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Electric Wind Pumping for Meeting Off-Grid Community Water Demands

Brett G. Ziter
University of Guelph, School of Engineering, Guelph, ON, N1G 2W1, Canada

The current state of community scale electrical wind pumping technology is examined. Wind pumping is considered an economically competitive, sustainable means of providing water to communities without access to the electricity grid. A background is provided on the history of wind pumping systems, followed by a review of current technology and a discussion of its potential through several case studies. An analysis conducted using the performance curve of a Bergey Excel-PD wind pumping system shows that there is significant potential for the use of this technology in locations with average wind speeds of 5 m/s and greater. It is postulated that a lack of information to guarantee the success of new installations coupled with a lack of wind resource data in most locations is preventing electrical wind pumping from reaching its full potential.

Nomenclature

P	=	power available in the wind
U	=	instantaneous wind speed
$\overline{P}$	=	average power available in the wind
$\overline{U}$	=	average wind speed
$\dot{m}$	=	mass flow rate of water
H	=	required pumping height
C_p	=	wind turbine power coefficient
η_e	=	system electrical efficiency
η_w	=	water pump efficiency
h_p	=	required pumping head
h_f	=	headloss caused by friction
h_m	=	headloss caused by minor losses
p	=	absolute pressure
V	=	water velocity
z	=	elevation
f	=	friction factor
K	=	minor loss coefficient

I. Introduction

A promising application of small wind turbine technology is the use of wind energy to pump water in off-grid locations. Pumping water was one of the first uses of mechanical windmills hundreds of years ago, and is experiencing a revival with the introduction of electrical wind pumping systems. These systems involve the use small wind turbines (which typically output alternating current (AC) signals) to power variable speed pumps electrically. They are more efficient and often more practical then mechanical wind pumps which are inhibited by technological shortcomings. Electrical wind pumps are generally cost competitive with other off-grid technologies and have been used successfully in many situations (Argaw, 2003). However, due to the relative novelty of this technology and the lack of adequate wind resource assessment in many locations, wind pumping operations are not as numerous as their potential suggests they could be. This paper will review the history of wind pumping, examine the current technology and attempt to show that it can play a viable role in wind energy's future through an assessment of pumping demands at which it is and is not feasible. Finally the elements of a complete system design will be provided for an example water distribution scenario.

II. History of Wind Pumping Technology

The use of wind energy in water pumping applications dates back to 13th century Europe. Traditionally, water was pumped to drain marshes, produce salt from seawater and irrigate agricultural land. As windmill technology improved, water pumping applications grew in number and diversity. The introduction of the American wind pump in the late 19th century marked the arrival of mass availability of wind pumping technology. These systems were able to operate for long periods left unattended and were used to supply water for domestic use, livestock and steam engine operations throughout the United States. Millions of American wind pumps have been produced and installed around the world. It is thought that over a million are still in use today. However, this traditional wind pumping technology did not come without its drawbacks. Due to their simple multi-blade design, less than ideal material selection and inherent mechanical flaws, American wind pump output was only 4-8% of the energy available in the wind (Ackerman, 2000; Argaw, 2003).

Modifications have since been made to improve mechanical wind pump technology. Systems have been made lighter, less expensive and more efficient than in the past. One major development was the design of a counterbalance to oppose the weight of the pumping rod. Traditionally, cyclical loading caused by the pumping rod led to fluctuations in rotor speed, which caused fatigue and decreased pumping efficiency. Use of a counterbalance helps to dampen this effect. Another major development was the use of variable stroke to increase the system's effectiveness over a range of wind speeds. Other developments include lighter materials, cheaper manufacturing methods and modifications to blade and rotor design (Argaw, 2003).

Even with these developments, there are fundamental limits to the efficiency of mechanical wind pumps. Due to the mechanical pumping system, a windmill must be located directly on top of the source from which it is drawing water. This presents a problem, as the best water resource sites are generally poor wind resource sites. It also places restrictions on maximum tower height (Argaw, 2003). Mechanical windmills are often designed with as many as twenty blades. This high rotor solidity allows them to provide high torque at low wind speeds, but limits their productivity as wind speeds increase (Ackerman, 2000). Further, inefficiencies are inherent in the mechanical pumping process and modern design improvements can only go so far. Ultimately, pumping water is a promising application of wind energy but there are many limitations to the effectiveness of mechanical wind pumps Modern mechanical wind pumps are still limited to an overall conversion efficiency of 7-27% (Argaw, 2003).

Wind turbines, capable of converting the kinetic energy in the wind into electricity have been in development since the 1890s. Recently, work has begun on the design of electrical wind turbines for water pumping applications. Electrical wind pump systems can be designed with lower solidity rotors than traditional wind pumps, which are capable of generating higher tip speed ratios and producing more power. Although they require a higher starting wind speed, wind turbines are twice as efficient in energy terms as traditional wind pumps. They have fewer moving parts, reducing the need for maintenance, and are cost competitive with traditional wind pumps as well as other alternative pumping technologies such as diesel and PV systems (Argaw, 2003). Since electricity can be transmitted long distances though a simple power line, water pumping wind turbines can be placed far away from the site of water pumping, at locations where the wind resource is greater. They are capable of responding to a wide range of wind speeds without a significant reduction in efficiency and can do this affordably by using variable speed generators that do not require complex power rectification systems. Electrical wind pumping technology is gaining popularity and has significant potential to make water accessible where grid power is not. One study estimates that this technology could supply power for 50,000 new pumping applications each year in India alone (Jayadev, 1995).

III. Wind Pumping System Design

A. Mechanical Wind Pump Design

Key components of mechanical wind pump design include a windmill (rotor and tower) integrated with a pumping system ending in a borehole which acts as a well from which water is pumped. The windmill must be located directly over the borehole to utilize vertical piston motion to extract water from the well.

Windmill rotors are designed to capture the kinetic energy in the wind and the convert it to useful mechanical energy. Traditional wind pump rotors had 15-20 curved steel blades, designed to provide high solidity for high torque and operation at low starting wind speeds. Their rotor diameters ranged from 2 to 5 meters. Modern wind pumps are designed with rotors as large as 8 m containing 6-8 true airfoil blades, still providing high solidity while reducing weight and material cost.

The piston must extend vertically from the well, the entire length of the tower to connect to a gearbox behind the windmill's rotor. When the wind speed is high enough to generate the force required to lift the piston and the water it contains, the pumping process will begin. This places restrictions on maximum tower height and creates fatigue loading on the system. Modern windmills often use a direct drive system rather than a gearbox with the intention of reducing the required starting torque and maintenance requirements (Argaw, 2003).

B. Electrical Wind Pump Design

Key components of an electrical wind pumping system include the turbine rotor, tower, electrical generator, motor and pump as well as electrical wiring.

The rotor is designed to optimize the power generated for a given wind resource. Generally a three blade design is selected, with composite airfoil blades for optimal performance and durability. The low solidity of these rotors provides a high tip speed ratio but requires a higher startup wind speed (around 4-5 m/s for a 1 kW turbine, and higher for larger turbines) (Argaw, 2003).

A synchronous generator is ideal for wind pumping applications, as this type of generator is capable of outputting AC current at variable frequency, which is directly proportional to the rotor speed of the turbine. As the turbine rotor accelerates, the rotational speed of the generator increases, providing a corresponding increase in output frequency and ultimately more power delivered to the pump (Muljadi, 2000). Variable speed systems are ideal as they require no gearbox and can operate at high rotor speeds with less structural loading on the turbine. They are considered more reliable and less costly to maintain. This is important in off-grid applications where maintenance can be difficult (Ackermann, 2000).

To power the pump, an induction motor is selected that is capable of operating according to the frequency provided by the generator. For a given operating frequency, the torque supplied by the motor is a function of its RPM. When the generator output changes, the torque-speed relationship of the motor will shift according to the new operating frequency. In this way, the motor can always respond to changing wind speeds to produce a desirable output torque. An appropriate pump must be selected to match the expected output conditions of the motor (Muljadi, 2000). In many cases, pumps are designed with built in multi-stage motors designed to operate over a range of input conditions. An example of this is the Grundfos SQ series recommended for use with Bergey water pumping turbines (Grundfos, 2008).

In addition to selecting an appropriate wind turbine and pumping system, many other aspects need to be taken into consideration when designing a wind pumping system. These include the construction of a well or storage reservoir from which water is to be pumped, a storage tank at the desired water output location and all necessary plumbing. A location must be selected for the turbine that will give the best wind resource. An appropriate tower height must be selected and wiring must connect the turbine to the pump motor. An overview of complete mechanical and electrical wind pumping systems is presented in Fig. 1.

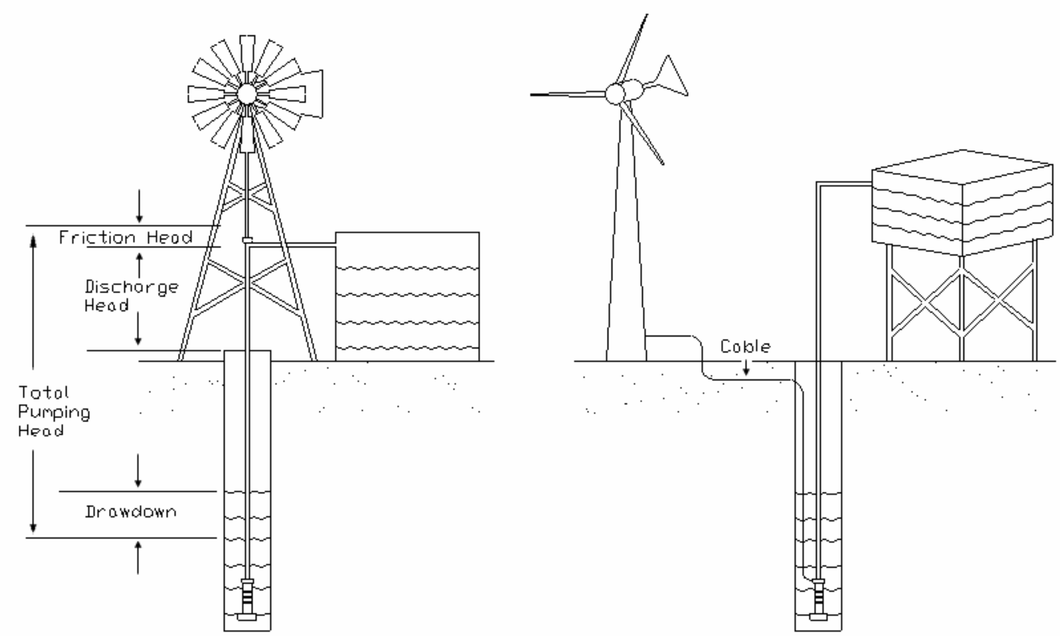

Figure 1. Wind Pump System Overviews. a) Mechanical Wind Pump, b) Electrical Wind Pump.

IV. Case Studies

Several case studies of wind pumping in off-grid communities are available in the literature. Applications range from water distribution to irrigation and watering livestock. Three uses of wind pumping in developing countries are presented below:

A. Niama Water Network, Morocco

A 10 kW Bergey Excel wind turbine has been installed to drive an electric water pump in Ain Tobin, Morocco, a semi-arid location where water supplies are often scarce. Children are typically given the task of gathering water, in this case from a source as far as 4.5 km away. This wind pumping application is a retrofit of an old diesel installation that the community can no longer afford. When wind speeds are sufficient, water is pumped from a spring fed storage tank to a larger tank half a kilometer away, which then services four villages and 3500 people. The system was installed in 1989 and has provided water in excess to the community ever since (Bergey, 2008).

B. Llasaria, Altiplano, Bolivia

Llasaria, a community of about 1000 people, received its drinking water from a stream contaminated with cholera-causing bacteria. In 1995 a 10 kW Bergey Excel wind turbine was installed to pump water from a well, 1 km away. To maximize wind availability, the turbine was located on a hill 700 m from the well. It was capable of providing the community with about 35 m^3 of safe drinking water per day. Recent grid access has eliminated the need for this system. It has been removed for redeployment in a new location (Bergey, 2008).

C. Heelat Ar Rakah, Oman

In 1996, Oman’s first electric wind pumping system was installed at a Ministry of Water Resources camp in Heelat Ar Rakah. A 10 kW Bergey Excel-PD turbine was selected. It was installed on a 24 m tower and equipped with a submersible water pump. In addition a full weather station was installed to monitor the relationship between wind speed and power output. The mean annual 10 m wind speed in the area is 5.7 m/s. The turbine provides 70 m vertical lift and has roughly 30 m of losses, giving a total head of 100 m. A pumping rate of 30 m^3/d was intended to meet irrigation demands at the camp. It was found that the system operates as expected and meets the water requirements more than 80% of the time during the months of interest. The rest is provided by a backup diesel generator system (Al Suleimani, 2000).

V. Analysis

The case studies above suggest that there is significant potential for the use of wind electric pumping for water distribution in off-grid locations. In an attempt to better understand this potential, an analysis has been conducted to determine the required pumping heads and water demands that may be feasibly supplied for a range of average wind speeds. An analysis has been conducted from general assumptions and first principles to determine the maximum possible theoretical output of a water pumping system. Using this relationship, a model has been developed to determine the output of any system with specifications of rotor diameter, average wind speed, required pumping head and system efficiency. To verify the model, it has been compared to the performance curve of a Bergey Excel-PD 10 kW electric pumping system and an example scenario has been analyzed including calculations and basic system components.

A. Development of a General Performance Model

At a given wind speed, the power available in the wind is given by:

$$P(U) = \frac{1}{2} \rho A U^3 \qquad (1)$$

where: ρ is air density,
A is the swept area of the rotor,
U is the instantaneous wind speed

For a wind resource with probability distribution p(U), the average power available in the wind can be calculated as:

$$\overline{P} = \int_0^\infty P(U)\, p(U)\, dU \tag{2}$$

If all of the power in the wind were used to pump water, the theoretical maximum pumping rate over a given averaging period could be calculated as:

$$\dot{m}_{avg} = \frac{\overline{P}}{gH} \tag{3}$$

where: $\dot{m}_{avg}$ is the theoretical maximum mass flow rate of water over the averaging period,
g is acceleration due to gravity, 9.81 m/s,
H is the required height of pumping (an estimate of required pumping head)

To express the maximum pumping capacity as a function of wind speed, the Rayleigh probability distribution given in Equation 4 was used.

$$p(U) = \frac{\pi}{2}\left(\frac{U}{\overline{U}^2}\right)\exp\left[\frac{-\pi}{4}\left(\frac{U}{\overline{U}}\right)^2\right] \tag{4}$$

Using Rayleigh distributions with $\overline{U}$ ranging from 3 m/s to 7 m/s, $\dot{m}$ was calculated numerically for a range of heads. Recognizing that in even the most efficient system possible the power extracted from the wind would be limited by the Betz's limit efficiency of 59% (Manwell, 2002), the theoretical maximum pumping rates have been reduced to match this efficiency. Results are presented in Fig. 2 below.

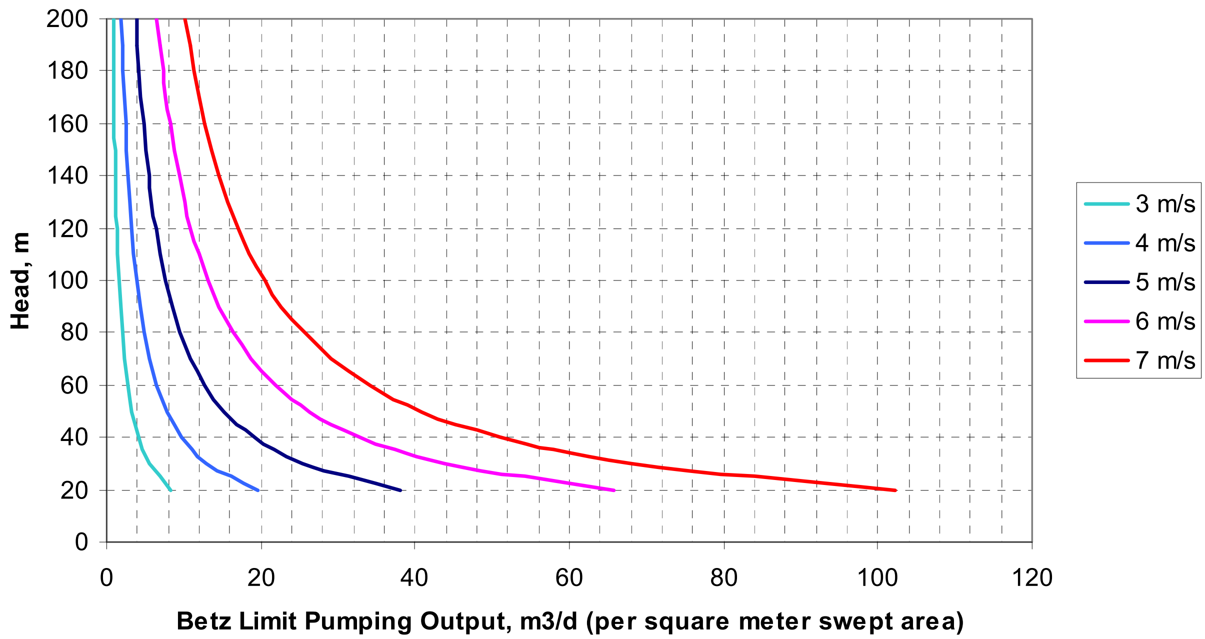

Figure 2. Betz's Limit Performance of a Wind Electrical Pumping System

Due to numerous inefficiencies throughout the system, no practical application of this technology can be expected to operate at Betz's limit. If the local wind resource closely follows a Rayleigh probability distribution, the expected performance for a given head can be calculated from Fig. 2 by multiplying by the swept area of the proposed turbine, dividing by Betz's limit and multiplying by the combined system efficiency (taking into account inefficiencies in the rotor, generator, motor, and pump). Alternative, if a more accurate probability distribution can be used to describe the local wind resource, the expected performance can be calculated using Equation 5.

$$\dot{m}_{avg} = \frac{\int_0^\infty P(U)\,p(U)\,dU}{gH} \times C_p \eta_e \eta_w \qquad (5)$$

where: C_p is the power coefficient of the wind turbine,
η_e is the system's electrical efficiency,
η_w is the efficiency of the water pump

B. Notes on Efficiency

Although Betz's limit states that 59% of the power available in the wind can be harnessed, even state-of-the-art utility scale wind turbines only achieve about 40% efficiency at rated power, with average efficiencies of just over 20% (DWIA, 2003). This is caused by a number of factors including turbulence, aerodynamic drag and blade tip losses (Manwell, 2002). Smaller turbines are not designed with the same level of mechanical and aerodynamic emphasis and have even smaller power coefficients. A wind turbine's power coefficient is a measure of how well the turbine converts energy in the wind into electricity.

Synchronous generators capable of operating at a range of wind speeds can convert from mechanical to electrical energy at high efficiency. Well designed synchronous generators can achieve maximum efficiencies close to 100% (Ryff, 1994). Generator losses are typically included in the power coefficient of a turbine and do not need to be assessed further for the purpose of this analysis. It will be assumed that other electrical losses throughout the system are small compared to rotor and pump losses and will be considered negligible.

Pumps operate at a wide range of efficiencies depending on their design and application (White, 2003). To estimate the efficiency of a centrifugal pump suitable for this application, performance curves have been used for the Grundfos submersible pumps recommended for use with the Bergey Excel-PD (Grundfos, 2008). Converting the expected output of various Grundfos pumps into units of power and dividing by the power required to operate them, it can be shown that they operate at close to 70%. It can be expected that similar pumps for this application operate at similar efficiencies.

If an average power coefficient of 0.15 is assumed and multiplied by a pumping efficiency of 0.70, a combined system efficiency on the order of 10% can be expected.

C. Comparison to a Bergey Excel-PD Wind Pumping System

In order to assess the accuracy of this model, the performance curve of a Bergey Excel-PD will be used. A review of the literature suggests that the most widely used small wind turbines for pumping applications are the Bergey 1500 1.5 kW turbine and the Bergey Excel-PD 10 kW turbine, which has been taken off the market in recent years. Reasons for this discontinuation are unavailable, yet it is speculated that the high cut-in wind speed to initiate pumping may have limited it to too few applications. Turbines less commonly used for water pumping include various models by Whisper and Air X (Solardyne, 2008). Potentially, any wind turbine with a synchronous, variable speed generator could be used; however, the Excel-PD is ideal for this analysis due to the availability of a published performance curve relating water output to head for various average wind speeds.

The Excel-PD's performance curve relates water output to required pumping head for various average wind speeds. It has been created for the use of an Excel-PD turbine in combination with a series of Grundfos submersible pumps, so that for a known head and average wind speed the curve can be used to estimate a pumping rate and recommend the appropriate pump.

For clarity, the performance curve has been adapted to meet the purposes of this analysis. It has been converted to metric units, and is displayed as a single function (ignoring the fact that it spans the output of several pumps) for several average wind speeds in Fig. 3.

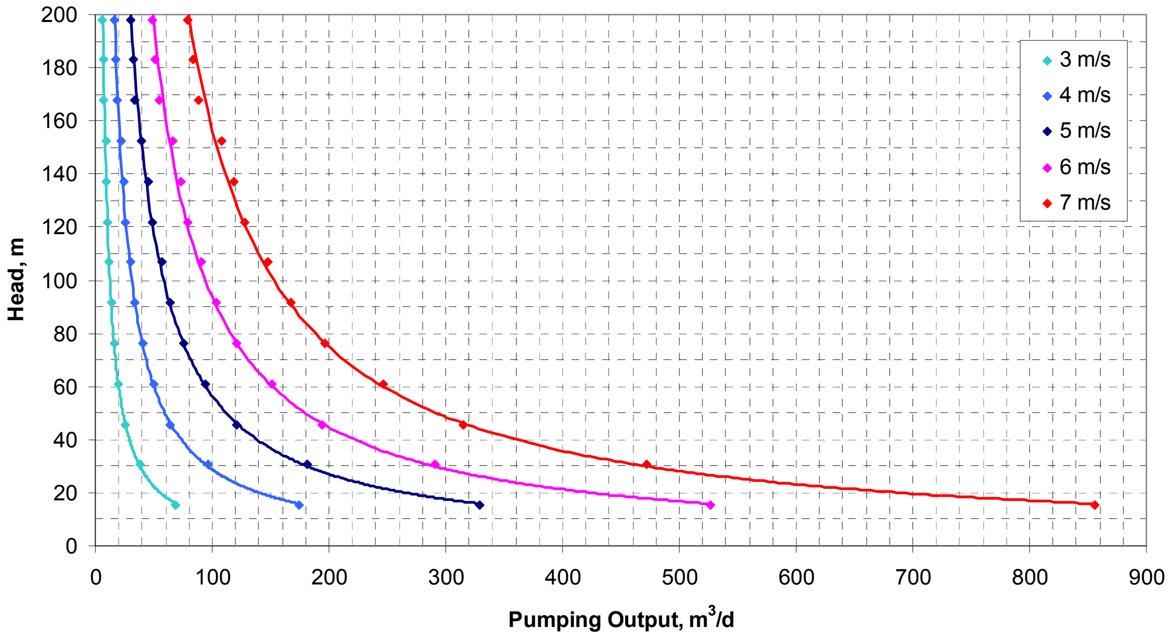

Figure 3. Performance of Bergey Excel-PD Wind Pumping System. *Derived from Manufacturer's Performance Curve with Grundfos Submersible Pumps (Al Suleimani, 2000).*

Figure 3 can be used to verify the accuracy of the model presented in this paper. The Bergey Excel-PD has a rotor diameter of 6.7 m, giving it a swept area of 35.2 m^2. Selecting a point on Fig. 2 and following the proposed algorithm of multiplying by swept area, dividing by Betz's limit and multiplying by system efficiency, it is observed that the two figures match up very well if the combined efficiency of the Excel-PD pumping system is 12.5%. This corresponds fairly well to the expected power coefficient and pumping efficiencies estimated in the previous section but may suggest a slightly exaggerated performance curve. Drawing from this analysis, it can be concluded that the proposed model is accurate at least as a basic estimate.

D. System Design using an Example Scenario

To observe how the above information can be applied to a given scenario, an example has been set up to which the design process will be applied. Suppose a community of 2000 people experiences a situation of long term water scarcity. The proposed solution is to construct a well in a recessed area 20 m below the community and 1 km away. Assume the groundwater table in the area supports pumping from a 30 m deep well, consistent with many geographical locations (Bergey, 2008; Omer, 2000) and the average 10 m wind speed in the area is 5 m/s. Feasibility of a wind pumping system can be assessed taking the following steps.

First, it is necessary to determine the community's water demand. It is suggested that to meet the basic human needs of drinking, hygiene, sanitation, and food preparation, a minimum of 50 L per capita per day are required, although not always met in developing nations (Butler, 2006). To meet the community's needs, 100 m^3 of clean water must be supplied each day.

The system would be comprised of the following: a well from which water is pumped, a multi-stage motor pump, an upper reservoir or storage tank from which the community can draw water as needed and all the necessary plumbing in between. The suggested system design is given in Fig. 4.

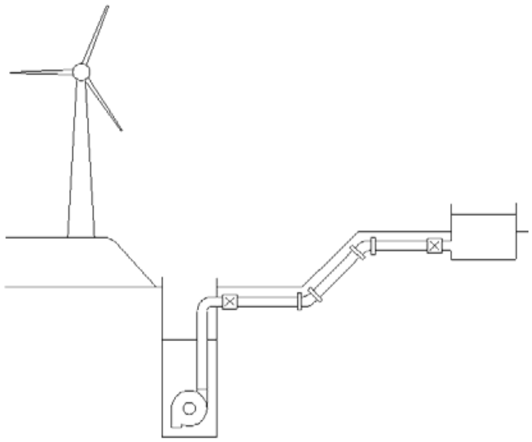

Figure 4. System Design Schematic.

If the required pumping head is calculated, and an overall system efficiency of 10% is assumed, Fig. 2 can be used to optimize the turbine size needed for this situation.

To calculate the required pumping head, Bernoulli's equation can be used:

$$h_p + \frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_f + \Sigma h_m \qquad (6)$$

where: h_p is the required pumping head,
h_f is the head loss caused by friction,
h_m are the minor losses throughout the system,
ρ, p, V and z are density pressure, velocity and elevation
Subscripts 1 and 2 represent the well and storage tank locations

It is recognized that $p_1 = p_2$ and $V_1 \approx V_2 \approx 0$, making the pumping head equal to only the change in elevation plus the losses that occur throughout the system. These losses can be calculated as follows:

$$h_f + \Sigma h_m = \frac{V^2}{2g}\left(\frac{fL}{d} + \Sigma K\right) \qquad (7)$$

where: V is the water velocity through the pipes,
g is gravity (9.81 m/s^2),
f is the friction factor
L and d are the pipe length and diameter, respectively,
K are the various minor loss coefficients throughout the system

Values of K are given in Table 2. The friction factor, *f* is obtainable from a Moody diagram if the Reynolds number (R = Vd/ν; ν is kinematic viscosity of water) is known. The Moody diagram and K values were obtained from White, 2003. To calculate the water velocity through the pipe, the following equation has been used:

$$V = \frac{Q}{A} \qquad (8)$$

where: Q is the required flow rate,
A is the cross sectional area of the pipe

Flow rate can be assumed by recognizing that 100 m^3 of water are needed each day but the pump will not necessarily be operating all day. Using the Grunfos pumps integrated into the Excel-PD performance curve as an example, if the pump operates at an average of 25 gallons per minute (Grundfos, 2008), the flow rate can be expressed as 1.58 x 10^{-3} m^3/s (corresponding to an operating time of over 17 hours per day). If a 4″ pipe diameter is selected to match the Grunfos pump specifications, the corresponding velocity is 0.194 m/s. The required length of pipe to pump water from the well to the community is approximately 1 km, friction factor, *f* = 0.027, and a summary of minor loss coefficients is presented in Table 2.

Table 1. Minor Loss Coefficients. *All values obtained from White, 2003.*

Loss	K
Sharp entrance	0.50
Open globe valve	5.70
90^o bend	0.25
Screwed 90^o elbow	0.64
Open gate valve	0.11
Sharp exit	1.00
	∑K = 8.2

Substituting all values, the total pumping head required for the system is 50.5 m. It is apparent that due to the low velocity, losses throughout the system have an almost negligible effect on the pumping head. This suggests that the design would optimally use a smaller pipe to save on cost. If similar calculations are performed using a 2″ pipe, the velocity increases to 0.776 m/s and the required pumping head increases to 64.2 m. Due to additional power requirements at this head it is likely that a fairly large pipe should be selected. To be safe, a required head of 60 m will be assumed.

Looking at Fig. 2, the expected Betz's limit output for a 60 m pumping head and 5 m/s average wind speed is 12 m^3/d per square meter of swept area. If a combined system efficiency of 12.5% is assumed, this drops to about 2.0 $m^3/d{\cdot}m^2$. To meet the demand of 100 m^3/d, a swept area of 50 m is require. This corresponds to a rotor diameter of just less than 8 m. Comparing this to the Excel-PD, the requirements are only slightly larger and an appropriate turbine could be designed.

To achieve the highest possible wind speeds, a detailed wind resource assessment should be conducted for the area. For the purpose of this analysis, it is suggested that the turbine is located at the highest elevation available, within reasonable distance of the well. A Bergey Excel-PD has been documented operating successfully as far as 700 m from its pumping source (Bergey, 2008).

The design should include an oversized storage tank to help in the event that wind is low for a short period of time. The exact size of the tank should be determined based on the wind intermittency of the area. For example, a tank of 300 m^3 would provide the community's water demand for three days at a time and would be appropriate if winds rarely stayed low for durations greater than three days. Inclusion of an emergency storage tank at the location of the well could provide for the community in the event that the wind was low for an extended period. The required pumping head into this tank would be significantly lower than a tank located far away and uphill at the community, and the water demand could be met at much lower wind speeds.

VI. Additional Problems and Considerations

A fundamental flaw in this analysis is that it does not account for seasonal variations in wind speed. The majority of water pumping applications require year round production and it is important to know the expected output at all times of the year. It is also worth noting that water demand may vary over the course of a year, likely being highest in the summer for most developing country applications. Wind speed variations could be incorporated into the analysis by reading using the developed model with monthly average wind speed estimates for a site where they are available. If more information was known about the response of the pumping system to variations in power supply, a more detailed analysis could be performed based on time series wind data.

Because any off-grid pumping solution for this scenario would require similar piping and storage units, the cost competitiveness of the wind pumping system would ultimately come down the cost of the turbine against the costs associated exclusively with another system. For example a diesel system would be compared based on the cost of the generator and the cost of fuel required to meet the water demand.

Before any installation is carried out, a groundwater assessment would need to conclude that the area can support the additional water extraction and that the water is of sufficient quality for human consumption.

In some situations, cultural issues need to be assessed. A community cannot be provided with a water pumping system that they do not want or are morally or religiously opposed to.

VII. Conclusions

A model has been presented to estimate the performance of an electrical wind pumping system as a function of average wind speed, required pumping head and rotor diameter. It has been verified using the performance curve of a Bergey Excel-PD 10 kW wind pumping system.

Electrical wind pumping technology has significant potential to supply water for numerous off-grid applications. Preliminary analysis shows that at a site requiring 60 m of pumping head, a community of 2000 people can be supported by a turbine slightly larger than existing 10 kW turbines if the average wind speed is consistently 5 m/s or greater over the course of a year.

Major hindrances to this technology include a lack of wind resource assessment in most locations, high cut-in wind speeds needed for pumping and high capital costs at sites with low average wind speeds.

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