from the more expensive structures towards the less expensive ones. This will involve positive savings to the utility. The figure below shows this impact graphically.

Figure 6.2


Power Cost ($/MW)
P1
P2
P3
C3
C2
C1
0
plant 1 in use
plant 2 in use
plant 3 in use
Time -----)
Pi = Power Cost Curve (capital plus running) for plant type i
Power Demand (MW)
Initial Capacity Shares Without WECS
1
2
3
Capacity Shares with WECS
Demand (Load) Before Introduction of WECS
Net Demand with WECS
0
Time -----)

6.15 The top graph in figure 6.2 shows the relationship between power cost and capacity output for various plant types. Plant type 1 can be thought of as a low capital cost/high fuel cost plant such as the gas turbine (peak plant). Similarly, plant 2 would correspond to a coal plant and plant 3 to a nuclear plant, with high capital cost but relatively low fuel cost. As can be seen from the graph, plant 3 would be used all of the time because it has the lowest running costs. Plant 2 would be in operation less of the time but more than would plant 1. The bottom graph of figure 6.2 shows the power demand distribution. The solid line shows the power demand profile before any WECS are introduced. The dotted line shows the net power demand on plants 1, 2, and 3 after the introduction of WECS. The power provided by the WECS is subtracted from the total demand to arrive at this net demand. Now considering the solid power demand line (i.e. before the introduction of WECS), the intersections of this line with the corresponding cross-over points on the time axis in the top graph, give the proportion of the optimal capacities of the various plant types before WECS are introduced. These are shown on the left side of the Y axis. The corresponding points on the dotted power demand curve (i.e. with WECS) show the optimal capacity shares of the various plants with the WECS. These are shown on the right side of the Y axis. As can be seen, the proportion of time that plant 1 will be used does not change but the amount of power produced from it increases, implying a greater capacity of this plant type; similarly for plant 2. However, the size of plant 3 with high capital cost will now need to be reduced relative to the others.

6.16 Thus, in this example the introduction of WECS has allowed the utility company to alter the relative shares of the various conventional plant types away from the more capital intensive ones towards the lower capital cost one; i.e. overall conventional capital investment can be reduced. It should be mentioned that implicit in this example and the results is the fact that WECS supply base load as well as peaking power.

CHAPTER 7. ENVIRONMENTAL ASPECTS

Introduction

7.1 In the past, wind energy was universally recognized as a clean form of energy: pollution free. It is still seen as that by many, but the fact is that as its use became more widespread, experience has shown that it sometimes has a notable impact on the environment. It is therefore important to be aware of the potential negative environmental impact from WECS, in order to include plans to avoid or minimize it. Although the environmental impact of windmills tends to be predominant in the context of larger wind generators or clusters of windmills, they are experienced to some extent with any wind machine. There are basically four types of "impacts" related to WECS: visual, noise, ecological, and electro-magnetic. The characteristics of these impacts are discussed in turn.

Visual Impact

7.2 There are two distinct types of "impacts" which fall under this category. One is the effect of large wind turbines or clusters of turbines, on the natural beauty of landscapes. It is often the case that the best sites for wind machines are in wide open areas or on top of hills where wind speeds tend to be greater. At these sites, WECS stand out sharply, making them even more blatant to eyes scanning the scenic sites. In California, where rows of wind generators have been set up, stretching great distances, authorities have been receiving increasing number of complaints from people about the disturbing impact of these WECS on the quality of the landscape. Furthermore, since windmills involve a large rotating mechanism, they are more eye-catching than some other structures of equal size. In other words, the impact is even more pronounced than it would have been for some other similarly sized non-rotating structure. Thus, in planning the siting of WECS, this visual impact should be kept in mind.

7.3 There is a second type of visual impact caused by wind machines. This one pertains predominantly to the larger wind generators and involves the shadow of the rotating blades as they cause an annoying flicker on the eyes of passers-by or into the homes of people who are within the line of shadow from the blades. Because of the sun's east-west movement during the course of a day and its north-south movement in the course of a year, the total area affected at one time or another by this shadow flicker can be quite large.

Noise Impact

7.4 This type of impact applies primarily to the large WECS generators although some small windmill (pumps) are also known to make some annoying noises. Clearly, the importance of this noise pollution will depend on the location of the machine (close to or far from people) and the existing background noise level at the site. In fact, it is the intensity level of noise due to the WECS relative to the background noise that ultimately matters.

Ecological Impact

7.5 Here again there are two sub-categories. One is the direct impact of WECS on wild life, in particular, birds. Claims have been made that the rotating blades have caused more than incidental casualties on birds flying by. On the other hand, many researchers following the performance of WECS at test grounds claim that they have never experienced such an occurrence; that in fact the birds seem well acclimated to the presence of the WECS and fly around and between the rotating blades with great ease. More information would be needed before one can establish whether or not this impact aspect is of real concern or not.

7.6 The second ecological impact type is less direct and more of a concern for the future when use of WECS may become more widespread. It involves the effect of large clusters of WECS in altering the existing wind flows and thereby altering the climatological characteristics of the area. This factor clearly would become relevant only for large expanded wind farms and its severity has not been verified in actuality but is based on theoretical deduction. Although this impact is not expected to be significant because of the limited sizes of wind farms envisioned in the near future, it is mentioned here for the sake of completeness.

Electromagnetic Impact

7.7 The rotating blades of WECS which are often made of metallic material can cause interference in the use of electromagnetic communication devices, such as radios, television, satellite services, radars, etc. In some of these communication applications, this impact from WECS can be more than just a nuisance. For example, because airports are often located in windy, open spaced areas for which wind information is available, it is not uncommon for areas in the vicinity of airports to be prime candidates for WECS siting. These WECS could cause electromagnetic interference on airport communication and airplane radar systems which could be a hazard. It is important that the actual potential impact of this type be carefully evaluated before installation at a particular site begins.

Conclusion

7.8 On a large scale, and particularly in the context of electricity generation, WECS have been on stage for a very short time. Nevertheless, at what will probably still be shown to be a very small scale, WECS are already beginning to cause some concern with respect to their impact on the environment. Proper planning, in terms of site selection and machine characteristics can help minimize the potential impact from wind machines. This is important to preserve the environment and the image of WECS as a pollution free energy technology which is both reliable and renewable.

CHAPTER 8. CONCLUSION

8.1 The previous chapters provide information and techniques which could be helpful when analyzing the possibility for exploitation of wind energy. Whether or not wind will be the most appropriate energy form for any particular energy need will depend ultimately on the relative economic attractiveness of the alternatives available. However, unless site selection, choice of WECS size and design, and other factors important to the performance of wind energy are properly carried out, the results of the economic analysis exercise will not correctly and fully reflect the qualities of the wind alternative.

8.2 For example, particularly in the case of wind pumping for developing countries, costs for wind mills (especially the 'American' type) can seem very high. When these costs are used to evaluate the economics of a particular pumping need the results are often discouraging. However, simpler, lighter models have been designed which can do the job and which can be produced locally, using local materials, at a fraction of the cost of the more expensive types. Thus, it is important that this possibility be considered also. On the other hand there are other costs which also must be considered and which in fact work against the wind energy option. For example, the special experience in California with wind farms for electricity generation has indicated that the overhead and management costs of wind farms can be very high. These overhead costs, related to the development of the windfarm, can significantly increase the overall cost per kW for the installed system. In some instances in the case of California, these development overhead costs have reached levels of 50% of the equipment cost. Although California is a special case because of the importance of third party financing and special tax-credit incentives, the point remains that one should not overlook these overhead costs related to the development of the wind system. In addition, the operation and maintenance costs of windgenerators have been estimated at about US$ 0.015 per kWh. Thus, when looking at costs for wind electricity as was done in Chapter 5, all these costs should properly be included in the analysis.

8.3 Finally, the possibility for wind energy must be explored for each case individually. It is not possible to generalize about where it is most likely to have technical and economic success. Clearly, areas with excellent wind conditions are prime candidates. But if other energy sources are abundant and inexpensive there or if there is no need for additional energy, wind energy will have no purpose. In fact, it is usually the case when one compares the patterns of wind conditions with that of energy demand at one location that the two don't match. For wind energy to succeed would then require a storage facility or load management. Storage systems were discussed in chapter 5. Load management involves regulating demand for energy through prices or other means to better match the fluctuations in energy demand to those in power output.

8.4 If properly planned, designed, and implemented wind energy can undoubtedly be the most economical energy source for specific needs. Its decentralized nature means that it can reach isolated areas and villages immediately. Many areas in developing countries lie outside the scope of national grid expansion plans for at least the next 20 years. Such areas could have immediate cost effective electrification through wind energy with potentially dramatic developmental impact. On a smaller scale, small machines have been used in isolated areas to charge batteries for use in small appliances (radios, communication etc.). Some small wind machines of 50 to 200 W costing about $400 to $600 have been used for small electric loads in isolated area; they are generally much more economical than photovoltaics.

8.5 Thus, the potential for wind energy is seen to be significant. The spectrum of possibilities includes small systems to supply small amounts of electric or pumping power for isolated communities to large electric wind systems feeding the national grid. During the 'energy crisis' of the mid 1970's, this wind energy potential was seen as a significant possible contributor to ease the long run pressure on energy demand. With the more plentiful availability of oil and its lower price, interest in wind energy has diminished some. However, the advent of large scale commercial wind farms in California and elsewhere, along with the continued external debt problem facing many developing countries and the conviction in many that the existing situation of plentiful oil supplies is only a temporary phenomenon, has sustained interest in this technology. What is important to note is that even in the present situation of plentiful and inexpensive oil supplies, wind energy is often the most cost effective energy source.

SOURCES OF TEXT FIGURES/TABLES

Figures 3.1, 3.2, and 3.3. from US Department of Energy, "Wind Energy for a Developing World."

Figure 5.1 from CWD "Catalog of Wind Machines".

Figure 5.2 from CWD "Holland and Wind Energy."

Table 6.1 from Imperial College, "Principles of Wind Energy Conversion."

Table 5.10 and Figures 6.1 and 6.2 from Imperial College, "Principles of Wind Energy Conversion."

Remainder of figures and tables are from Bank staff estimates and sources.

REFERENCES

Both, D., Stelt L.E.R van der, Catalogue of wind machines, Steering Committee Wind Energy Development, March 1983.

Consultancy Services Wind Energy Developing Countries, "Holland and Wind Energy; Efforts for a Worldwide Application," October 1984.

Consultancy Services Wind Energy Developing Countries "Catalog of Windmachines," March 1983

Dosik R. S., Internal memo re Wind Turbine Cost Quotations from California Windfarms, December 21, 1984.

Dosik, R.S. and Moreno, R., Internal memo re "Wind Electricity Generation - A Status Report," May 1985.

Electric Power Research Institute, "Cost Estimates for Large Wind Turbines," November 1983.

Fish, J., Internal memo re "Wind Turbines - Status Report," February 4, 1985.

Fraenkel, Peter L., Small Scale Renewable Energy Becomes Respectable, CME February, 1985.

Frandsen, Sten (ed.), "Recommended Practices for Wind Turbine Testing and Evaluation", International Energy Agency Programme, 1982.

Imperial College, "Principles of Wind Energy Conversion"--Course Notes, July, 1985.

Little, Arthur D., for Electric Power Research Institute, "Wind Turbine Performance Assessment," April 1984.

Moreno, R., Internal memo re "A Comparative Analysis of Four Studies on the Relative Economics of Wind, Solar, and Diesel Pumping," November 1984.

Mueller, A.M.(ILRI) and Jansen, W.A.M (DHV), "Cost Analysis of water-lifting windmills and diesel-powered pumps used for small-scale irrigation," Consultancy Services Wind Energy Developing Countries, June 1984.

Solar Energy Research Institute, "Foreign Applications and Export Potential for Wind Energy Systems," December 1982.

United States Department of Energy, "Wind Energy for a Developing World."

World Bank, "Guidelines for Marginal Cost Analysis of Power System", Energy Department Paper No. 18, 1984

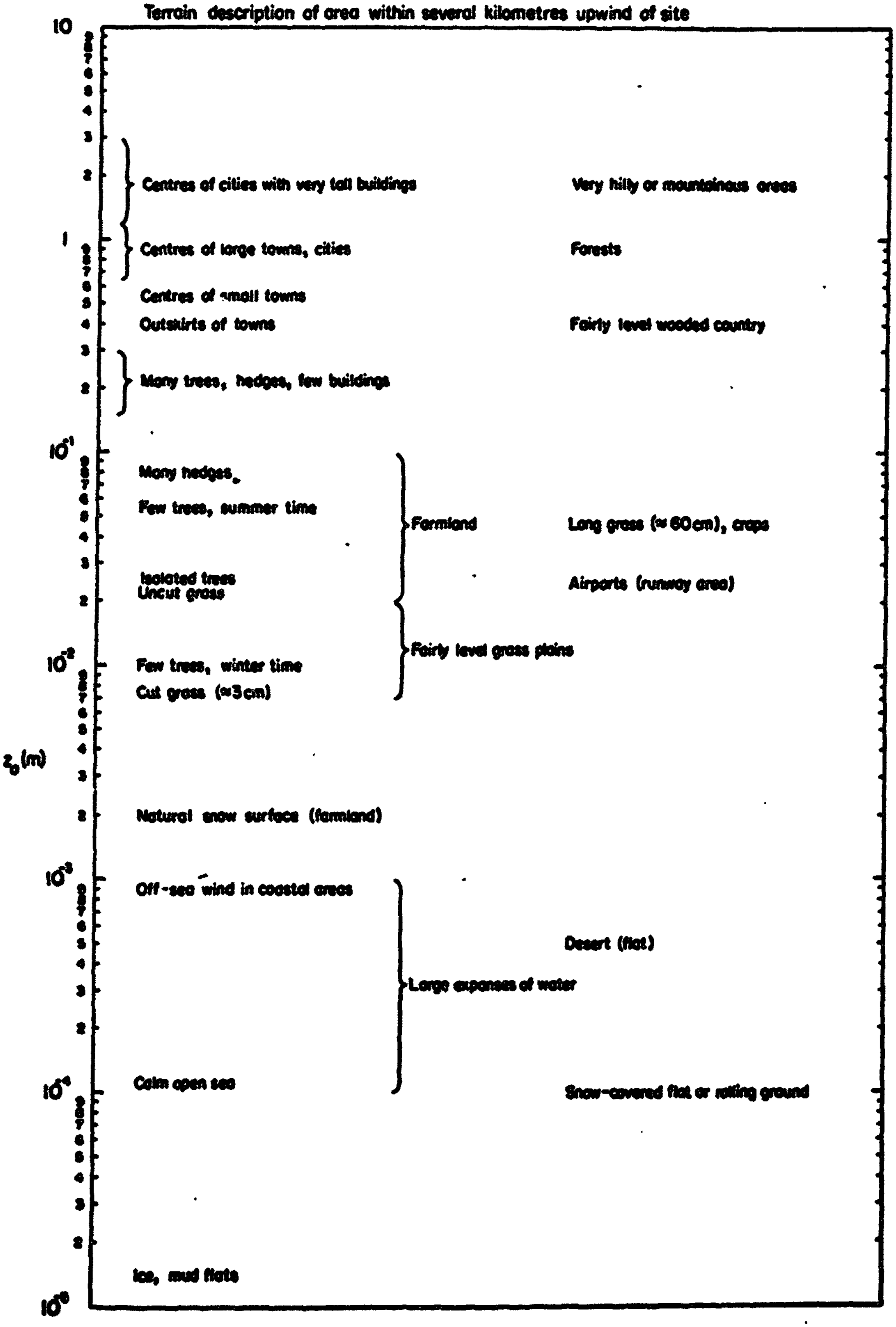
World Bank, "Small Hydroelectric Components in Irrigation and Water Supply Projects", Energy Policy and Advisory, Energy Department, July 1985

Appendix 1

CONVERSION BETWEEN WIND SPEEDS AND POWER DENSITY

m/s	mi/hour	km/hour	knots	Power Density (Watts/m2)
1.00	2.23	3.60	1.94	0.62
2.00	4.46	7.20	3.89	4.96
3.00	6.70	10.80	5.83	16.74
4.00	8.93	14.40	7.78	39.68
5.00	11.16	18.00	9.72	77.50
6.00	13.39	21.60	11.66	133.92
7.00	15.62	25.20	13.61	212.66
8.00	17.86	28.80	15.55	317.44
9.00	20.09	32.40	17.49	451.98
10.00	22.32	36.00	19.44	620.00
11.00	24.55	39.60	21.38	825.22
12.00	26.78	43.20	23.33	1071.36
13.00	29.02	46.80	25.27	1362.14
14.00	31.25	50.40	27.21	1701.28
15.00	33.48	54.00	29.16	2092.50
16.00	35.71	57.60	31.10	2539.52
17.00	37.94	61.20	33.05	3046.06
18.00	40.18	64.80	34.99	3615.84
19.00	42.41	68.40	36.93	4252.58
20.00	44.64	72.00	38.88	4960.00
21.00	46.87	75.60	40.82	5741.82
22.00	49.10	79.20	42.76	6601.76
23.00	51.34	82.80	44.71	7543.54
24.00	53.57	86.40	46.65	8570.88
25.00	55.80	90.00	48.60	9687.50
26.00	58.03	93.60	50.54	10897.12
27.00	60.26	97.20	52.48	12203.46
28.00	62.50	100.80	54.43	13610.24
29.00	64.73	104.40	56.37	15121.18
30.00	66.96	108.00	58.32	16740.00
31.00	69.19	111.60	60.26	18470.42
32.00	71.42	115.20	62.20	20316.16
33.00	73.66	118.80	64.15	22280.94
34.00	75.89	122.40	66.09	24368.48
35.00	78.12	126.00	68.03	26582.50
36.00	80.35	129.60	69.98	28926.72
37.00	82.58	133.20	71.92	31404.86
38.00	84.82	136.80	73.87	34020.64
39.00	87.05	140.40	75.81	36777.78
40.00	89.28	144.00	77.75	39680.00
41.00	91.51	147.60	79.70	42731.02
42.00	93.74	151.20	81.64	45934.56
43.00	95.98	154.80	83.59	49294.34
44.00	98.21	158.40	85.53	52814.08
45.00	100.44	162.00	87.47	56497.50
46.00	102.67	165.60	89.42	60348.32
47.00	104.90	169.20	91.36	64370.26
48.00	107.14	172.80	93.30	68567.04
49.00	109.37	176.40	95.25	72942.38

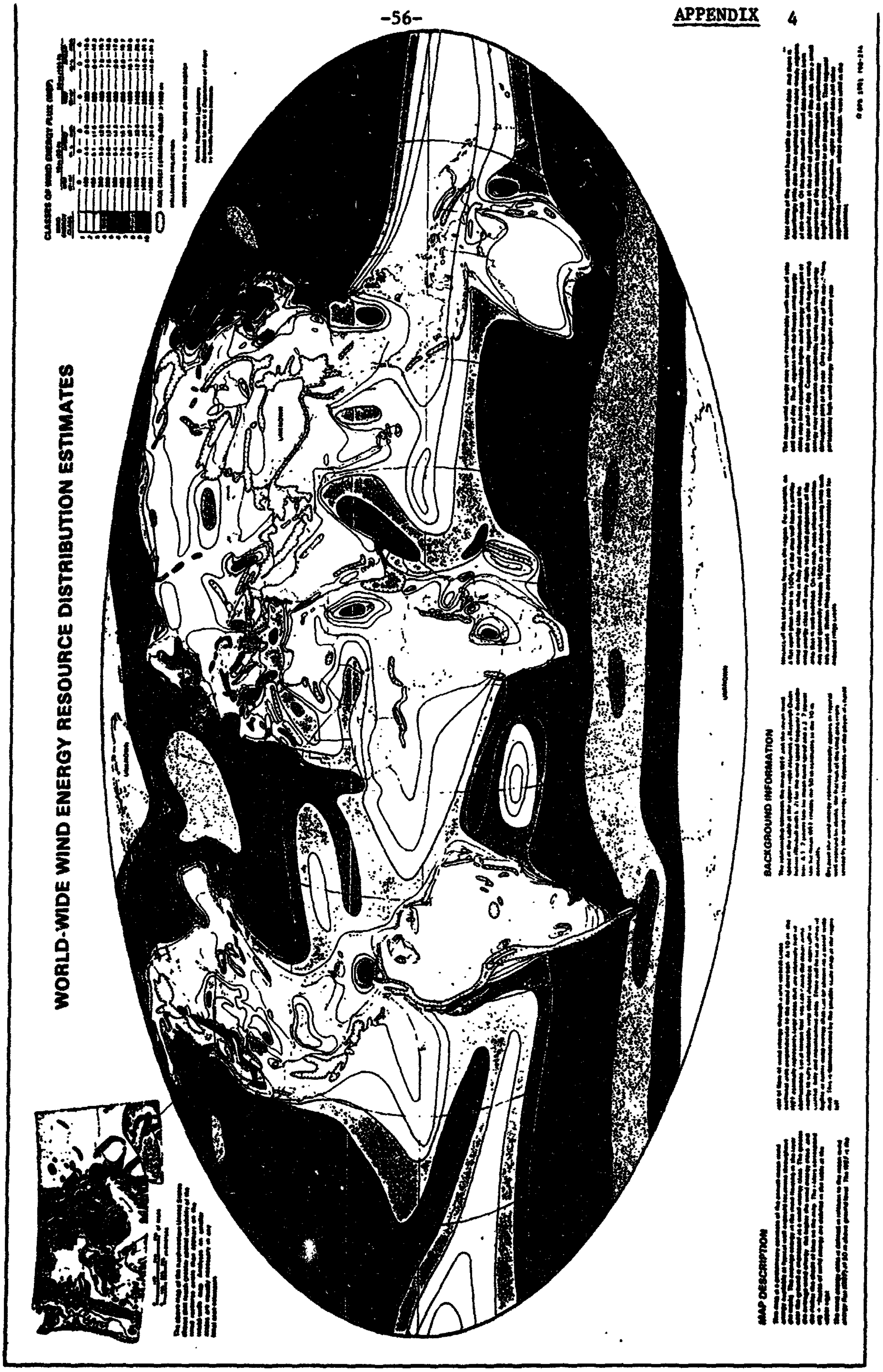
SURFACE ROUGHNESS INDEX (R)



Appendix 3

Rated Output, Windspeed, and Rotor diameter for various models of WECS

Rated Output in (kW)	Rated Windspeed (m/s)	Rotor Diameter (m)	Estimated Power (kW) 1/
2.50	11.60	2.40	1.77
4.00	10.10	4.10	3.40
4.50	10.00	5.50	5.94
6.00	11.00	5.50	7.91
6.80	7.80	7.50	5.24
8.00	11.60	4.30	5.67
9.00	11.00	6.10	9.72
10.00	8.00	8.00	6.43
10.00	10.00	8.00	12.57
10.00	8.90	10.00	13.84
10.00	10.00	7.70	11.64
10.00	10.00	5.50	5.94
11.00	8.00	11.50	13.30
12.00	11.00	6.70	11.73
12.00	11.60	6.00	11.03
15.00	11.00	7.30	13.93
15.00	12.00	7.00	16.63
15.00	11.00	8.00	16.73
20.00	9.50	9.70	15.84
25.00	11.60	9.75	29.14
26.00	11.60	7.70	18.17
30.00	9.00	12.00	20.61
36.00	10.00	13.00	33.18
40.00	11.00	10.70	29.92
40.00	11.60	11.50	40.53
40.00	9.00	19.50	54.43
40.00	9.00	17.70	44.85
45.00	9.00	16.00	36.64
55.00	12.00	15.00	76.34
58.00	8.00	24.00	57.91
60.00	11.20	16.00	70.62
100.00	11.00	18.00	84.68
100.00	11.40	21.80	138.25
100.00	11.60	14.80	67.13
150.00	12.50	21.80	182.26


WORLD-WIDE WIND ENERGY RESOURCE DISTRIBUTION ESTIMATES
CLASSES OF WIND ENERGY FLUX
MAP DESCRIPTION
BACKGROUND INFORMATION

Appendix 5

COSTS PER M3 WATER PUMPED ($/M3)

Assumptions:

volume (m3/day)= 60
life (years)= 10
discount rate= 10%
amort. factor= 0.163
O&M as % of cost= 5%
no. days pumped= 365

average wind speed (m/s)	water lifting head (m)	Cost ($) per m2 rotor area			
		$100	$200	$400	$600
2	1	0.0083	0.0166	0.0331	0.0497
	5	0.0414	0.0828	0.1656	0.2485
	10	0.0828	0.1656	0.3313	0.4969
	20	0.1656	0.3313	0.6625	0.9938
	40	0.3313	0.6625	1.3251	1.9876
3	1	0.0025	0.0049	0.0098	0.0147
	5	0.0123	0.0245	0.0491	0.0736
	10	0.0245	0.0491	0.0982	0.1472
	20	0.0491	0.0982	0.1963	0.2945
	40	0.0982	0.1963	0.3926	0.5889
4	1	0.0010	0.0021	0.0041	0.0062
	5	0.0052	0.0104	0.0207	0.0311
	10	0.0104	0.0207	0.0414	0.0621
	20	0.0207	0.0414	0.0828	0.1242
	40	0.0414	0.0828	0.1656	0.2485
5	1	0.0005	0.0011	0.0021	0.0032
	5	0.0027	0.0053	0.0106	0.0159
	10	0.0053	0.0106	0.0212	0.0318
	20	0.0106	0.0212	0.0424	0.0636
	40	0.0212	0.0424	0.0848	0.1272
6	1	0.0003	0.0006	0.0012	0.0018
	5	0.0015	0.0031	0.0061	0.0092
	10	0.0031	0.0061	0.0123	0.0184
	20	0.0061	0.0123	0.0245	0.0368
	40	0.0123	0.0245	0.0491	0.0736
7	1	0.0002	0.0004	0.0008	0.0012
	5	0.0010	0.0019	0.0039	0.0058
	10	0.0019	0.0039	0.0077	0.0116
	20	0.0039	0.0077	0.0155	0.0232
	40	0.0077	0.0155	0.0309	0.0464
8	1	0.0001	0.0003	0.0005	0.0008
	5	0.0006	0.0013	0.0026	0.0039
	10	0.0013	0.0026	0.0052	0.0078
	20	0.0026	0.0052	0.0104	0.0155
	40	0.0052	0.0104	0.0207	0.0311

Appendix 6

Some Wind Machines with their Specifications 1/

Make	Type 2/	Rotor Diameter (m)	Oper. wind speeds (m/s)			Rated Power (kW)
			cut-in	cut-out	rated	
WIND PUMPS						
Aermotor (USA)	H	1.8	4	11	9	
Aermotor (USA)	H	3	4	11	9	
Aermotor (USA)	H	4.9	4	11	9	
Enermecanica (Peru)	H	4.5	4	15	7	
South. Cross (Aust)	H	4.3	3.2	11	8.9	
South. Cross (Aust)	H	7.6	3.2	11	8.9	
Kijito (Kenya)	H	2.44	2	11.2	-	
Kijito (Kenya)	H	7.32	2	11.2	-	
Sparco (Holland)	H	10	3.5	20	7.5	
Sparco (Holland)	H	16	3.5	20	7.5	
Ujuzi (Tanzania)	H	5	2.5	12	6-9	
Sanit (Thailand)	H	3	0.5	12	-	
Sanit (Thailand)	H	6.1	0.5	12	-	
Reymill (Philip.)	H	3.05	3	-	-	
Reymill (Philip.)	H	4.3	3	-	-	
WIND GENERATORS						
Aeroman (W. Germ)	H	11	3.5	24	8.5	11
Airlite (U.K)	H	1.8	3	20	8.5-11	0.2
Airlite (U.K)	H	6.1	3	20	8.5-11	5
Astral (USA)	H	7.7	3.5	-	10	10
Carter (USA)	H	9.75	3.6	none	11.6	25
DanskVindmolle(Denm	H	12	5	30	20	30
Howden (Scotland)	H	15	4	30	15	60
Howden (Scotland)	H	31	5	26	13	330
Mehrkam (USA)	H	18	3	17.5	11	100
McDonell (USA)	H	17.7	5.4	-	9	40
Tumac (USA)	V	7.5	4.7	-	7.8	6.8
Windmatic (Denmark)	H	14.5	5	>48	12	55
VAWT Power (USA)	V	17.9	5.5	27.5	17	185
Volund (Holland)	H	8	4	-	11	15
Wesco (U.K.)	H	3	3.5	50	10	1.2
Wesco (U.K.)	H	5.5	5	50	10	4.5

1/ These are only a few examples and are in no way all inclusive

2/ H= Horizontal axis and V= Vertical axis machines

ENERGY SERIES PAPERS

No. 1 Energy Issues in the Developing World, February 1988.

No. 2 Review of World Bank Lending for Electric Power, March 1988.

No. 3 Some Considerations in Collecting Data on Household Energy Consumption, March 1988.

No. 4 Improving Power System Efficiency in the Developing Countries through Performance Contracting, May 1988.

No. 5 Impact of Lower Oil Prices on Renewable Energy Technologies, May 1988.

No. 6 A Comparison of Lamps for Domestic Lighting in Developing Countries, June 1988.

No. 7 Recent World Bank Activities in Energy (Revised October 1989).

No. 8 A Visual Overview of the World Oil Markets, July 1988.

No. 9 Current International Gas Trades and Prices, November 1988.

No. 10 Promoting Investment for Natural Gas Exploration and Production in Developing Countries, January 1988.

No. 11 Technology Survey Report on Electric Power Systems, February 1989.

No. 12 Recent Developments in the U.S. Power Sector and Their Relevance for the Developing Countries, February 1989.

No. 13 Domestic Energy Pricing Policies, April 1989.

No. 14 Financing of the Energy Sector in Developing Countries, April 1989.

No. 15 The Future Role of Hydropower in Developing Countries, April 1989.

No. 16 Fuelwood Stumpage: Considerations for Developing Country Energy Planning, June 1989.

No. 17 Incorporating Risk and Uncertainty in Power System Planning, June 1989.

No. 18 Review and Evaluation of Historic Electricity Forecasting Experience, (1960-1985), June 1989.

No. 19 Woodfuel Supply and Environmental Management, July 1989.

No. 20 The Malawi Charcoal Project - Experience and Lessons, January 1990.

No. 21 Capital Expenditures for Electric Power in the Developing Countries in the 1990s, February 1990.

No. 22 A Review of Regulation of the Power Sectors in Developing Countries, February 1990.

No. 23 Summary Data Sheets of 1987 Power and Commercial Energy Statistics for 100 Developing Countries, March 1990.

No. 24 A Review of the Treatment of Environmental Aspects of Bank Energy Projects, March 1990.

No. 25 The Status of Liquified Natural Gas Worldwide, March 1990.

No. 26 Population Growth, Wood Fuels, and Resource Problems in Sub-Saharan Africa, March 1990.

No. 27 The Status of Nuclear Power Technology - An Update, April 1990.

No. 28 Decommissioning of Nuclear Power Facilities, April 1990.

No. 29 Interfuel Substitution and Changes in the Way Households Use Energy: The Case of Cooking and Lighting Behavior in Urban Java, October 1990.

No. 30 Regulation, Deregulation, or Reregulation--What is Needed in LDCs Power Sector? July 1990.

No. 31 Understanding the Costs and Schedules of World Bank Supported Hydroelectric Projects, July 1990.

No. 32 Review of Electricity Tariffs in Developing Countries During the 1980s, November 1990.

No. 33 Private Sector Participation in Power through BOOT Schemes, December 1990.

No. 34 Identifying the Basic Conditions for Economic Generation of Public Electricity from Surplus Bagasse in Sugar Mills, April 1991.

No. 35 Prospects for Gas-Fueled Combined-Cycle Power Generation in the Developing Countries, May 1991.

No. 36 Radioactive Waste Management - A Background Study, June 1991.

No. 37 A Study of the Transfer of Petroleum Fuels Pollution, July 1991.

No. 38 Improving Charcoaling Efficiency in the Traditional Rural Sector, July 1991.

No. 39 Decision Making Under Uncertainty - An Option Valuation Approach to Power Planning, August 1991.

No. 40 Summary 1988 Power Data Sheets for 100 Developing Countries, August 1991.

No. 41 Health and Safety Aspects of Nuclear Power Plants, August 1991.

No. 42 A Review of International Power Sales Agreements, August 1991.

No. 43 Guideline for Diesel Generating Plant Specification and Bid Evaluation, September 1991.

No. 44 A Methodology for Regional Assessment of Small Scale Hydro Power, September 1991.

No. 45 Guidelines for Assessing Wind Energy Potential, September 1991.

For copies, please call extension 33616 (afternoons only).

INDUSTRY SERIES PAPERS

No. 1 Japanese Direct Foreign Investment: Patterns and Implications for Developing Countries, February 1989.

No. 2 Emerging Patterns of International Competition in Selected Industrial Product Groups, February 1989.

No. 3 Changing Firm Boundaries: Analysis of Technology-Sharing Alliances, February 1989.

No. 4 Technological Advance and Organizational Innovation in the Engineering Industry, March 1989.

No. 5 Export Catalyst in Low-Income Countries, November 1989.

No. 6 Overview of Japanese Industrial Technology Development, March 1989.

No. 7 Reform of Ownership and Control Mechanisms in Hungary and China, April 1989.

No. 8 The Computer Industry in Industrialized Economies: Lessons for the Newly Industrializing, February 1989.

No. 9 Institutions and Dynamic Comparative Advantage Electronics Industry in South Korea and Taiwan, June 1989.

No. 10 New Environments for Intellectual Property, June 1989.

No. 11 Managing Entry Into International Markets: Lessons From the East Asian Experience, June 1989.

No. 12 Impact of Technological Change on Industrial Prospects for the LDCs, June 1989.

No. 13 The Protection of Intellectual Property Rights and Industrial Technology Development in Brazil, September 1989.

No. 14 Regional Integration and Economic Development, November 1989.

No. 15 Specialization, Technical Change and Competitiveness in the Brazilian Electronics Industry, November 1989.

INDUSTRY SERIES PAPERS *cont'd*

No. 16 Small Trading Companies and a Successful Export Response: Lessons From Hong Kong, December 1989.

No. 17 Flowers: Global Subsector Study, December 1989.

No. 18 The Shrimp Industry: Global Subsector Study, December 1989.

No. 19 Garments: Global Subsector Study, December 1989.

No. 20 World Bank Lending for Small and Medium Enterprises: Fifteen Years of Experience, December 1989.

No. 21 Reputation in Manufactured Goods Trade, December 1989.

No. 22 Foreign Direct Investment From the Newly Industrialized Economies, December 1989.

No. 23 Buyer-Seller Links for Export Development, March 1990.

No. 24 Technology Strategy & Policy for Industrial Competitiveness: A Case Study of Thailand, February 1990.

No. 25 Investment, Productivity and Comparative Advantage, April 1990.

No. 26 Cost Reduction, Product Development and the Real Exchange Rate, April 1990.

No. 27 Overcoming Policy Endogeneity: Strategic Role for Domestic Competition in Industrial Policy Reform, April 1990.

No. 28 Conditionality in Adjustment Lending FY80-89: The ALCID Database, May 1990.

No. 29 International Competitiveness: Determinants and Indicators, March 1990.

No. 30 FY89 Sector Review Industry, Trade and Finance, November 1989.

No. 31 The Design of Adjustment Lending for Industry: Review of Current Practice, June 1990.

INDUSTRY SERIES PAPERS *cont'd*

No. 32 National Systems Supporting Technical Advance in Industry: The Brazilian Experience, June 26, 1990.

No. 33 Ghana's Small Enterprise Sector: Survey of Adjustment Response and Constraints, June 1990.

No. 34 Footwear: Global Subsector Study, June 1990.

No. 35 Tightening the Soft Budget Constraint in Reforming Socialist Economies, May 1990.

No. 36 Free Trade Zones in Export Strategies, December 1990.

No. 37 Electronics Development Strategy: The Role of Government, June 1990

No. 38 Export Finance in the Philippines: Opportunities and Constraints for Developing Country Suppliers, June 1990.

No. 39 The U.S. Automotive Aftermarket: Opportunities and Constraints for Developing Country Suppliers, June 1990

No. 40 Investment As A Determinant of Industrial Competitiveness and Comparative Advantage: Evidence from Six Countries, August 1990 *(not yet published)*

No. 41 Adjustment and Constrained Response: Malawi at the Threshold of Sustained Growth, October 1990.

No. 42 Export Finance - Issues and Directions Case Study of the Philippines, December 1990

No. 43 The Basics of Antitrust Policy: A Review of Ten Nations and the EEC, February 1991.

No. 44 Technology Strategy in the Economy of Taiwan: Exploiting Foregin Linkages and Investing in Local Capability, January 1991

No. 45 The Impact of Adjustment Lending on Industry in African Countries, June 1991.

Note: For extra copies of these papers please contact Miss Wendy Young on extension 33618, Room S-4101