Renewable Energy Systems R&D Group

Eastern Mediterranean University

Physics Department

Wind-power for Rural Water Pumping

by
Kefa Rabah

Introduction

This paper is expected to provide an introduction to specific state-of-the-art wind-power technologies that would be of interest and beneficial to people working in *rural water development* in developing countries. It is developed for use as guidelines to help people choose from various options wind energy-derived technologies that are suitable to their situations.

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 end-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 and future sustainability.

II. DECISION MAKING PROCESS

The following summarizes the key aspects of above steps.

1. Identify the Users

This step seems quite obvious, but should not be ignored.

- Pay attention to who will use the wind machine and its water
- If possible, develop a project that can have continuing success and sustainability.
- Questions to consider are whether the end-users 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 own the equipment; who will be responsible for keeping it running; and who will be benefiting 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

- These are: a) domestic use, b) livestock watering, c) irrigation, d) drainage.

a) Domestic requirements:

- 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.
- A flush toilet consumes 25 liters (6½ gallons) with each use and, a shower may take up to 230 liters (60 gallons) per single use.
- *One must also consider population growth.*
    - If the growth rate is 3 percent, water use increases by nearly 60 percent at the end of 15 years, a reasonable lifetime for a water pump.

b) 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 single milking cows.
- A single cattle dip might use up to 7500 liters (2000 gallons) a day.

c) Estimation of irrigation requirements:
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.

Example, in one semi-arid region irrigation requirements may vary widely:

- From 35,000 liters (9,275 gallons) per day per hectare (2.47 acres) for fruits and vegs
- to 100,000 liters (26,500 gallons) per day per hectare for cotton.

d) 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.

Consumptions Estimate

- In order to make the estimate for the water demand, each user's consumption is identified, and summed up to find the overall total requirement.
- As will become apparent later. It is desirable to do this on a monthly basis so that the demand can be related to monthly 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 neighborhood 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, P_w, is proportional to its mass per unit volume, or density (1000 kg/m^3); the acceleration due to gravity (g = 9.8 m/s^2; the total pumping head, H (m); and $\dot{V}$ the volume flow rate of water (m^3/s). *Note that 1 cubic meter equals 1000 liters*.

Expressed as a formula:

$$P_w = \rho_w gH \times \dot{V} \tag{1}$$

Power is also inversely proportional to the pump efficiency.

Example:
To pump 50 m^3 in one day (0. 000579 m^3/s) up a total head of 15 m would require:

$$Power = 1000\,kg/m^3 \times 9.8\,m/s^2 \times 15m \times \left(5.79 \times 10^{-4}\ m^3/s\right) = 85 \text{ watts}$$

- 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, m/day. *For example*, in the above example the hydraulic requirement is 750 m^3, m/day.

4. Evaluate Wind Resources

Extraction of power from the wind with modern turbine and energy conversion systems is already well established. Wind power conversion depends on two main factors:

- Wind turbine geometry and
- The way wind passes over the airfoils or blades.

If u_0 is the unperturbed wind speed, ρ the air density, and A the area of turbine intercepting cross-section wind front, then total wind power delivered is given by:

$$P_T = \tfrac{1}{2} C_p A\rho u_0^3 = C_p P_0 \tag{2}$$

where P_0 is the power in the unperturbed wind and is given by:

$$P_0 = \tfrac{1}{2} A\rho u_0^3 \tag{3}$$

From Eq. (2), the total average annual wind-power is given by

$$\bar{P}_T \approx C_p A\rho \left(\bar{u}_0\right)^3 \tag{4}$$

where $\bar{u}$ is the wind mean speed, and C_p (= 0.59) is the fraction of power extracted or power coefficient, also known as Betz Criterion. Thus, power in the wind varies with the cube of the wind speed, and hence, if the wind speed doubles, the available power increases by a factor of eight.

Good understanding of the wind speed patterns at a given site is important.

Example
Using Eq. (3), the moderate power that can be harnessed in a moderate winds with $u_0 \sim 10$ m/s is $P_0 \approx 600$ W/m^2. While in gale force wind with $u_0 \sim 25$ m/s gives $P_0 \sim 10$ kW/m^2.

Good rule of thumb:
At least an average wind speed of 2.5 m/s at the height of a wind rotor is required in order to have a reasonable potential for water pumping.

Other important factors are:

- 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.
- 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.

Note: that 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, Eq. (2), the effect on the latter is even more dramatic.

5. Estimate Wind Machine Size

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 in general 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.

Good rule of thumb:

- Develop good characteristics curve for the wind within the preferred site.
- Generate good wind pattern in order to accurately estimate the 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.

1) By referring to the characteristic curve,
2) one could determine how much water was pumped in each of the groups of hours corresponding to those wind speed ranges.
3) The sum of water from all groups would be the monthly total.

Simple Method
Following simplified formula from Eq. (2), can be used:

$$P = A \times 0.6 \times v_{mean}^3 \tag{5}$$

where P = useful power delivered in pumping the water, watts; A = swept area of rotor (= πR^2, where R is the radius of the blade), m^2; v_{mean} = mean wind speed, m/s

By rearranging the above equation, an approximate diameter, D, (twice the radius, r) of the wind rotor can be found, i.e.,

$$D = 2R = 2\times\sqrt{\frac{P}{\pi\times 0.6\times v_{mean}^{3}}} \tag{6}$$

Example
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, D, would be:

$$D = 2\times\sqrt{\frac{85}{3.14\times 0.6\times 4^{3}}} = 1.8\,m$$

6. Compare Seasonal Water Production to Requirement

- This procedure is usually done on a monthly basis.
- This information is needed to perform a realistic economic analysis.
- The results may suggest a change in the size of machines to be used.
- Aid in determining the necessary storage size, usually about one or two days of usage.

7. Select Type of Wind Machine and Pump

- Traditional wind pumps operate with highest efficiency when the tip speed ratio is about 1.0.
- Recently developed machines, with less blade area relative to their swept area, perform best at higher tip speed ratios (such as 2.0).

Tip speed ratio, λ, is the most important parameter of an aero-generator design. It is defined mathematically as follows:

$$\lambda = \frac{v}{u_0} = \frac{\omega R}{u_0} \tag{7}$$

Tip speed ratio contains the three most important variables: blade swept radius R, the unperturbed wind speed u_0 and, ω the rotor frequency. Where *v* is outer blade tip speed. Further being a dimensionless quantity, it becomes essential a perfect scaling factor parameter in design and analysis of aero-generator machines. Tip speed ratio is also related to Cp via the following equation:

$$\lambda = \frac{C_p}{C_\Gamma} = \frac{0.59}{C_\Gamma} \tag{8}$$

where C_Γ is the shaft coefficient for a working machine producing a shaft torque Γ.

For most wind pump applications, there are four possible types of sources of equipment. These are:

- Commercially available machines developed in the late 1800s.
- Refurbished machines of the first types that have been abandoned;
- Intermediate technology machines, developed over the last 20 years for production and use in developing countries; and

- Low or appropriate technology machines, built of local materials.

The key site conditions are:

- 1) Mean wind speed and, 2) well-depth.
- These site factors can be combined with the machine parameters, from Eq. (6), to find the pump diameter.

$$D_p = \sqrt{\frac{0.6(\pi D^3 v_{mean}^3 G)}{\rho_w g H \lambda L_p}} \tag{9}$$

This equation assumes that the pump is selected so that the machine performs best at the mean wind speed. Where D_p = diameter of piston, m, π = 3.1416; D = diameter of the rotor, m; v_{mean} = mean wind speed, m/s; G = gear down ratio; ρ_w = density of water, 1000 kg/m^3; g = acceleration due to gravity, 9.8 m/s^2; H = total pumping head, m; λ = design tip speed ratio; Lp = 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:

$$D_p = \sqrt{\frac{0.6\times3.14\times(1.8)^3\times(4.0)^2\times3.5}{1000\times9.8\times15\times1.0\times0.3}} = 0.118m$$

8. Identify Suppliers of Machinery

- Once the 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 energy resources 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), etc.
- Internal combustion engines (gasoline, diesel, or biogas),
- External combustion engines (steam, Stirling cycle),
- Small hydropower and solar power (thermodynamic cycles, and 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 5*).

- The life cycle analysis should take into account the 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.

11. Conclusion

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.

Reference

1. James F. Manwell, "*Understanding Wind Energy for Pumping Water*"; ISBN: 0-86619-281-6 [C] 1988, Technical Paper # 62, Volunteers in Technical Assistance.
2. Twidel, J and Weir, T**, "***Renewable Energy Resources*", Chapman and Hall, London, 1990.

Web site designed and managed by **Assoc. Prof. Dr. Kefa Rabah**

http://physics.emu.edu.tr/~kefa/Physics503/index.htm

Email: krabah@hotmail.com