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Design and Cost Analysis of 3 Kw Wind-Diesel Hybrid Water Pumping System for Ban Village

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ABSTRACT

Underground water from boreholes is probably the most reliable alternative source of potable drinking water especially in rural areas. Adequate, reliable and affordable energy is required to pump the water to the surface for use. Most rural areas do not have access to grid-connected electricity and the burning of fossil fuels to provide energy is environmentally unfriendly. Solar energy is only available in the day time and wind energy is stochastic. These necessitated the design of a wind-diesel hybrid water pumping system, which is more reliable for a rural community in Ban village in Nigeria. The hybrid system will pump water from underground to an overhead tank to supply the village for a period of 20 years. A design analysis gave results that for adequate water supply to the village, a 3 kW wind-diesel hybrid system is required. A cost analysis via the annuity method gave the cost of water to be $0.2/m^3, which is considered economical in view of the value attached to water in that location.

***KEY WORDS**: Annuity, Design, Hybrid energy, Underground water*

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I. INTRODUCTION

Water is essential to man, animals and plants and without water life on earth would not exist. About 80% of all diseases in the world are associated with unsafe water [1]. In spite of the significance of water most rural areas do not have access to adequate potable drinking water. The existing surface water sources such as rivers, ponds, streams, and lakes, which may not be fit for direct usage, cannot meet the rural water demand due to increase in population.

Underground water seems to be the possible alternative to this dilemma, but the underground water table is also decreasing, which makes traditional hand pumping and bucketing from shallow wells difficult [2]. Thus, mechanised or motorised water pumping will become the only reliable alternative for lifting water from underground.

However, there are challenges in using motorised water pumping due to the poor energy situation in Nigeria. The few rural areas connected to the national grid do not have efficient power supply thus making motorised water pumping difficult. Diesel, gasoline, and kerosene pumps used to pump water are great contributors of greenhouse gases and the occasional scarcity and price-hike of the product in Nigeria and the routine maintenance of the systems are hindrances to using them.

Renewable energy technologies such as solar and wind, are better options in remote locations especially in Nigeria in the face of the current energy crisis. However, solar energy can only be harnessed in the day time while wind energy is stochastic. A hybrid energy system which is a combination of renewable and non-renewable, such as wind and diesel engine would produce a steady energy supply for pumping water from boreholes.

Wind-diesel hybrid power system is defined as a combination of diesel generators/engine and wind turbines, usually alongside ancillary equipment such as energy storage, power converters, and various control components, to generate electricity/or pump water [3]. Wind-diesel hybrid systems reduce reliance on diesel fuel, which creates pollution and is costly to transport [3]. This technology can be applied in rural areas, which is the case for Ban village to pump water from boreholes to an overhead tank for community use.

Ban is a village in Plateau State, Nigeria. It is about 2 km away from Jos airport. It is located at an altitude of 1200 m above sea level between longitudes 8^0 53' E and 8^0 54' E and between latitude 9^0 39' N and latitude 9^0 40' N. It has an average annual rainfall of 1,400 mm, which lasts between 6-7 months [4]. It has the lowest temperature record of 15^0 C between December and January and the highest record of 32^0 C in March. The dry season is dominated by the north-easterly wind between October and April and the wet season is dominated by the south-westerly moist tropical maritime wind between May and September [4]. The natural vegetation of Ban village is close to guinea savannah. The vegetation is characterised by shrubs and grass with few scattered trees planted by the people in the village.

II. MATERIALS AND METHOD

2.1 Description and principle of operation of the wind-diesel hybrid system

The wind-diesel hybrid water pumping system comprises of the following main components as shown in figure 1: (i) Tower, (ii) Wind turbine, (iii) Diesel engine, (iv) Gearing system, (v) Bearing (vi) Reciprocating pump. (vii) Shafts, crank shaft and couplings, (viii) Suction and Delivery pipes, (ix) Water storage tank and support. The kinetic energy from the wind is converted to mechanical torque by the wind turbine. The torque on the turbine shaft is transmitted to the differential gear through the bevel gear by the vertical shaft. The differential gear synchronises the speed of the wind turbine and diesel engine [5]for onward transmission to the crank shaft. The rotary motion of the crank shaft is converted to the reciprocating motion of the piston through the pump rod in the pump cylinder. The upward motion of the pump rod creates a partial vacuum in the cylinder thereby sucking water from the borehole through the foot valve which opens while the piston valve remains closed. During the downward motion of the pump rod, the foot valve closes while the piston valve opens thereby forcing the water in the cylinder to the storage tank for community use. The moment the water level drops to the critical level L_1 (level L_1 is determined by the amount of water that will meet the water need of the community for two days) the floating regulator sends electrical signals to the diesel engine which starts automatically. The torque from the diesel engine shaft is transmitted to the crank shaft through the spur gear and differential gear systems thereby pumping water alone or in collaboration with the wind turbine. As soon as the water level reaches L_2, (level L_2 is determined by the amount of water that will meet the water need of the community for one day) the floating regulator switches off the diesel engine living only the wind turbine to operate the piston thus saving fuel. The hybrid system can operate in any of the following ways:

i. Only wind turbine driving the pump, if the water is at level L_1 and above
ii. Only the diesel engine driving the pump, if the water is at level L_2 and the wind speed is below the cut-in wind speed or above the cut-out wind speed.
iii. Both the wind turbine and the diesel engine driving the pump, if the water level is at L_2 and the wind speed is equal to or above the cut-in wind speed but less than the cut-out wind speed.

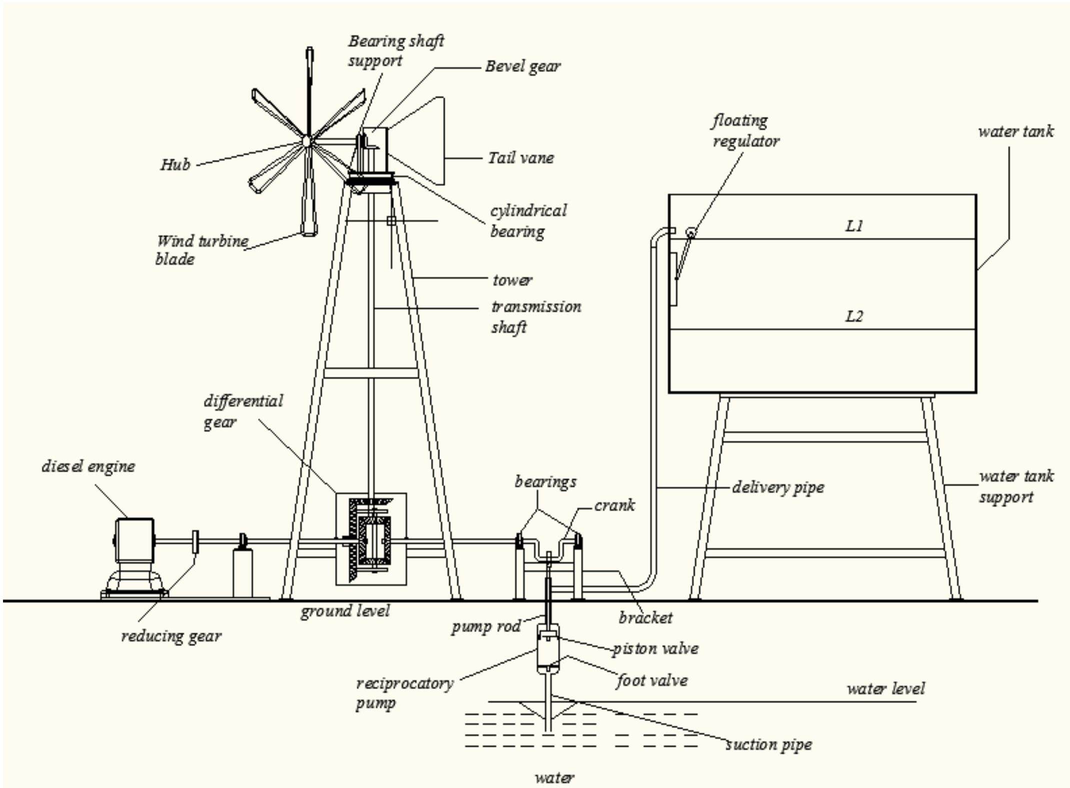

Figure 1: A schematic diagram of the designed wind-diesel hybrid water pumping system

2.2 Design Considerations

i. The design of the hybrid wind-diesel water pump system is based on stand-alone operation. The capacity of the windmill or diesel engine should be able to pump the water required in the village alone. Thus, the hybridisation of the system is an added advantage as it gives availability and reduces diesel consumption.
ii. The transmission systems such as the reducing gear, differential gear and the bevel gear are not designed but selected from products catalogues based on their operational requirements in the system.
iii. The pumping rate of the system is not to exceed the yield of the borehole, or else the borehole will dry up thereby wearing up the reciprocating pump.
iv. Water storage capacity is also considered in the design of the wind-diesel hybrid pump as it depends on factors such as the daily water consumption of the village, energy availability for pumping and cost and the availability of other water sources.
v. The availability of the wind-diesel hybrid wind pump system components in the market, their cost and maintenance are other factors considered in the design of the system.

2.3 Design Theories

2.3.1 Projected population of Ban village

The water consumption of a community is a function of the population and the standard of living of the community. Thus, the projected population growth of the community is determined as given in [6]:

$$P(t) = P_o e^{r_p t} \tag{1}$$

Where P_o the initial population of the community, r_p is the population growth rate of Nigeria, t is the life span of the system and $P(t)$ is the projected population at time t.

2.3.2 Water requirement of Ban village

The water consumed in a community is determined as given in [1]:

$$q_v = P_{t20} W_{pc} \tag{2}$$

Where, q_v is water consumed by community, P_{t20} is projected population of the community after 20 years and W_{pc} is the per capita water consumption.

2.3.3 Borehole depth and safe yield of underground water of Ban village

The optimum characteristics of boreholes in Ban village as given in [7] and [8] are:

i. Total depth of bore hole - 30 m
ii. Pump installation depth - 27 m
iii. Yield of boreholes - 1.5 litre/second

2.3.4 Total head of the system

Total head of the system, according to Darcy-Weisbach formula, taking into consideration losses on the delivery and suction side of the pipe, is given in [9] as:

$$H = \frac{8Q^2}{\pi^2 {D_d}^4 g}\left[f\frac{L_p}{D_d} + K + 1 \right] \tag{3}$$

Where, H is total head of the system, Q is volume flow rate, f is friction factor, which can be determined from the Moody chart, L_p is the length of pipe, K is loss coefficient of the pipe, D_d is diameter of pipe and g is acceleration due to gravity.

2.3.5 Hydraulic power requirement

The hydraulic power needed to lift the water from the source (borehole) to an overhead tank can be calculated as given in [10]:

$$P_{hyd} = q_v \rho_w g H \tag{4}$$

Where, P_{hyd} is hydraulic power, ρ_w is density of water, g is acceleration due to gravity, q_v is water consumed by community, H is total head which includes (Static and dynamic height of the water source below ground level and head losses in suction and delivery pipes due to friction.

2.3.6 Wind power potential

The wind power potential is given as the specific wind power or the power per unit area. It is given in [11] as:

$$P_{wind} = \frac{1}{2}\rho_a V^3 \tag{5}$$

Where, P_{wind} is the wind potential, ρ_a is the density of air and V is the wind velocity.

2.3.7 Reference area and size of windmill

The ratio of the hydraulic power of each month divided by the specific wind power potential for that same month has the dimension of area and is referred to as the reference area. The reference area as given in [11] is:

$$R_a = \frac{P_{hyd}}{P_{wind}} \tag{6}$$

The size of the windmill depends on the diameter of the rotor. This can be obtained from the reference area as given in [11]:

$$D_r = \sqrt{\frac{4R_a}{\pi}} \tag{7}$$

Where, R_a is the reference area, P_{hyd} is the hydraulic power of the system, P_{wind} is the wind power potential and D_r is the rotor diameter.

2.3.8 Pump size

The size of a wind pump depends on the volume of water required to be discharged by the pump and is given in [10] as:

$$q_v = \eta_{vol}\frac{\pi D_p^2 N_r S}{4} \tag{8}$$

Where, q_v is the water consumed by community, η_{vol} is the volumetric efficiency of the pump, N_r is the rotational speed of rotor, D_p is the diameter of the pump and S is the stroke of the pump.

2.3.9 Design speed

The design wind speed is that which the overall efficiency of the system reaches a maximum. In practice, it is the wind speed at which the power coefficient C_p reaches its maximum value $C_{p\max}$. It is also determined by equating the net rotor power to hydraulic power as given in [12]:

$$V_d = \sqrt{\frac{\eta_{vol} S D_p^2 \lambda_d \rho_w g H}{4(C_p)_{\max}\eta_{mech}\rho_a \pi R^3}} \tag{9}$$

Where, η_{mech} is mechanical efficiency, $(C_p)_{\max}$ is maximum power coefficient of the windmill, ρ_a is density of air, V_d is design velocity, R is radius of turbine, ρ_w is density of water, g is acceleration due to gravity, S is the stroke of the pump and H is total head.

2.3.10 Sizing of diesel engine

The required shaft power can then be calculated as given in [13]:

$$P_s = \frac{P_{hyd}}{\eta_p \times \eta_c \times \eta_r \times \eta_d} \tag{10}$$

Also, the required engine power is given in [13] as:

$$P_E = \frac{P_{hyd} \times L_f}{D_f} \tag{11}$$

Where, P_s is shaft power, P_E is diesel engine power, P_{hyd} is hydraulic power, L_f is Load factor, η_p is pump element efficiency, η_c is friction losses at coupling, η_r efficiency of spur gear, η_d is efficiency of differential gear, D_f is derating factor for altitude and temperature.

2.3.11 Capacity of storage tank

The capacity of the storage tank can be determined from the product of the daily water requirement and the number of days required for constant water supply as given in [14]:

$$V_S = W_d \times S_F \quad (12)$$

Where, V_S is storage tank capacity, S_F is days for constant water supply, W_d is daily water consumption.

2.3.12 Transmission systems

2.3.12.1 Gearing system

The basic steps for the selection of transmission systems such as differential gear, bevel gear and spur gear from catalogues as given in [15] are:

- Determination of the service factor, K_S from table
- Calculation of the equivalent power.

Equivalent power P_G = Actual power $P_{AG} \times$ Service factor K_S (13)

- Determination of the speed ratio:

$$i_r = \frac{Speed\ of\ input\ shaft}{Speed\ of\ output\ shaft} = \frac{N_I}{N_O} \quad (14)$$

Where, i_r is gear ratio, $i_r > 1$ is gear reducer and $i_r < 1$ is gear multiplier.

2.3.12.2 Shaft

The power transmitted by a shaft at a given revolution is given in [16] as:

$$P_{SP} = T_s \times \omega_s \quad (15)$$

For a shaft subjected to only twisting moment:

$$T_s = \frac{\pi}{16} \tau\, d^3 \quad (16)$$

For shaft subjected to combined twisting moment and bending moment, the equivalent twisting moment based on the maximum shear stress theory or Guest's theory used for ductile materials such as mild steel as given in [16]:

$$T_e = \sqrt{(T^2 + M^2)} = \frac{\pi}{16} \tau\, d^3 \quad \text{(solid shaft)} \quad (17)$$

Where, P_{SP} is the power transmitted by shaft, T_s is the torque on the shaft, ω_s is the angular velocity of the shaft, T_e is equivalent twisting moments, T is twisting moment, M is the bending moment, τ is shear stress, d is diameter of solid shaft.

2.4 Theoretical efficiency of wind-diesel hybrid pump system

The actual power need is always greater than the hydraulic power needs, because losses inevitably occur when producing and transmitting power due to friction. The quality of a system in terms of minimising losses is defined as its efficiency. Thus,

$$Total\ efficiency\,\eta_T = \frac{Hydraulic\ power\ output\ P_{hyd}}{Actual\ power\ input\ of\ wind\ pump\ system\ P_I} \quad (18)$$

2.5 Cost analysis of the wind-diesel hybrid water pumping system

The total yearly cost is obtained by adding the annuities (which is a conversion of the investment into an equivalent yearly amount of money that would have to be paid every year during the (economic) lifetime of the installation, if the investment were financed through a loan)of the investment and recurrent costs together. The annuity is determined as given in [12]:

$$A = I \times \frac{r_r}{1-(1+r_r)^{-t}} \tag{19a}$$

Components such as diesel engine and pump have lifespans shorter than the lifespan of the whole system, thus, there will be replacement of these components before the lifespan of the system elapses. The future cost of replacement of components is given in [10] as:

$$F_{cv} = I(1+i)^N \tag{19b}$$

Similarly, the annuity of the future cost can be calculated as in [10]:

$$A = \frac{F_{cv} \times r_r}{(1+r_r)^t - 1} \tag{19c}$$

Where, I is the total investment excluding replacement cost, F_{cv} is future cost of replacement, r_r is real interest rate, t is the life span of the system, N is the number of years before replacement and i is the inflation rate.

2.5.1Cost of operation, maintenance and repair

The total cost of operation, maintenance and repair of a diesel engine is determined as given in [12]:

$$C_{Tomr} = C_{omr}(1+i)t \tag{20}$$

Where, C_{Tomr} is the total cost of operation, maintenance and repair of diesel engine C_{omr} is the operation, maintenance and repair cost, i is the inflation rate, t is the lifetime of the diesel engine.

2.5.2 Cost of diesel fuel consumed

The total cost of diesel fuel consumed by a diesel engine is determined as given in [12]:

$$C_{f\,T} = F \times C_f(1+e)t \tag{21}$$

Where, F is the annual fuel consumption (litre/year), C_f is the cost of fuel ($/litre), e is the escalation rate, t is the lifetime of diesel engine.

2.5.3 Cost per m^3 of water pumped

The cost per m^3 of water pumped by the wind-diesel hybrid water pump system is determined by dividing the total annuity of the system by the annual volume of water pumped by the system.

The prices of the components of the wind-diesel hybrid system were obtained from the internet [17]and market survey as shown in table 3.1. The exchange rate for the conversion of naira to US dollar is ₦157 to $1[18]

The cost analysis of the systems is based on the following assumptions:

i. Based on the information from a CE-211CC model of 4.2 HP (3.1kW), diesel engine maintenance technicians, the fuel consumption of 0.5 litre per hour and monthly maintenance of the diesel engine are here assumed to be constant for the period of 20 years;
ii. The pump has a life span of 10 years [19], which will require replacement after 10 years of service before the lifespan of the system.
iii. The current inflation rate of 9 % per annum [20] is assumed to be constant over a period of 20 years.
iv. The diesel engine has a life span of 5 years, thus, four sets of diesel engine will be required throughout the life span of the system;
v. The cost of diesel at $1.15 per litre is constant for 20 years.
vi. The current loan interest rate from banks of 12 % per annum maximum [20] will be constant over a period of 20 years;.
vii. Escalating rate of 3% per annum [12], of the fuel is constant over the period of 20 years;
viii. Salvage value of the diesel engine is negligible.

2.6 Wind pump Availability Estimation

The water output from the pump varies with the wind speed. Matching the power of windmill and the hydraulic power gives the water output by the system as a function of the wind speed of the site. The water output by the wind pump stand-alone operation is calculated as given in [12]:

$$q = \frac{C_E (C_p \eta)_{\max} \rho \pi R^2 V^3}{2 \rho_w g H} \qquad (22)$$

Where $(C_p \eta)_{\max}$ is overall power coefficient of windmill, C_E is energy production coefficient, ρ_a is density of air, R is radius of windmill, ρ_w is density of water, H is total head, g is acceleration due to gravity and V is the wind velocity.

A multi-bladed windmill designed by ironman company of 3.6 m diameter, cut-in velocity of 3 m/s, rated velocity of 8 m/s and the cut-out velocity of 12 m/s., $(C_p \eta)_{\max}$=0.36 and C_E =0.4 was selected to determine the availability of the windmill in the hybrid system [18]. These parameters and the wind speed data collected from the meteorological station Jos airport (as according to literature, when there are no remarkable changes in terrain, wind speed can be applied as far as 25 km [21]),are used in equation (22) to determine the availability of the windmill as showed in table 3.4.

III. RESULTS AND DISCUSSION

3.1 Results

Tabel.3.1: Wind-diesel hybrid system components, units and cost

S/N	Components	Unit	Total cost ($)
1	Ironman 702 windmill/3.6 m diameter	1	6,450
2	Heavy steel 4-leg tower 16 m high	1	6,150
3	150 mm diameter well pump and seals	1	955
4	6 m length Pump rod	5	200
6	160 mm diameter PVC well pipe	12	77
7	44 mm diameter rising main (suction and delivery pipes)	20	64
8	Bearing bracket pillow with bearing	1	26
9	NRV050-E spur gear (reducing gear)	1	210
10	ANDEX-ANDANDEX bevel gear	1	204
11	200 mm bore BMT cylindrical roller bearing	1	200
12	Specon differential gear	1	192
13	2000 x 2000 x 20 mm metal sheet	1	300
14	Crank web and pin	1	39
15	A CE-211CC model of 4.2 HP (3.1kW), 3600 rpm diesel-engine with DC battery and starter	1	192
16	Installation		956
17	Miscellaneous		418
18	Cost of surveying and drilling of boreholes in Ban village		3,504
20	Water storage tank construction and installation	130 m^3	17,437
	Total Investment of hybrid system excluding replacement cost		37,572
	Total annuity of hybrid system		6,318.31

Source: internet and local market survey

Table 3.2: Results of design calculations

Items	Results
Present population	2600
Projected population	4600
Water consumed by Ban village	41,975 m^3/year
Total head	35 m
Hydraulic power required	446 W
Wind power potential	44.45 W/m^2
Pump size	Diameter =150 mm, Stroke =220 mm
Wind turbine size	Diameter=3.6 m, Power= 3 kW
Size of Diesel engine	Power=3 kW
Design speed	7.3 m/s
Storage tank	130 m^3

Table 3.3: Total annuity of the wind-diesel hybrid system

Cost	($)
Annuity of Investment and replacement cost	5,029.35
Annuity of operation, maintenance and repair cost	70.04
Annuity of diesel fuel consumed	1,219
Total annuity	6,318.31
Cost per m^3 of water pumped	0.2 /m^3

Table 3.4: Computation of water pumped by the wind turbine

Wind speed interval (m/s)	Frequency distribution of site wind speed (Hr)	Water output at H=35 m (m^3)
0-1	71	0
1-2	164	0
2-3	571	227
3-4	654	549
4-5	1921	2941
5-6	1358	3431
6-7	893	3474
7-8	1526	8640
8-9	742	4207
9-10	549	3108
10-11	268	1517
11-12	33	0
12-13	10	0
Total	8760	28,095

3.2 Discussion

Table 3.1 shows the design calculation results of the wind-diesel hybrid water pump system. The projected population growth of the village after 20 years is 4600 and the water consumption is 41,975m^3/year. Based on the water requirement of the village, it needs a 3 kW wind-diesel hybrid water pump system to adequately pump water from a borehole of 30 m depth to an overhead tank for standpoint supply. Also, as shown in table 3.2, the cost per m^3 of water by the hybrid system is $ 0.2/m^3.

Table 3.4 shows the wind speed frequency distribution and the water pumped by the wind pump based on the wind pump stand-alone operation. Analysis based on the wind speed regime of Ban village, as obtained from the Jos airport which is about 2 km away from Ban village, show that the wind pump is 97% available and it will supply about 70% of the annual total water requirement of the community. Thus, the remaining 30% can be supplied by the diesel-engine, thereby reducing the amount of the greenhouse gases emission and cost of operation as less fuel is consumed.

IV. CONCLUSION

The wind-diesel hybrid water pumping system comprising of a windmill and a diesel engine powering a reciprocating pump was designed and the components selected. This was done by sizing the three components (windmill, diesel engine and reciprocating pump) to give a reliable water supply to the village.

The availability of the windpump in the hybrid system is very high which results in far less fuel consumption than would be if the diesel engine is used alone

The cost of water from the wind-diesel hybrid pump system is economical considering the value attached to water in a remote location like Ban village.

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