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UNDERSTANDING WIND ENERGY FOR WATER PUMPING

By

James F. Manwell

Volunteers in Technical Assistance
1815 North Lynn Street, Suite 200
Arlington, Virginia 22209 USA

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PREFACE

This paper is one of a series published by Volunteers in Technical Assistance (VITA) to provide an introduction to specific state-of-the-art technologies of interest to people in developing countries. The papers are intended to be used as guidelines to help people choose technologies that are suitable to their situations. They are not intended to provide construction or implementation details. People are urged to contact VITA or a similar organization for further information and technical assistance if they find that a particular technology seems to meet their needs.

The papers in the series were written, reviewed, and illustrated almost entirely by VITA Volunteers technical experts on a purely voluntary basis. Some 500 volunteers were involved in the production of the first 100 titles issued, contributing approximately 5,000 hours of their time. VITA staff included Margaret Crouch as editor and project manager and Suzanne Brooks handling typesetting, layout, and graphics.

The author of this paper, VITA Volunteer James F. Manwell, heads the Renewable Energy Research Laboratory, Department of Mechanical Engineering, at the University of Massachusetts in Amherst. Dr. Manwell is also the co-author with his colleague Dr. Duane E. Cromack of "Understanding Wind Energy," another paper in this series.

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UNDERSTANDING WIND ENERGY FOR WATER PUMPING

I. OVERVIEW

There are many places in the world where wind energy is a good alternative power source for pumping water. These include windy areas with limited access to other forms of power. In order to determine whether wind power is appropriate for a particular situation an assessment of its possibilities and the alternatives should be undertaken. The necessary steps include the following:

1. Identify the users of the water.
2. Assess the water requirement.
3. Find the pumping height and overall power requirements.
4. Evaluate the wind resources.
5. Estimate the size of the wind machine(s) needed.
6. Compare the wind machine output with the water requirement on a seasonal basis.
7. Select a type of wind machine and pump from the available options.
8. Identify possible suppliers of machines, spare parts, repair, etc.
9. Identify alternative sources for water.
10. Assess costs of various systems and perform economic analysis to find least cost alternative.
11. If wind energy is chosen, arrange to obtain and install the machines and provide for maintenance.

II. DECISION MAKING PROCESS

The following summarizes the key aspects of these steps.

1. Identify the Users

This step seems quite obvious, but should not be ignored. By paying attention to who will use the wind machine and its water it will be possible to develop a project that can have continuing success. Questions to consider are whether they are villagers, farmers, or ranchers; what their educational level is; whether they have had experience with similar types of technology in the past; whether they have access to or experience with metal working shops. Who will be paying for the projects? Who will be owning the equipment; who will be responsible for keeping it running; and who will be benefitting most? Another important question is how many pumps are planned. A large project to supply many pumps may well be different than one looking to supply a single site.

2. Assess the Water Requirements

There are four main types of uses for water pumps in areas where wind energy is likely to be used. These are: 1) domestic use, 2) livestock watering, 3) irrigation, 4) drainage.

Domestic use will depend a great deal on the amenities available. A typical villager may use from 15 - 30 liters per day (4-8 gallons per day). When indoor plumbing is used, water consumption may increase substantially. For example, a flush toilet consumes 25 liters (6 1/2 gallons) with each use and a shower may take 230 (60 gallons.) When estimating water requirements, one must also consider population growth. For example, if the growth rate is 3 percent, water use would increase by nearly 60 percent at the end of 15 years, a reasonable lifetime for a water pump.

Basic livestock requirements range from about 0.2 liters (0.2 quart) a day for chickens or rabbits to 135 liters (36 gallons) a day for a milking cow. A single cattle dip might use 7500 liters (2000 gallons) a day.

Estimation of irrigation requirements is more complex and depends on a variety of meteorological factors as well as the types of crops involved. The amount of irrigation water needed is approximately equal to the difference between that needed by the plants and that provided by rainfall. Various techniques may be used to estimate evaporation rates, due for example to wind and sun. These may then be related to plant requirements at different stages during their growing cycle. By way of example, in one semi-arid region irrigation requirements varied from 35,000 liters (9,275 gallons) per day per hectare (2.47 acres) for fruits and vegetables to 100,000 liters (26,500 gallons) per day per hectare for cotton.

Drainage requirements are very site dependent. Typical daily values might range from 10,000 to 50,000 liters (2,650 to 13,250 gallons) per hectare.

In order to make the estimate for the water demand, each user's consumption is identified, and summed up to find the total. As will become apparent later. It is desirable to do this on a monthly basis so that the demand can be related to the wind resource.

3. Find Pumping Height and Total Power Requirement

If wells are already available their depth can be measured directly. If new wells are to be dug, depth must be estimated by reference to other wells and knowledge of ground water characteristics in the area. The total elevation, or head, that the pump must work against, however, is always greater than the static well depth. Other contributors are the well draw down (the lowering of the water table in the vicinity of the well while pumping is underway), the height above ground to which the water will be pumped (such as to a storage tank), and frictional losses in the piping. In a properly designed system the well depth and height above ground of the outlet are the most important determinants of pumping head.

The power required to pump water is proportional to its mass per unit volume, or density (1000 kg/m^3), the acceleration of gravity (g= 9.8 m/s^2, the total pumping head (m), and the volume flow rate of water (m^3/s). Power is also inversely proportional to the pump efficiency. Note that 1 cubic meter equals 1000 liters. Expressed as a formula,

$$\text{Power} = \text{Density} \times \text{Gravity} \times \text{Head} \times \text{Flow rate}$$

Example:

To pump 50 m^3 in one day (0.000579 m^3/s) up a total head of 15 m would require:

$$\text{Power} = (1000\ kg/m^3)\ (9.8 m/s^2)\ (15m)\ (.000579 m^3/s) = 85 \text{ watts.}$$

Actual power required would be more because of the less than perfect efficiency of the pump.

Sometimes needed pumped power is described in terms of daily hydraulic requirement, which is often given in the units of $m^3 \cdot m$/day. For example, in the above example the hydraulic requirement is 750 $m^3 \cdot m$ /day.

4. Evaluate Wind Resource

It is well known that the power in the wind varies with the cube of the wind speed. Thus if the wind speed doubles, the available power increases by a factor of eight. Hence it is very important to have a good understanding of the wind speed patterns at a given site in order to evaluate the possible use of a wind pump there. It is sometimes recommended that a site should have an average wind speed at the height of a wind rotor of at least 2.5 m/s in order to have potential for water pumping. That is a good rule of thumb, but by no means the whole story. First of all, one seldom knows the wind speed at any height at a prospective windmill site, except by estimate and correlation. Second, mean wind speeds generally vary with the time of day and year and it makes an enormous difference if the winds occur when water is needed.

The best way to evaluate the wind at a prospective site is to monitor it for at least a year. Data should be summarized at least monthly. This is often impossible, but there should be some monitoring done if a large wind project is envisioned. The most practical approach may be to obtain wind data from the nearest weather station (for reference) and try to correlate it with that at the proposed wind pump site. If at all possible the station should be visited to ascertain the placement of the measuring instrument (anemometer) and its calibration. Many times anemometers are placed too near the ground or are obscured by vegetation and so greatly underestimate the wind speed. The correlation with the proposed site is best done by placing an anemometer there for a relatively short time (at least a few weeks) and comparing resulting data with that taken simultaneously at the reference site. A scaling factor for the long-term data can be deduced and used to predict wind speed at the desired location.

Of course, possible locations for wind machines are limited by the placement of the wells, but a few basic observations should be kept in mind. The entire rotor should be well above the surrounding vegetation, which should be kept as low as possible for a distance of at least ten times the rotor diameter in all directions. Wind speed increases with elevation above ground, usually by 15-20 percent with every doubling of height (in the height range of most wind pumps). Because of the cubic relationship between wind speed and power, the effect on the latter is even more dramatic.

5. Estimate Wind Machine Size

A typical wind pump is shown in Figure 1. Most wind pumps have a horizontal axis (that is, the rotating shaft is parallel to the ground). Vertical axis machines, such as the Savonius rotor, have usually been less successful in practice.

In order to estimate a wind machine's size, it is first necessary to have some idea how it will perform in real winds. As previously mentioned, the power in wind varies with the cube of the wind speed. It is also proportional to the density of the air. Atmospheric density is 1.293 kg/m^3 at sea level at standard conditions but is affected by temperature and pressure. The power that a wind machine produces, in addition, depends on the swept area of its rotor and the aerodynamic characteristics of its blades.

Under ideal conditions the rotational speed of the rotor varies in direct relation to the wind speed. In this case the efficiency of the rotor remains constant and power varies as the cube of the wind speed (and rotational speed). With wind pumps, however, the situation is more complicated. The majority use piston pumps,

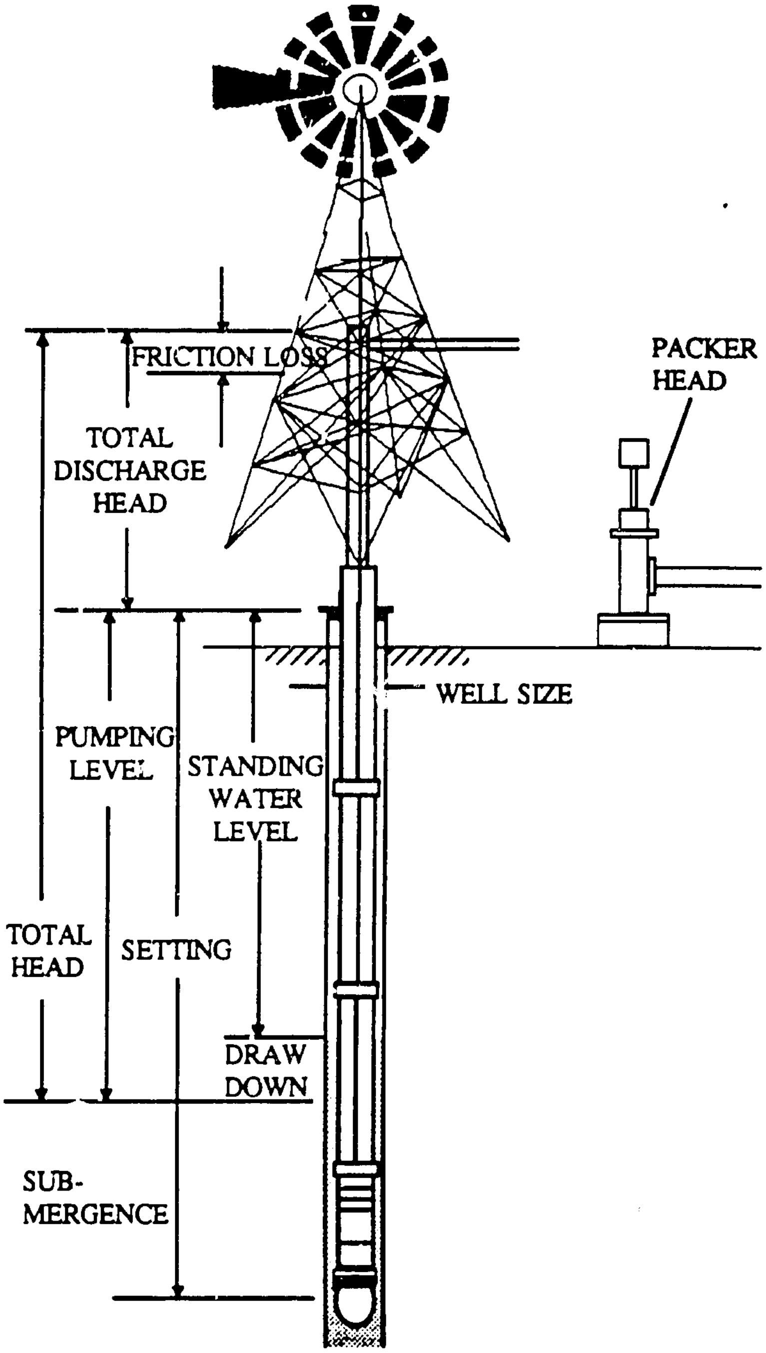


FIGURE 1: Typical Wind Pump

whose power requirements vary directly with the speed of the pump. At high wind speeds the rotor can produce more power than the pump can use. The rotor speeds up, causing its efficiency to drop, so it produces less power. The pump, coupled to the rotor, also moves more rapidly so it absorbs more power. At a certain point the power from the rotor equals the power used by the pump, and the rotational speed remains constant until the wind speed changes.

The net effect of all this is that the whole system behaves rather differently than an ideal wind turbine. Its actual performance is best described by a measured characteristic curve (Figure 2), which relates actual water flow at given pumping heads to the wind speed. This curve also reflects other important information such as the wind speeds at which the machine starts and stops pumping (low wind) and when it begins to turn away in high winds (furling).

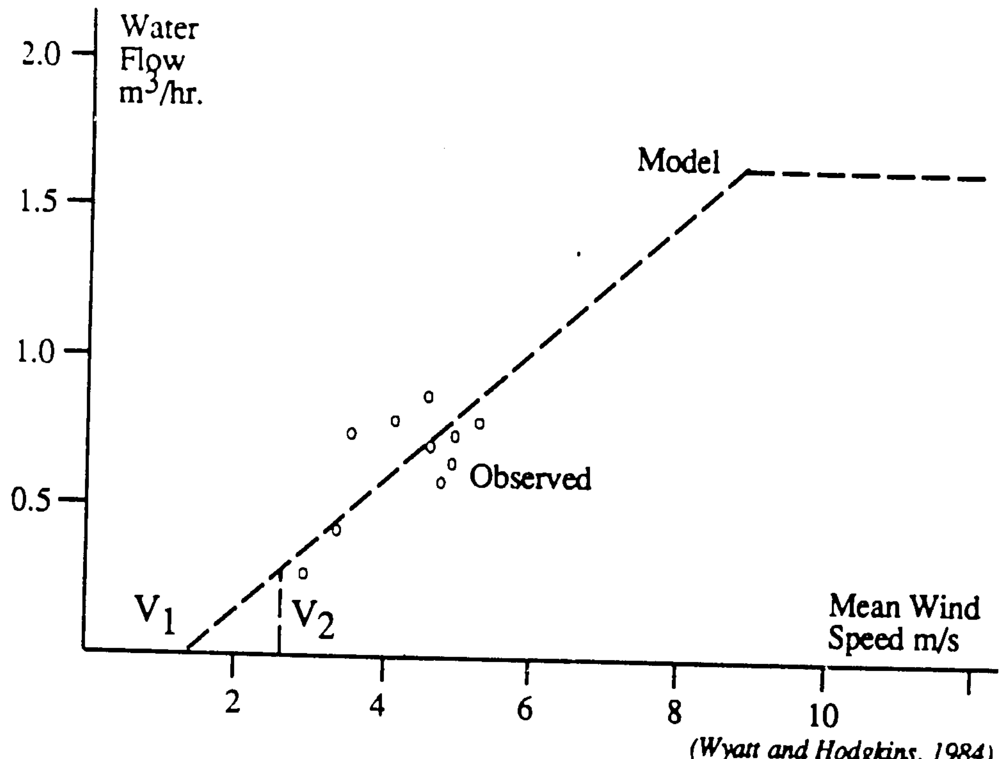


FIGURE 2: Multiblade Windmill Performance, Observed And Model Results, One Minute Average Readings

Most commercial machines and those developed and tested more recently have such curves and these should be used if possible in predicting wind machine output. On the other hand, it should be noted that some manufacturers provide incomplete or overly optimistic estimates of what their machines can do. Sales literature should be examined carefully.

In addition to the characteristic curve of the wind machine, one must also know the pattern of the wind in order accurately to estimate productivity. For example, suppose it is known how many hours (frequency) the average wind speed was between 0-1 m/s, 1-2 m/s, 2-3 m/s, etc., in a given month. By referring to the characteristic curve, one could determine how much water was pumped in each of the groups of hours corresponding to those wind speed ranges. The sum of water from all groups would be the monthly total. Usually such detailed information on the wind is not known. However, a variety of statistical techniques are available from which the frequencies can be predicted fairly accurately, using only the long-term mean wind speed and, when available, a measure of its variability (standard deviation). See Lysen, 1983, and Wyatt and Hodgkin, 1984.

Many times there is little information known about a possible machine or it is just desired to know very approximately what size machine would be appropriate. Under these conditions the following simplified formula can be used:

Power = **Area** x 0.1 x (Vmean)^3
where
Power = useful power delivered in pumping the water, watts

Area = swept area of rotor (3.14 x Radius squared), m^2

Vmean = mean wind speed, m/s

By rearranging the above equation, an approximate diameter of the wind rotor can be found. Returning to the earlier example, to pump 50 m^3/day, 15 m would require an average of 85 watts. Suppose the mean wind speed was 4 m/s. Then the diameter (twice the radius) would be:

Diameter = 2 [Power/(3.14) x 0.1 x Vmean^3)]
or
Diameter = 2 x [85/(3.14 x 0.1 x 4^3)] = 4.1 m

6. Compare Seasonal Water Production to Requirement

This procedure is usually done on a monthly basis. It consists of comparing the amount of water that could be pumped with that actually needed. In this way it can be told if the machine is large enough and conversely if some of the time there will be excess water. This information is needed to perform a realistic economic analysis. The results may suggest a change in the size of machines to be used.

Comparison of water supply and requirement will also aid in determining the necessary storage size. In general storage should be equal to about one or two days of usage.

7. Select Type of Wind Machine and Pump

There is a variety of types of wind machines that could be considered. The most common use relatively slow speed rotors with many blades, coupled to a reciprocating piston pump.

Rotor speed is described in terms of the tip speed ratio, which is the ratio between the actual speed of the blade tips and the free wind speed. Traditional wind pumps operate with highest efficiency when the tip speed ratio is about 1.0. Some of the more recently developed machines, with less blade area relative to their swept area, perform best at higher tip speed ratios (such as 2.0).

A primary consideration in selecting a machine is its intended application. Generally speaking, wind pumps for domestic use or livestock supply are designed for unattended operation. They should be quite reliable and may have a relatively high cost. Machines for irrigation are used seasonally and may be designed to be manually operated. Hence they can be more simply constructed and less expensive.

For most wind pump applications, there are four possible types or sources of equipment. These are: 1) Commercially available machines of the sort developed for the American West in the late 1800s; 2) Refurbished machines of the first types that have been abandoned; 3) Intermediate technology machines, developed over the last 20 years for production and use in developing countries; and 4) Low technology machines, built of local materials.

The traditional, American "fan mill," is a well developed technology with very high reliability. It incorporates a step down transmission, so that pumping rate is a quarter to a third of the rotational speed of the rotor. This design is particularly suitable for relatively deep wells (greater than 30m--100'). The main problem with these machines is their high weight and cost relative to their pumping capacity. Production of these machines in developing countries is often difficult because of the need for casting gears.

Refurbushing abandoned traditional pumps may have more potential than might at first appear likely. In many windy parts of the world a substantial number of these machines were installed early in this century, but were later abandoned when other forms of power became available. Often these machines can be made operational for much less cost than purchasing a new one. In many cases parts from newer machines are interchangeable with the older ones. By coupling refurbishing with a training program, a maintenance and repair infrastructure can be created at the same time that machines are being restored. Development of this infrastructure will facilitate the successful introduction of newer machines in the future.

For heads of less than 30m, the intermediate technology machines may be most appropriate. Some of the groups working on such designs are listed at the end of this entry. These machines typically use a higher speed rotor and have no gear box. On the other hand they may need an air chamber to compensate for adverse acceleration effects due to the rapidly moving piston. The machines are made of steel, and require no casting and minimal welding. Their design is such that they can be readily made in machine shops in developing countries. Many of these wind pumps have undergone substantial analysis and field testing and can be considered reliable.

Low technology machines are intended to be built with locally available materials and simple tools. Their fabrication and maintenance, on the other hand, are very labor intensive. In a number of cases projects using these designs have been less successful than had been hoped. If such a design is desired, it should first be verified that machines of that type have actually been built and operated successfully. For a sobering appraisal of some of the problems encountered in building wind machines locally, see Wind Energy Development in Kenya (see References).

Although most wind machines use piston pumps, other types include mono pumps (rotating), centrifugal pumps (rotating at high speed), oscillating vanes, compressed air pumps, and electric pumps driven by a wind electric generator. Diaphragm pumps are sometimes used for low head irrigation (5-10 m or 16-32'). No matter what type of rotor is used, the pump must be sized appropriately. A large pump will pump more water at high wind speeds than will a small one. On the other hand, it will not pump at all at lower wind speeds. Since the power required in pumping the water is proportional to the head and the flow rate, as the head increases the volume pumped will have to decrease accordingly. The piston travel, or stroke, is generally constant (with some exceptions) for a given windmill. Hence, piston area should be decreased in proportion to the pumping head to maintain optimum performance.

Selecting the correct piston pump for a particular application involves consideration of two types of factors: 1) the characteristics of the rotor and the rest of the machine, and 2) the site conditions. The important machine characteristics are: 1) the rotor size (diameter); 2) the design tip speed ratio; 3) the gear ratio; and 4) the stroke length. The first two have been discussed earlier. The gear ratio reflects the fact that most wind pumps are geared down by a factor of 3 to 4. Stroke length increases with rotor size. The choice is affected by structural considerations. Typical values for a machine geared down 3.5:1 range from 10 cm (4") for a rotor diameter of 1.8 m (6') to 40 cm (15")for a diameter of 5 m (16'). Note that it is the size of the crank driven by the rotor (via the gearing) that determines the stroke of the pump.

The key site conditions are: 1) mean wind speed and 2) well depth. These site factors can be combined with the machine parameters to find the pump diameter with the use of the following equation. This equation assumes that the pump is selected so that the machine performs best at the mean wind speed.

$$DP = \sqrt{\frac{(0.1)\,(Pi)\,(DIAMR)^3\,(VMEAN)^2\,(GEAR)}{(DENSW)\,(G)\,(HEIGHT)\,(TSR)\,(STROKE)}}$$

where:

DP = Diameter of piston, m
Pi = 3.1416
DIAMR = Diameter of the rotor, m

VMEAN = Mean wind speed, m/s
GEAR = Gear down ratio
DENSW = Density of water, 1000 kg/m^3
G = Acceleration of gravity, 9.8 m/s^2
HEIGHT = Total pumping head, m
TSR = Design tip speed ratio
STROKE = Piston stroke length, m

Example:

Suppose the wind machine of the previous examples has a gear down ratio of 3.5:1, a design tip speed ratio of 1.0 and a stroke of 30 cm. Then the diameter of the piston would be:

$$DP = \sqrt[3]{\frac{(0.1)\ (3.14)\ (4.1)^3}{(1000)\ (9.8)\ (15)}\ \frac{(4.0)^2}{(1.0)}\ \frac{(3.5)}{(0.3)}} = .166m$$

8. Identify Suppliers of Machinery

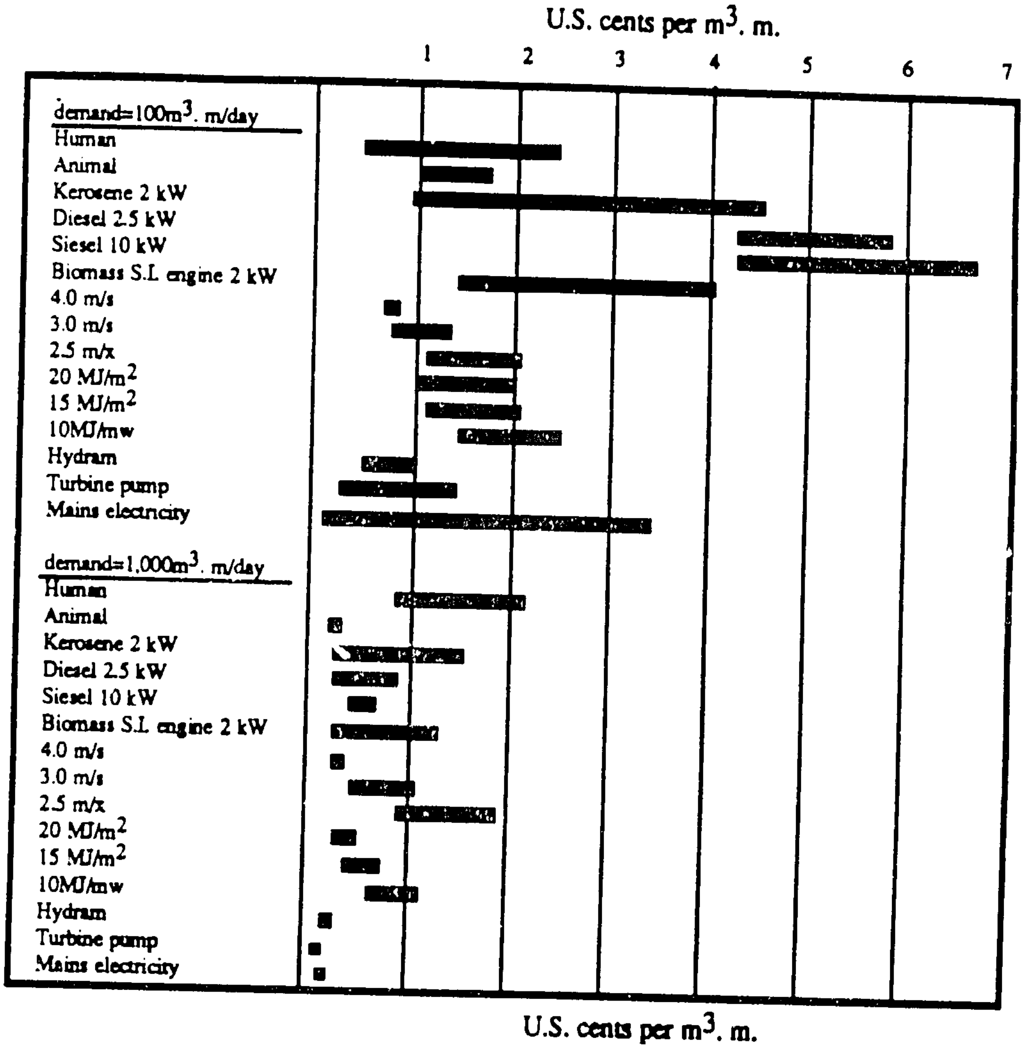
Once a type of machine has been selected, suppliers of the equipment or the designs should be contacted for information about availability of equipment and spare parts in the region in question, references, cost, etc. If the machine is to be built locally, sources of material, such as sheet steel, angle iron, bearings, etc. will have to be identified. Possible machine shops should be visited and their work on similar kinds of fabrication should be examined.

9. Identify Alternative Power Sources for Water Pumping

There are usually a number of alternatives in any given situation. What might be a good option depends on the specific conditions. Some of the possibilities include pumps using human power (hand pumps), animal power (Persian wheels, chain pumps), internal combustion engines (gasoline, diesel, or biogas), external combustion engines (steam, Stirling cycle), hydropower (hydraulic rams, norias), and solar power (thermodynamic cycles, photovoltaics).

10. Evaluate Economics

For all the realistic options the likely costs should be assessed and a life cycle economic analysis performed. The costs include the first cost (purchase or manufacturing price), shipping, installation, operation (including fuel where applicable), maintenance, spare parts, etc. For each system being evaluated the total useful delivered water must also be determined (as described in Step 6). The life cycle analysis takes account of costs and benefits that accrue over the life of the project and puts them on a comparable basis. The result is frequently expressed in an average cost per cubic meter of water (Figure 3).



(Fraenkel, 1986)

FIGURE 3: Expected range of unit energy costs for two levels of demand, 100 and 1000 m^3.m/day, for different types of prime mover.

It should be noted that the most economic option is strongly affected by the size of the project. In general, wind energy is seldom competitive when mean winds are less than 2.5 m/s, but it is the least cost alternative for a wide range of conditions when the mean wind speed is greater than 4.0 m/s.

11. Install the Machines

Once wind energy has been selected, arrangements should be made for the purchase or construction of the equipment. The site must be prepared and the materials all brought there. A crew for assembly and erection must be secured, and instructed. Someone must be in charge of overseeing the installation to ensure that it is done properly and to check the machine out when it is up. Regular maintenance must be arranged for.

With proper planning, organization, design, construction, and maintenance, the wind machines may have a very useful and productive life.

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IV. GROUPS INVOLVED WITH WIND PUMPING IN DEVELOPING COUNTRIES

Consultancy for Wind Energy in Developing Countries, P.O. Box 85, 3800 AB, Amersfoort, The Netherlands

Intermediate Technology Development Group, Ltd., 9 King Street, Coven Garden, London, WC2E 8HW, UK

IPAT, Technical University of Berlin, Sekr. TH2, Lentzallee 86, D-1000 Berlin 33, West Germany

Renewable Energy Research Laboratory, Dept. of Mechanical Engineering, University of Massachusetts, Amherst, Massachusetts 01003 USA

SKAT, Varnbuelstr. 14, CH-9000 St. Gallen, Switzerland

The Danish Center for Renewable Energy, Asgaard, Sdr. Ydby, DK-7760 Hurup Thy, Denmark

Volunteers in Technical Assistance (VITA), 1815 N. Lynn Street, Suite 200, Arlington, Virginia 22209-2079 USA

V. MANUFACTURERS OF WATER-PUMPING WINDMILLS

Aermotor, P.O. Box 1364, Conway, Arkansas 72032, USA

Dempster Industries, Inc., Beatrice, Nebraska 68310, USA

Heller Aller Company, Perry & Oakwood St., Napoleon, Ohio 43545, USA