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E.E. ANYANWU[1,2], N.V. OGUEKE[1]

DESIGN CONSIDERATIONS FOR WIND ENERGY POWERED WATER PUMPING FACILITY FOR SITES IN NIGERIA

The design considerations for sizing wind energy conversion system (WECS), pump and motor subsystems of wind powered water pumping facility for use in some communities in Nigeria are presented. These include the community population, water requirement per capita per day, the static head and the on-site wind data. The designs of the facility for all the locations utilized water requirements of 40 m^3/day and static head of 120 m. The results revealed that for aerogenerator hub heights of 50 and 100 m the rotor diameters in the range of 11–31 m and 9–28 m, respectively, are required for a pump power of 1.10 kW. Jos, a hill top city, with an altitude of 1286 m gave the most practicable size of WECS rotor diameter followed by Sokoto, Enugu, Maiduguri, Kano, and the coastal cities of Port Harcourt and Lagos with altitudes of 196 m and 39 m, respectively, in that order. Thus, wind energy powered water pumping is possible in all the cities, although a group of WECS may be necessary in some of the locations.

NOMENCLATURE

A – rotor swept area (m^2),
C_p – power coefficient,
D – rotor diameter (m),
E – energy (J),
g – acceleration due to gravity (m/s^2),
h – height (m),
P – power (W),
P_R – atmospheric pressure (mm Hg),
Q – volume (m^3),
T – temperature (°C),
V – mean velocity (m/s).

[1] Mechanical Engineering Department, Federal University of Technology, P.M.B 1526, Owerri, Nigeria.
[2] To whom all correspondence should be addressed.

GREEK SIGNS

η – efficiency,
ρ – density (kg/m^3),
π – constant = 22/7,
α – altitude (Hellman's) exponent.

SUBSCRIPTS

1 – reference height,
2 – height of interest,
a – aerogenerator,
e – electrical,
h – hydraulic,
p – pump.

1. INTRODUCTION

Water is of immense importance in the life of man. Its use ranges from drinking and cooking in home to irrigation for farming. Provision of clean water for domestic use is an important factor in government's effort to eradicate water-borne diseases such as cholera and guinea worm. Furthermore, it is largely responsible for rural-urban migration. Thus, there is the need to have steady and affordable clean water supply.

Obtaining clean water for domestic use has been a major problem in our rural areas. This is primarily due to economic factors which often make it difficult to have grid-connected electricity in these areas, thus making it impossible to sink electricity-powered bore holes. The rural dwellers are constrained depending on rainwater in wet seasons, accessibility to streams, wells, etc., during the dry season to meet their average daily water needs. According to World Health Organization (WHO), domestic water demand varies around 35–90 dm^3 per capita per day [1].

Fossil fuel powered and hand pumps can serve as alternatives in these areas. However fossil fuel powered pumps require well-trained personnel for maintenance and the fuel for running them. The fuel is often expensive and the supply becomes unreliable. Hand pumps, on the other hand, have only one outlet point and can only handle low flows. It can only serve one person at any point-in-time. Thus, many of such pumps are required to effectively serve a community. It is therefore necessary to develop an alternative and cost-effective means of providing clean water for use in the rural areas.

Wind energy powered water pumping is one such means of making water available in remote locations. Wind energy is freely available, environmentally friendly and inexhaustible. The cost of using it appears only in the means of harnessing it. The use of wind as small-scale sources of mechanical and electrical energy dates back to the 19^{th} century [2]. With the advent of other sources of mechanical and electrical energy like hydro, nuclear and thermal, little attention was paid to it. However, the current energy shortages, the need to reduce emission of green-house gases and the progress in the design of more efficient wind powered equipment have rekindled interest in wind-driven devices. Wind powered pumps are known to have a long history for lifting water in rural and remote areas for water supply and irrigation [3]. In Nigeria, in the 1960s windmills were successfully operated in Dundaye village in Sokoto State for water pumping from a borehole [4] and in Garo near Kano, where it was used until the early 1980s to supply water to a school dispensary and some 20 houses [5].

However information for wind powered facilities for many Nigerian communities, where numerous wind-favourable sites (hilltops, coastal, forested, etc.) abound, are not available. We, therefore, present the design considerations for wind powered water pumping facility for some Nigerian localities. Some communities in these locations are known to have no grid electricity and their water supply is mainly from streams, wells, etc.

2. THE DESIGN BASIS

A wind energy powered water pumping facility that will provide only the domestic water requirements of the community is considered. Forty (40) cubic decimetres per capita per day within the range specified by WHO [1] is considered plausible. This is expected to be met by the facility only. For the purpose of this study, the pipe work has been omitted in order to reduce hydraulic energy requirement and the size of the wind energy conversion system. Furthermore, water is to be collected only at the water-pumping site. Figure 1 shows a schematic illustration of a wind energy powered water pumping facility. Water supply requirements do not vary significantly month by month. However, it is necessary to provide storage to account for periods of low wind speeds. Records of the depth of boreholes sunk by the various States governments water corporation in the vicinity of these areas reveal average borehole depths in the range of 50–85 m. Accordingly the wind energy conversion system is to supply enough energy to lift water through this height. Considering the height of storage tank from ground, the total static head for this study may be assumed to be 120 m. This static head is assumed constant throughout the year, ignoring any variations that may arise due to drawdown. The water outlet points are gravity fed from the elevated storage tank.

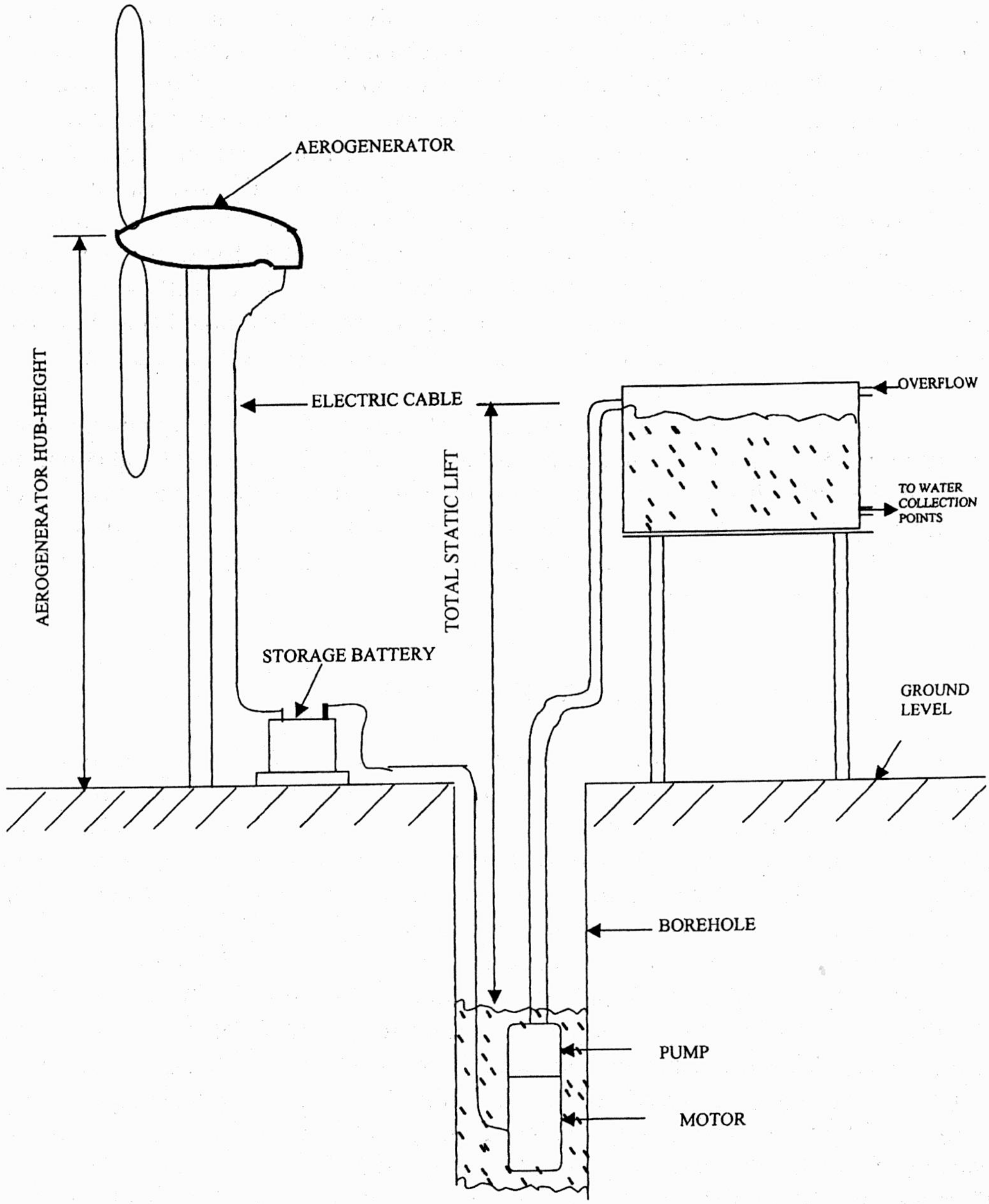

Fig. 1. Schematic diagram of the wind energy water system

The total water pumping energy requirement, the available wind velocity data for localities considered and the estimates of the WECS size for each of the locations are therefore presented.

3. WATER PUMPING ENERGY

The water pumping (hydraulic) energy E_{wpe} is related to the volume of water Q delivered according to equation (1):

$$E_{\text{wpe}} = \rho g Q h, \tag{1}$$

where Q and h are in cubic metres and metres, respectively. Thus for a community with an average population of 1000 people, the total energy required to pump 40 dm^3 per capita per day through a lift of 120 m is obtained from equation (1) as

$$E_{\text{wpe}} = 47.09 \text{ MJ/day}.$$

This translates to a water pumping power of 0.55 kW. This is the power that should be delivered to the water by the pump.

4. WIND DATA BASE

WECS is very sensitive to wind speed and there are periods of low output. Since it is expected to supply water throughout the year, the monthly mean daily wind velocity data are required. Such data as well as their frequency distribution and cumulative occurrence duration for seven different locations of interest are presented in figures 2–4. They are based on measurements at a height of 10 m from ground level. A careful examination of figure 2 shows that the wind velocity varies over 1.90–5.00 m/s. The available wind power density at any speed V may be estimated from equation (2) [4], [6]:

$$(P/A) = \tfrac{1}{2}\, \rho V^3. \tag{2}$$

However, it is not possible to convert completely all the available wind power to usable form. Betz's relation [7] assigns a power coefficient to the maximum extractable power from an optimum wind energy conversion system. Thus,

$$P/A = \tfrac{1}{2}\, C_p \rho V^3, \tag{3}$$

where C_p and ρ are the power coefficient and location air density (kg/m^3), respectively. Since the air density varies with an atmospheric pressure and air temperature, it is necessary to estimate the air density at the location. SIRISENA et al. [8] gave the relation for this as:

$$\rho = \frac{0.464\, P_R}{T + 273}, \tag{4}$$

where P_R is in mm Hg and T in °C. The values of air density for various locations obtained from equation (4) are given in table 1.

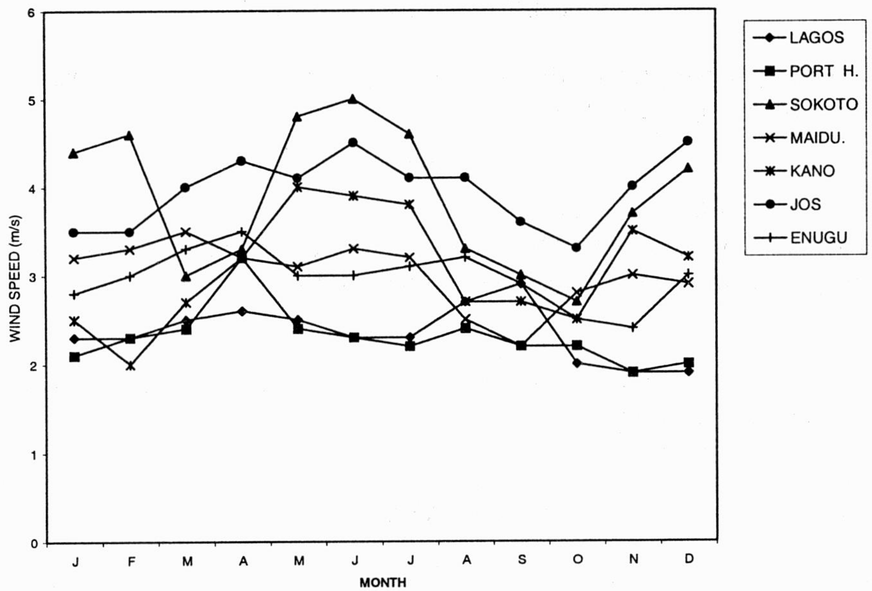

Fig. 2. Average daily wind speeds for the locations of study at 10 m height

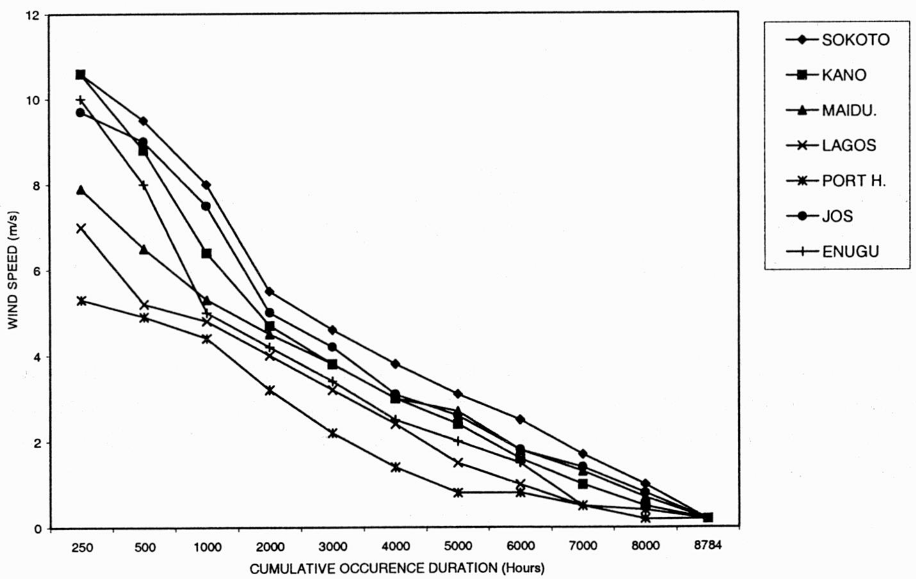

Fig. 3. Yearly wind speed cumulative occurrence curves at 10 m

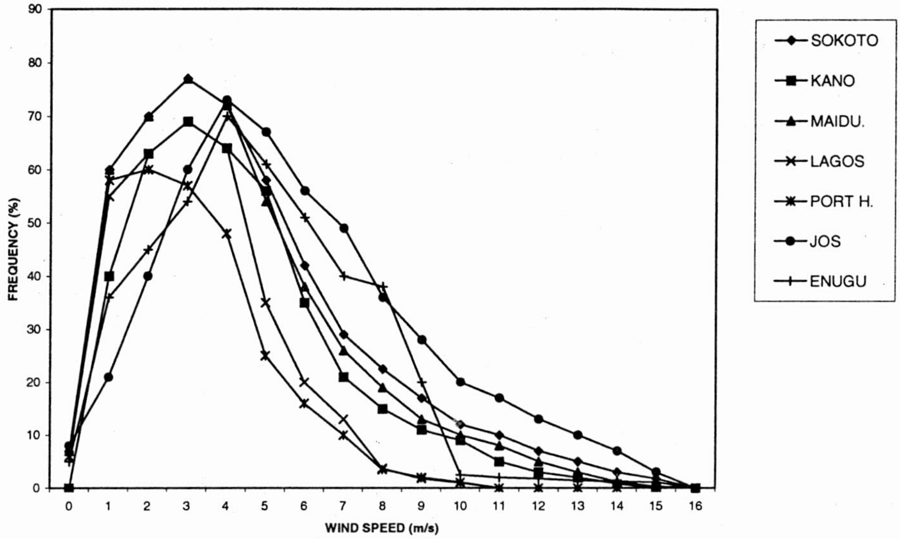

Fig. 4. Annual mean wind speed frequency measured at 10 m

Table 1

Rotor diameter size for a wind power plant at 50 m hub height for the locations

Location	Lagos (Ikeja)	Port Harcourt	Sokoto	Maiduguri	Kano	Jos	Enugu
Design month	October	November	October	September	February	October	November
Air density (kg/m^3)	1.179	1.177	1.171	1.176	1.174	1.183	1.177
Monthly mean wind velocity at 50 m (m/s) (calculated from eqn. (5))	2.39	2.39	3.55	2.89	2.63	4.93	3.31
Rotor diameter (m)	31	31	18	24	28	11	20

It is seen from equation (2) that the extractable wind power varies directly with the cube of the wind speed. This implies that an increase in wind speed of only 50% results in a wind power increase of above 200%. Wind speed also varies significantly with height and time [9]. This, perhaps, explains why WECS could be placed as high as 100 m or more above ground level. Hellman's exponential law [4], [6], [9] given below may be used to estimate the wind speed at any height from measurement taken at a reference height:

$$V_2 = V_1\left(\frac{H_2}{H_1}\right)^{\alpha}. \tag{5}$$

The value of Hellman's exponent α for use in equation (5) depends on the surface roughness and thermal stratification. Its value is given in ref. [10] as $\alpha = 0.143$ for coastal regions and α ranges from 0.2 to 0.3 for forested or hilly regions. Therefore for a selected hub height of 50 m for the wind energy conversion system, the corresponding wind velocities are given in figure 5.

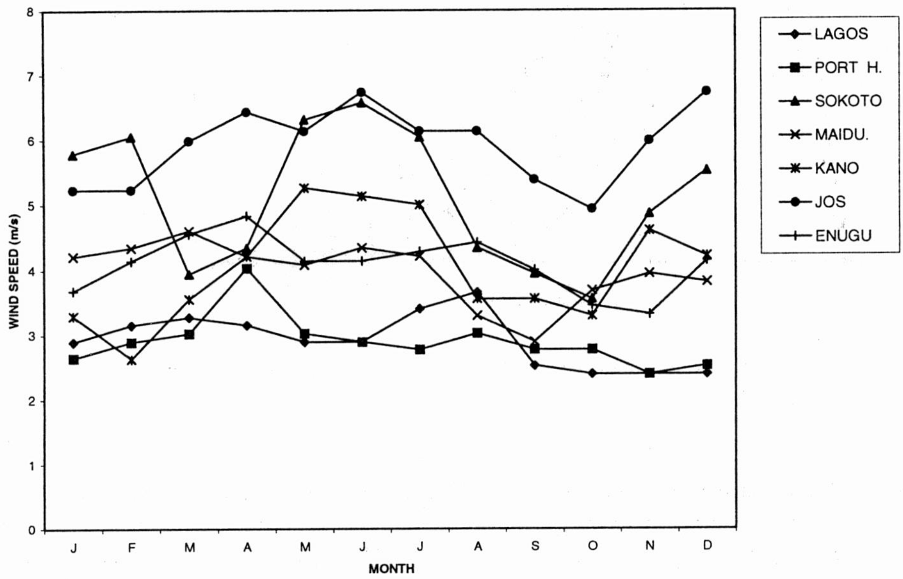

Fig. 5. Average daily wind speeds at 50 m above ground as calculated from equation (5)

5. SELECTION OF DESIGN MONTH

Wind power systems need a minimum velocity, the so-called cut-in velocity, to start operation. This cut-in velocity must be able to develop the minimal torque required at the start of a wind power plant. MUSGROVE [11] and DARWISH and SAYIGH [12] recommend cut-in velocity in the range of 2.2 m/s–3.1 m/s. In Nigeria, the mean wind speed exceeds 2.2 m/s at 25 m height for more than 80% of all stations [6], thus a cut-in velocity of 2.2 m/s is adequate. Furthermore, the fluctuation of wind velocity determines the type of energy storage facility that will be adopted. The fluctuations can be categorized according to whether their length of duration is in the range of seasons, weeks, days, hours, and minutes or seconds [10]. For a single wind power plant that requires a low content, low generating (short-term) energy facility, wind velocity fluctuations in the range of seconds or minutes are allowed. Consequently any month on which the design of the WECS is based should have a monthly mean wind velocity of at least 2.2 m/s with relatively high cumulative occurrence duration. The wind velocities in our chosen locations, with high frequencies and high cumulative occurrence duration, lie between 1.0–3.5 m/s (see figures 3 and 4). Thus selecting a month with higher mean wind velocity will increase power generation but reduce regularity of power supply. Since the interest is in supplying enough power for the pumps regularly, the design month should be the month with the lowest mean wind velocity that is, however, higher than or at least equal to the cut-in velocity. This will ensure enough power production from the WECS throughout the year.

Table 1 shows that the design month differs for the different locations considered. Lagos, Sokoto, and Jos have October as their design month. Port Harcourt and Enugu have November as their design month, while for Maiduguri and Kano it is September and February, respectively.

6. SIZING OF THE WIND ENERGY CONVERSION SYSTEM

The electrical power P_e and the hydraulic power P_h are related by equation (6)

$$P_e = \frac{P_h}{\eta_p}, \tag{6}$$

where η_p is the efficiency of the pump system required to lift the daily water requirement. Under usual operating conditions centrifugal pumps have efficiencies between 50% and 85% [13]. From equation (6) it can be seen that there is an inverse relationship between the pump efficiency and its electrical power requirement. Selecting a high-efficiency pump will reduce the electrical power required. However, any small drop in the pump efficiency due to usage will stop the water pumping operation. Thus, it is necessary to base the design on a relatively low efficiency pump. Selecting an efficiency of 50%, therefore, gives

$$P_e = 2.0P_h. \tag{7}$$

The electrical power P supplied by an aerogenerator as a function of the wind velocity V (for the moment assumed to be homogeneous over the rotor area, A) is given by a modified form [10] of equation (3):

$$P = 0.5\,\eta_a C_p \rho V^3 A, \tag{8}$$

where η_a is the efficiency of conversion of mechanical energy into electrical energy. Substituting the value of power coefficient C_p given in ref. [7] as 0.593 gives

$$P = 0.297\,\eta_a\, \rho V^3 A. \tag{9}$$

The electrical power supplied by the aerogenerator should be equal to the electrical power requirement P_e. We therefore combine equations (7) and (9) to obtain

$$2.0\,P_h = 0.297\,\eta_a \rho V^3 A. \tag{10}$$

Thus

$$A = \frac{P_h}{0.148\,\eta_a \rho V^3}.$$

Aerogenerators have low efficiency of conversion of mechanical energy into electrical energy [2]. For such systems, the value for η_a recommended is about 0.3 [6]. Thus

$$A = \frac{P_h}{0.044\,\eta_a \rho V^3}. \tag{11}$$

This rotor swept area is related to the rotor diameter by

$$A = \frac{\pi D^2}{4}. \tag{12}$$

Inserting equation (12) into equation (11) gives the rotor diameter as

$$D = \left(\frac{4P_h}{0.044\,\pi \rho V^3} \right)^{1/2}. \tag{13}$$

We can therefore say that D is a function of P_h, ρ and V^3. That is,

$$D = f\left(\frac{P_h}{\rho V^3} \right)^{1/2}, \tag{14}$$

where f is a constant with the value equal to 28.94.

7. SIZING OF MOTOR

Electric motors are usually rated in terms of their electrical input power. This implies that the maximum rating of the motor to be used must be at least of the same magnitude as the electrical power generated by the aerogenerator. The current and voltage limitations of the motor will, therefore, be matched by selecting the appropriate aerogenerator.

8. SIZING THE PUMP

The pump should be able to lift water through the required height and at a flow rate that will enable the daily total water requirement to be met. The power required to run a pump is related to the hydraulic power by equation (6). Thus for a pump with an efficiency of 50%, the power requirement P_p is obtained from equations (6) and (7) as $P_p = 1.10$ kW.

9. RESULTS AND DISCUSSION

Figure 5 shows the values of velocities at a height of 50 m. Table 1 shows the air densities at the various locations and the rotor diameters obtained using equations (4) and (13), respectively. The required rotor diameter for a hub height of 50 m is seen to vary between 11 m for Jos, which is a hilly city with an altitude of 1285.58 m, and 31 m for Lagos and Port Harcourt, which are coastal cities with altitudes of 39.35 m and 195.51 m, respectively.

Unfortunately, wind energy conversion systems (WECS) with rotor diameter greater than 16 m need a threshold wind velocity of 5 m/s in order to keep the blade in rotation [14]. Furthermore, a large diameter wind energy conversion system with rotor diameter $D > 15$ m experiences a large velocity gradient of wind velocity along the blades which can result in a substantial change in blade loading during one revolution [15]. Consequently, Jos is the only location where a 50 m hub height WECS can be used effectively for the desired power generation. Any of the following two options will be available to the other locations if wind energy is used to provide water from boreholes:

(i) Increasing the hub height of the WECS.

(ii) Using more than one WECS at a hub height of 50 m to generate the same required power.

Table 2

Rotor diameter size for a wind power plant at 100 m hub height for the locations

Location	Lagos (Ikeja)	Port Harcourt	Sokoto	Maiduguri	Kano	Jos	Enugu
Design month	October	November	October	September	February	October	November
Monthly mean wind velocity at 100 m (m/s) (calculated from eqn. (5))	2.64	2.64	3.99	3.25	2.95	5.87	3.80
Rotor diameter (m)	28	28	15	20	23	9	16

Table 2 shows the wind velocities for the design months at a height of 100 m and the corresponding rotor diameters. It can be seen from the table that an increase of 50 m in hub height produces a reduction in rotor diameter between 2–6 m. Sokoto is the only location where the rotor diameter came within the allowable limit of 15 m after the increase. It is therefore obvious from the table that option (ii) is preferred. Although increasing the height up to and above 100 m may yield the desired result, the difficulty in installing and maintaining such a WECS and the danger it will pose to the aviation industry make it unattractive.

Generally, the range of sizes of rotor diameter obtained is indicative of the high available wind energy in these locations. The wind can be harnessed effectively and used to improve the living standard of the inhabitants of these communities, especially in the area of provision of portable water for domestic use.

10. CONCLUSIONS

A wind energy powered water pumping facility capable of handling up to 40 m^3/day has been designed. The design involved the estimation of WECS and pump sizes. The WECS size was found to be a function of the hydraulic power requirements and the site-specific wind speed. The method has been illustrated for seven cities in Nigeria using the on-site wind data. The cities are representative of the climatic conditions and favourable sites (hill tops, coastal and forested regions) in the country. It was found that Jos, a hill-top city, is the only location where 50 m high WECS could be used to provide the design rating of 1.10 kW for water pumping application. For the other locations, a group of WECS with electrical rating around this level is required to achieve the same purpose. These results indicate that WECS operation for water supplies is possible throughout the year in each of the cities, although a back-up may be needed at periods of low wind speeds.

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WYTYCZNE PROJEKTOWE DLA WODNYCH STACJI POMP NAPĘDZANYCH WIATREM

Zanalizowano parametry projektowe elektrowni wiatrowych wraz z podsystemem pompowo-silnikowym, co pozwoli wykorzystywać wodne stacje pomp na wybranych terenach Nigerii. Analiza obejmowała takie parametry, jak: liczba mieszkańców, dobowe zużycie wody przez jednego mieszkańca, wysokość statyczna oraz dane dotyczące wiatrów na danym terenie. W założeniach projektowych dla wszystkich lokalizacji przyjęto zapotrzebowanie na wodę na poziomie 40 dm^3/d i wysokość statyczną równą 120 m. Obliczenia wykazały, że dla aerogeneratorów (wiatraków) z piastą na wysokości 50 i 100 m średnice wirników powinny wynosić odpowiednio 11–31 m i 9–28 m. Wówczas moc pompy będzie równa 1,10 kW. Najpraktyczniejsze rozmiary wirników elektrowni wiatrowych uzyskano w przypadku miasta Jos, położonego na wysokości 1286 m. W dalszej kolejności dobre wyniki otrzymano dla miast: Sokoto, Enugu, Maiduguri, Kano oraz miast nadmorskich, Port Harcourt i Lagos, leżących na wysokości odpowiednio 196 m i 39 m. Stwierdzono, że budowa wodnych stacji pomp jest możliwa we wszystkich miastach, jednakże dla pewnych lokalizacji niezbędny jest zespół kilku elektrowni wiatrowych (wiatraków).