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Research article

Feasibility study of a wind powered water pumping system for rural Ethiopia

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Abstract: Water is the primary source of life for mankind and one of the most basic necessities for rural development. Most of the rural areas of Ethiopia do not have access to potable water. Is some regions of the country access potable water is available through use of manual pumping and Diesel engine. In this research, wind water pump is designed to supply drinking water for three selected rural locations in Ethiopia. The design results show that a 5.7 m diameter windmill is required for pumping water from borehole through a total head of 75, 66 and 44 m for Siyadberand Wayu, Adami Tulu and East Enderta to meet the daily water demand of 10, 12 and 15 m^3, respectively. The simulation for performance of the selected wind pump is conducted using MATLAB software and the result showed that monthly water discharge is proportional to the monthly average wind speed at the peak monthly discharge of 685 m^3 in June, 888 m^3 in May and 1203 m^3 in March for Siyadberand Wayu , Adami Tulu and East Enderta sites, respectively. An economic comparison is conducted, using life cycle cost analysis, for wind mill and Diesel water pumping systems and the results show that windmill water pumping systems are more feasible than Diesel based systems.

Keywords: Wind speed; wind pump; simulation; MATLAB software; cost analysis; feasibility

Nomenclature

A_T: Area of Rotor;
C_{pd}: Design Power Coefficient of the Wind Rotor;
A_y: Annualized Life Cycle Cost;
C_y: Annualized Capital Cost;

C_k: Present Worth of Replacement at Year K;
D_p: Diameter of Pump;
d_s: Days of constant water supply;
R_a: Reference area of the rotor;
D_r: Diameter of Wind Rotor;
D: Discount Rate;
E_s: Total energy available in the spectra;
E_D: Energy Density (kW/m^2);
E_I: Energy available for the unit area of the rotor;
n: Number of wind data;
$f(v)$: Cumulative distribution function;
N: Life Time Period;
h_f: Total friction head losses;
H: Total Head;
$F(v)$: Probability density function;
V_i: Cut-In Wind Speed;
P: Per capital water consumptions;
P_{wind}: Wind power (W/m2);
P_{hyd}: Hydraulic power required;
Q: Volume flow rate;
Q_{VP}: Instantaneous discharge of the system;
V: Wind stream velocity;
S: Storage tank capacity (m^3);
T: Time Period in Hours;
Q_p: Total water demand per day;
V_o: Cut-Out Wind Speed;
N_p: Total number of beneficiaries;
V_m: Average Wind Speed;
V_{Fmax}: The most frequent wind velocity (m/s);
V_d: Design Wind Speed;
R_k: Cost of Replacement of a System Component at Year K;
D_d: Diameter of pipe;
K: Sum of loss coefficient of the pipe, valve and fittings;
I: Interest Rate;
K_o: Constant to Define the starting behavior of Piston Pumps;
L_p: Length of pipe;
V_{Emax}: The velocity contributing the maximum energy (m/s);
f: Friction factor;
My: Yearly Operating and Maintenance Cost of the Initial Capital Cost C;
R_y: Present worth of All Replacement, Incurred during the Life Time N;
Q_{IP}: Discharge expected from the system installed at a given site, over a given period.

Greek Symbols

ρ_a: Density of Air;
ρ_w: Density of Water.

Abbreviations

AAU: Addis Ababa University;
CC: Capital Cost;
CRF: Capital Recovery Factor;
DC: Direct Current;
PWF: Present worth factor;
EC: Energy Cost;
DPS: Diesel Pumping System;
DP: Diesel Pump;
HAWT: Horizontal Axis Wind Turbine;
MC: Maintenance Cost;
NMSA: National Metreology Services Agency;
SC: Salvage Cost;
VAWT: Vertical Axis Wind Turbine;
RC: Replacement Cost;
WECS: Wind Energy Conversion System;
WP: Windmill pump;
O&M: Operation and Maintenance Cost;
FE: Fuel Escalation Rate;
WPS: Wind Pumping System.

1. Introduction

Wind power technology dates back many centuries. There are historical claims that wind machines which harness the power of the wind date back to the time of the ancient Egyptians. By the late part of the 17th century, the typical "European Windmill" became established and this became the norm until further developments were introduced during the 18th century. The major advances in the design of the wind pump, however, took place in the USA. By the 1920's, 6 million wind pumps were being used in the USA alone and their manufacture and use became commonplace on every continent [1].

Water is the primary source of life for mankind and one of the most basic necessities for rural development. The rural demand of water for domestic and crop irrigation supplies is increasing [2]. People living in rural areas of Ethiopia use different water sources for their domestic purpose, such as spring, pond, ground, etc. the ground water being considered as the best source for clean drinking water supply.

Therefore, mechanized water pumping system will be the only reliable alternative for lifting water from the ground. Diesel, gasoline and kerosene pumps including windmills have traditionally been used to pump water [2]. However, reliable solar photovoltaic (PV) and wind turbine pumps are now emerging on the market and are rapidly becoming more attractive than the traditional power sources. In addition, nowadays, with regular fuel crises and rising prices there has been a revival of interest in wind pump technology.

In Ethiopia, Diesel water pumping systems have been applied for long years. Currently, however, because of rising of fuel price all over the world, including Ethiopia, almost all the systems have become non-functional. Therefore, in 2006 the Government planned to replace all Diesel water pumping systems by solar/wind water pumping systems. According to the recent report prepared by HYDROCHINA Corporation, the country has a capacity of 1350 GW (> 7 m/s) wind energy potential. In most areas of the country, there is a low and medium wind energy potential (> 2.8 m/s), which can be applicable for water pumping.

The objective of this research is to study the feasibility of wind powered water pumping system for rural area application in Ethiopia. In a previous part of this research the feasibility of PV water pumping system was studied. In this paper, the feasibility of wind powered water pumping system in Ethiopia is studied by selecting three rural areas from three administrative regions of the country. The design and simulation of the proposed system is carried out using analytical methods and simulations in the MATLAB software. An economical comparison is also carried out, using life cycle cost analysis method, for both wind and Diesel water pumping systems.

2. Description of study areas

Nationwide renewable energy resource assessment has been conducted three times in Ethiopia. Wind and solar resource assessment were conducted by CESEN-ANSALDO in 1980s and by SWERA in 2007 [3]. Wind and solar resources assessment of the country was also carried out by the Chinese HYDROCHINA Corporation which was completed in 2012.

The government of Ethiopia in collaboration with the Chinese government prepared solar and wind Master Plan for the country, which can be very useful to identify the gross amount and distribution condition of wind and solar energy resources, construction conditions, cost and other limiting factors of wind and solar power generation projects. Based on the analysis of this Master Plan, Ethiopia has a capacity of 1350 GW (> 7 m/s) of energy from wind [3,4]. Figure 1a and b show the distribution of average wind speed in Ethiopia at 10 m and 50 m heights, respectively.

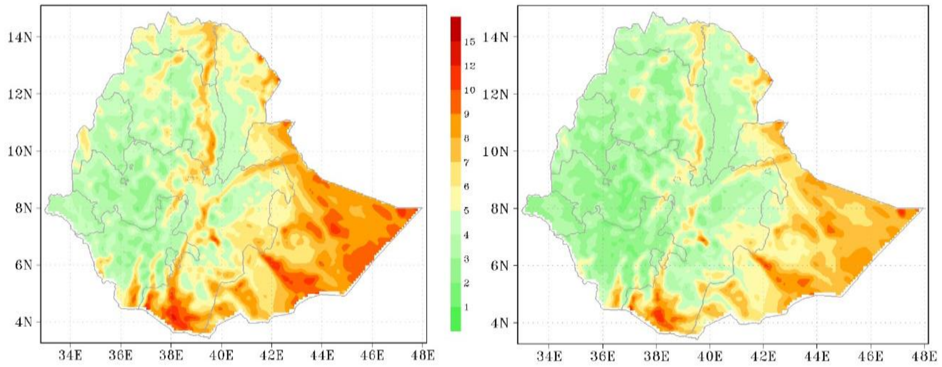

Figure 1. Distribution of average wind speed (m/s) in Ethiopia at height 50 and 10 m respectively, (during 2000–2009).

In this research, feasibility of wind powered water pumping system has been studied in Siyadberand Wayu woreda (latitude 9º46’N, longitude 39º40’E and altitude 2625 m a.s.l), Adami Tulu woreda (latitude 7 ̊52’N, longitude 38º42’E and altitude 1665 m a.s.l) and East Enderta Woreda (latitude 13º42’N, longitude 39º37’E and altitude 1926 m a.s.l) located in Amhara, Oromia and Tigray regional states of Ethiopia, respectively. The wind speed data for all sites are obtained from the NMSA (National Metrology Service Agency). Since there are no stations at the selected sites, nearby stations were considered during data collection for all sites. For confirmation purposes, data are also collected from Weatherbase SM [5], Meteonorm software [6] and NASA-SSE Satellite [7] using the latitude and longitude of the sites. Based on the data obtained from NMSA, the monthly average wind speed for the three sites at 10 m height is shown in Figure 2.

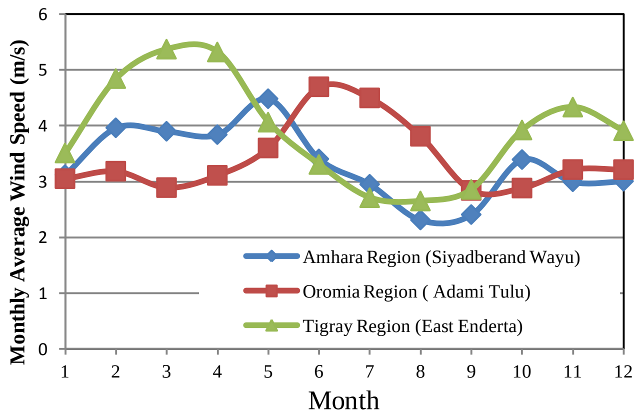

Figure 2. Monthly average wind speed at 10 m height for the selected three sites.

3. Material and Methods

3.1. Analysis of wind data

For estimating the wind energy potential of a site, the wind data collected from the location are analyzed and interpreted. Long-term wind data from the meteorological stations near to the candidate site can be used for making wind energy potential estimation. These data, which may be available for long periods, should be carefully extrapolated to represent the wind profile at the potential site [8].

In this research, five-year wind speed data were collected from NMSA for each site, which is grouped, on a daily average basis. These data are, thereafter analyzed using the Weibull distribution method to obtain the average monthly wind speed data for the selected sites.

3.1.1. Average wind speed

One of the most important information on the wind spectra available at a location is its average velocity. In simple terms, the average velocity (V_m) is given by:

$$V_m = \frac{1}{n}\sum_{i=1}^{n} V_i \qquad (1)$$

where: V_m is average wind velocity, V_i is wind velocity at each time and n is number of wind data

However, for wind power calculations, averaging the velocity using Equation (1) is often misleading. That is, the wind energy at the site can be under estimated by using the above formula. Therefore, for wind energy calculations, the velocity should be weighed for its power content while computing the average. Thus, the average wind velocity is given by Equation (2).

$$V_m = \left(\frac{1}{n}\sum_{i=1}^{n} {V_i}^3\right)^{1/3} \qquad (2)$$

3.2. Statistical models for wind data analysis

In this research, Rayleigh method which is the simplified form of Weibull distribution was used to describe the wind variation in the selected regions.

3.2.1. Rayleigh Distribution

The Weibull distribution in wind regime analysis depends on the accuracy in estimating k (shape parameter) and C (scale parameter). For the precise calculation of k and C, adequate wind data, collected over shorter time intervals are essential. In many cases, such information may not be readily available. The existing data may be in the form of the mean wind velocity over a given time period (for example daily, monthly or yearly mean wind velocity). Under such situations, a simplified case of the Weibull model can be derived, approximating k as 2. This is known as the Rayleigh distribution [8].

Therefore, the cumulative distribution and probability density function in case of Rayleigh distribution is given by the following two formulas respectively [8].

$$f(V) = \frac{\pi}{2}\frac{V}{{V_m}^2} e^{-\left[\pi/4\left(V/V_m\right)^2\right]} \qquad (3)$$

$$F(V) = 1 - e^{-\left[\pi/4\left(V/V_m\right)^2\right]} \qquad (4)$$

3.3. Energy estimation of wind regime

Wind energy density and the energy available in the regime over a period are usually taken as the yardsticks for evaluating the energy potential. The wind energy density (E_D) is the energy available in the regime for a unit rotor area and time. The total energy available in the spectra (E_S) can be arrived at by multiplying the wind energy density by the time factor [8].

Based on the Rayleigh approach the energy density (E_D) and the total energy available in the spectra (E_S) can be calculated using Equation (5) and (6), respectively

$$E_D = \frac{3}{\pi}\rho_a V_m{}^3 \quad (5)$$

From E_D, energy available for the unit area of the rotor, estimated using the expression

$$E_I = TE_D = \frac{3}{\pi}T\rho_a V_m{}^3 \quad (6)$$

Other factors of interest for evaluating the energy potential of the site are the most frequent wind velocity (V_{Fmax}) and the velocity contributing the maximum energy (V_{Emax}) to the regime.

$$V_{Fmax} = \sqrt{\frac{2}{\pi}}V_m \quad (7)$$

$$V_{Emax} = 2\sqrt{\frac{2}{\pi}}V_m \quad (8)$$

Therefore, the energy density (kW/m^2), the available energy for a certain period of time (kW/m^2/month), the most frequent wind velocity (m/s) and velocity contributing the maximum energy (m/s) for each selected site are calculated using the above formulas and the values are given in Table 1.

Table 1. Monthly average wind energy density, available energy within the month, maximum velocity frequency and velocity corresponding to maximum energy for the selected three sites.

	Siyadberand Wayu					Adami Tulu Site					East Enderta Site				
Month	V_m	E_D	E_I	V_{Fmax}	V_{Emax}	V_m	E_D	E_I	V_{Fmax}	V_{Emax}	V_m	E_D	E_I	$V_{F\,max}$	$V_{E\,max}$
Jan	3.12	0.03	19.89	2.49	4.98	3.05	0.03	20.66	2.43	4.87	3.51	0.04	30.51	2.80	5.60
Feb	3.96	0.05	36.75	3.16	6.32	3.18	0.03	21.22	2.54	5.08	4.84	0.11	72.41	3.87	7.73
Mar	3.90	0.05	38.78	3.11	6.22	2.89	0.02	17.58	2.31	4.61	5.37	0.15	109.31	4.29	8.57
Apr	3.84	0.05	35.85	3.07	6.13	3.11	0.03	21.18	2.48	4.96	5.32	0.14	102.78	4.25	8.49
May	4.48	0.08	58.95	3.58	7.16	3.60	0.05	33.98	2.87	5.75	4.06	0.06	47.29	3.24	6.49
Jun	3.40	0.03	24.97	2.72	5.43	4.70	0.10	73.04	3.75	7.50	3.30	0.03	24.62	2.64	5.27
Jul	2.95	0.02	16.78	2.35	4.71	4.50	0.09	66.23	3.59	7.18	2.71	0.02	14.02	2.16	4.32
Aug	2.31	0.01	8.06	1.84	3.69	3.81	0.05	40.26	3.04	6.08	2.65	0.02	13.12	2.11	4.23
Sep	2.41	0.01	8.82	1.92	3.84	2.84	0.02	16.14	2.27	4.53	2.86	0.02	15.92	2.28	4.56
Oct	3.39	0.03	25.54	2.71	5.42	2.88	0.02	17.43	2.30	4.60	3.92	0.06	42.56	3.13	6.26
Nov	3.00	0.02	17.01	2.39	4.78	3.21	0.03	23.38	2.56	5.13	4.33	0.08	55.53	3.46	6.92
Dec	3.00	0.02	17.74	2.40	4.80	3.21	0.03	24.14	2.56	5.13	3.91	0.06	42.13	3.12	6.24

3.4. Wind energy conversion system(WECS)

Wind Turbines are one of the recent machines for wind energy conversion. Wind turbines are mainly classified into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). The horizontal axis wind turbines are mostly used for electricity generation and also for water pumping. However, to use the recent wind turbines for water pumping, the average wind velocity of the region should be greater than 5 m/s. Windmills are one of the oldest methods of harnessing the wind energy to pump water. But currently, the technology has experienced are vival due to the increasing price of fossil fuel all over the world [9]. Different researchers suggested that windmills are the best options to harvest the wind energy for water pumping at low wind speed regions.

Most windmills for water-pumping applications are of the horizontal-axis variety, and have multi-bladed rotors that can supply the high torque required to initiate operation of a mechanical pump. Figure 3illustrates a typical water-pumping windmill.

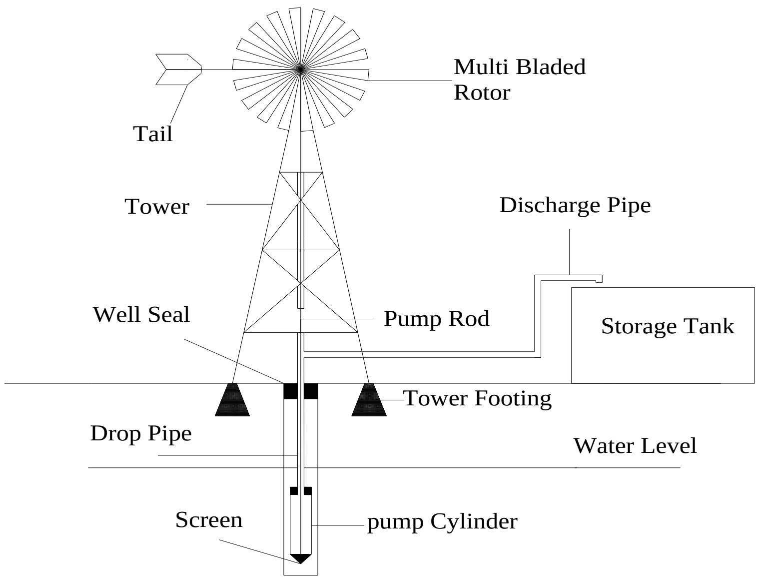

Figure 3. Schematic diagram of windmill water pumping system.

3.5. Wind pump

Wind pumps can be classified as mechanical and electrical systems. Mechanical wind pumps can further be categorized as systems with positive displacement and Roto-dynamic pumps. Various types of pumps like the screw pump, piston pump, centrifugal pump, regenerative pump and compressor pump are being used in mechanical wind pumping option [8].

3.5.1. Wind powered piston pumps

In this research, horizontal axis multi bladed windmill operated with positive displacement piston pump was selected for all sites. Detailed design steps of the windmill water pumping system are given in the next section.

3.6. *Windmill water pumping system design*

In this section, the main components of windmill water pumping system such as the rotor, piston pump, discharge pipe, storage tank and other accessories are designed for the selected three sites. The actual data have been collected from the field and from the Ministry of Water, Energy and Irrigation office for designing the system. Table 2 includes important parameters for the selected sites.

Table 2. Important parameters for the selected three sites.

Input Parameters	Siyadberand Wayu	Adami Tulu	East Enderta
No. of Beneficiary	500	600	1000
Wind Speed (m/s)	4–5	5–6	4–5
Bore Hole, Elevation (m) a.s.l	2625	1665	1926
Storage Tank, Elevation (m) a.s.l	2645	1665	1936
Well Depth (m)	73	85	60
Static Water Level (m)	36	50	25
Pumping level (m)	40	56	30
Pump Position (m)	62	68	52
Distance of Storage Tank to Well (m)	500	10	230
Base of Storage a.s.l (m)	10	10	4
Per capital water consumption (litter per person per day)	20	20	20
Vertical Elevation (m)	30	10	14

3.6.1. Determination of water demand

Determination of the water demand depends on the total number of beneficiaries of the site and the daily per capita water consumptions. In Ethiopia, the daily per capita water consumption for rural communities is estimated to be 20 L/person within the range of 0.5 to 1 km from the dwelling place [9,12].Therefore, the total daily water demand can be calculated using Equation (9).

$$Q_p = \mathrm{N_P} \times \mathrm{q} \qquad (9)$$

3.6.2. Determination of total head (H)

The total head is the sum of the static head (the distance from water level below ground to water outlet at the water storage container), friction head and velocity head. According to Figure 4, the total head is the sum of pumping level and total discharge head.

$$Total\ Head = Static\ head + Friction\ head + Velocity\ head \qquad (10)$$

Friction losses of the system can be calculated using Darcy-Weisbach formula (Equation (11)), taking into consideration losses on the pipe and minor losses (losses due to valves and fittings) and velocity head. The design of most pumps makes the total velocity head for the pumping system zero [10].

$$h_f = \frac{8Q^2}{\pi^2 {D_d}^4 g}\left[f\frac{L_P}{D_d} + K_{fittings} + 1\right] \qquad (11)$$

Once the appropriate velocity for the system is selected, the pipe diameter can be calculated based on the velocity and flow rate using Equation (12).

$$D_d = \sqrt{\frac{4\,Q}{\pi V}} \quad (12)$$

Furthermore, the loss coefficient and friction factor values are read from the Moody diagram and pipe friction loss charts based on the flow rate and pipe diameter to determine the total head of the system.

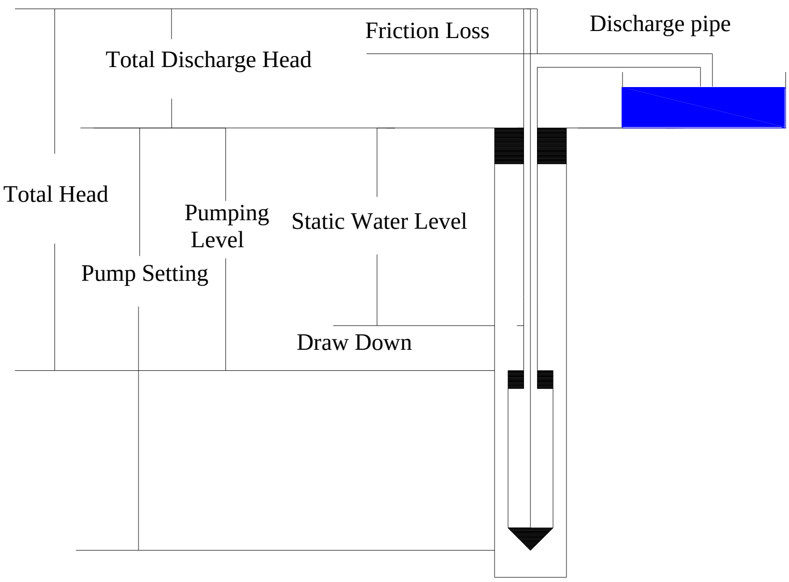

Figure 4. Diagram showing the total head in water pumping system.

3.6.3. Determination of hydraulic power

The hydraulic power required to lift water from the source (borehole) to the storage tank can be calculated using Equation (13) given in [8].

$$P_{hyd} = Q_p \times \rho_w \times g \times H \quad (13)$$

The hydraulic power requirement is constant for all months within a year because there is no pumping variation in water supply for the rural selected community, assuming constant supply.

3.6.4. Wind power potential determination

The wind power potential is given as the specific wind power or power per unit area. For a unit area of the rotor, power available (P_{wind}) in the wind stream of velocity V is given in [8].

$$P_{wind} = \frac{1}{2} \times \rho_a * V^3 \quad (14)$$

3.6.5. Reference area and size of windmill

The ratio of the hydraulic power of each month divided by specific wind power potential for that same month has the dimension of area and is referred as the reference area [11]. The reference area can be calculated based on Equation (15).

$$R_a = \frac{P_{hyd}}{P_{wind}} \quad (15)$$

The size of the windmill which depends on the diameter of the rotor can be obtained from the reference area given in Equation (15). The rotor diameter is given in Equation (16).

$$D_r = \sqrt{\frac{4R_a}{\pi}} \quad (16)$$

The sizing methodology for standalone windmill water pumping systems is based on the concept of the critical month or design month. This is the month in which the water demand is highest in relation to the wind power potential, i.e. the month when the system will be most heavily loaded [11]. The design month is found by calculating the ratio of the hydraulic power requirement to the wind power potential for each month. The month in which this ratio is a maximum is the design month [11].

3.6.6. 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 Equation (17).

$$S = Q_p * d_s \quad (17)$$

3.7. Wind pump simulation

In this paper, a MATLAB program was written, based on different equations given in [8], to determine the performance of wind driven piston pump. The instantaneous discharge of the system with respect to monthly average wind speed can be determined as given in [9] using Equation (18).

$$Q_{VP} = 2\, C_{Pd}\eta_{(T,P)} \left[\frac{\rho_a}{\rho_w}\right]\left[\frac{A_r V^3}{gH}\right]\left[1 - K_O\left(\frac{V_I}{V}\right)^2\right] K_O\left(\frac{V_I}{V}\right)^2 \quad (18)$$

The overall performance coefficient of a wind rotor coupled to a piston pump can be modeled as in [8] which is given as discharge expected from a wind driven piston pump installed at a given site, over a period *T* as given in [8]. Equation (19) gives the discharge expected from a wind driven piston pump, installed at a given site, over a period *T*.

$$Q_{IP} = 2\, T C_{Pd}\eta_{(T,P)} \frac{\rho_a}{\rho_w}\frac{A_r V_O{}^3}{gH}\left[1 - K_O\left(\frac{V_I}{V_O}\right)^2\right] K_O\left(\frac{V_I}{V_O}\right)^2 \left[\left\{\frac{4\, V_m{}^2}{\left(V_O{}^2 - V_I{}^2\right)}\left(e^{-X_I} - e^{-X_O}\right)\right\} - \left\{e^{-X_O}\right\}\right] \quad (19)$$

$$X_I = \frac{\pi}{4}\left(\frac{V_I}{V_m}\right)^2 \, and X_O = \frac{\pi}{4}\left(\frac{V_O}{V_m}\right)^2$$

4. Result and Discussion

Hydraulic power, specific wind power, reference area, rotor diameter and design month for the three sites were calculated using the equations given in the previous sections and results are summarized in Table 3.

AV55 (Aureka) wind pump with 5.7 m (19 ft) rotor diameter, 24 blades and direct driven single acting piston pump was selected Based on the design calculation results a for the selected three sites [13].

Table 3. Available hydraulic power, Available specific wind power, calculated reference area and rotor diameter for the selected three sites.

	For Siyadberand Wayu Site					For Adami Tulu Site					For East Enderta Site				
Months	Hydraulic Power P_{hydr}(W)	Specific Wind Power P_{wind} (W/m^2)	Reference Area P_{hydr}/P_{wind} (m^2)	Rotor Diameter (m)	Design Month	Hydraulic Power P_{hydr}(W)	Specific Wind Power P_{wind} (W/m^2)	Reference Area P_{hydr}/P_{wind} (m^2)	Rotor Diameter (m)	Design Month	Hydraulic Power P_{hydr}(W)	Specific Wind Power P_{wind} (W/m^2)	Reference Area P_{hydr}/P_{wind} (m^2)	Rotor Diameter (m)	Design Month
Jan	337	30.31	11.12	3.76		362.5	21	17	4.7		300	31	10	3.5	
Feb	337	27.71	12.16	3.94		362.5	24	15	4.4		300	81	4	2.2	
Mar	337	22.97	14.67	4.32		362.5	18	20	5.1		300	110	3	1.9	
Apr	337	18.81	17.92	4.78		362.5	22	16	4.5		300	107	3	1.9	
May	337	16.93	19.91	5.03		362.5	34	10	3.6		300	48	6	2.8	
Jun	337	22.97	14.67	4.32		362.5	76	5	2.4		300	26	12	3.9	
Jul	337	20.82	16.19	4.54		362.5	67	5	2.6		300	14	21	5.2	
Aug	337	15.18	22.20	5.32		362.5	41	9	3.4		300	13	23	5.4	DM
Sep	337	13.55	24.87	5.63	DM	362.5	17	21	5.2	DM	300	17	18	4.8	
Oct	337	15.18	22.20	5.32		362.5	18	20	5.1		300	43	7	3.0	
Nov	337	20.82	16.19	4.54		362.5	24	15	4.3		300	58	5	2.6	
Dec	337	22.97	14.67	4.32		362.5	24	15	4.3		300	42	7	3.0	

Table 4. Wind pump parameters as obtained from design calculations for the selected sites.

Parameters	SiyadberandWayu	Adami Tulu	East Enderta
Water consumption (m^3/day)	10	12	15
Total head (m)	75	66	44
Density of air (kg/m^3)	0.92	1.024	0.992
Reference area (m^2)	24.87	21.32	22.71
Rotor diameter (m)	5.63	5.21	5.38
Pipe diameter (mm)	25	40	50
Pump diameter(mm)	115	125	125
Hydraulic power (W)	337	360	300
Design month	September	September	August
Tower height (m)	16	16	16
Transmission/gear ratio/	direct	direct	direct

The instantaneous discharge with respect to the monthly average wind speed can be determined using the MATLAB program based on Equation 22. The results for the selected three sites are shown in Figure 5.

Figure 5 shows that instantaneous discharge varies from 395 m^3 to 254 m^3, 888 m^3 to 307 m^3 and 1203 m^3 to 455 m^3 in Siyadberand Wayu, Adami Tulu and East Enderta sites, respectively. The minimum discharges satisfy the monthly water demand in East Enderta site, there is 10% water missing in Siyadberand Wayu and Adami Tulu site. Therefore, it can be concluded that the proposed system satisfies the required water supply for all selected sites.

By considering the characteristics of the rotor, pump and wind region integrated system performance was developed by Mathew, et.al [8]. In this paper, a MATLAB program was developed based on Equation (19) to determine the integrated discharge for all sites within a given period of time.

Table 5. Detail specification of AV55 (Aureka) wind pump.

AV55 (Aureka) Wind Pump	
Rotor	Horizontal axis; upwind position
Rotor diameter (m)	5.7 m (19 ft)
No. of blades	24
Transmission ratio	1:1 direct driven
Control systems	Fully automatic
Pump system	Single acting piston pump
Pump strock (mm)	160–230 mm
Cut in wind speed	1.5 m/s
Cut out wind speed	10 m/s
Survival wind speed	40 m/s

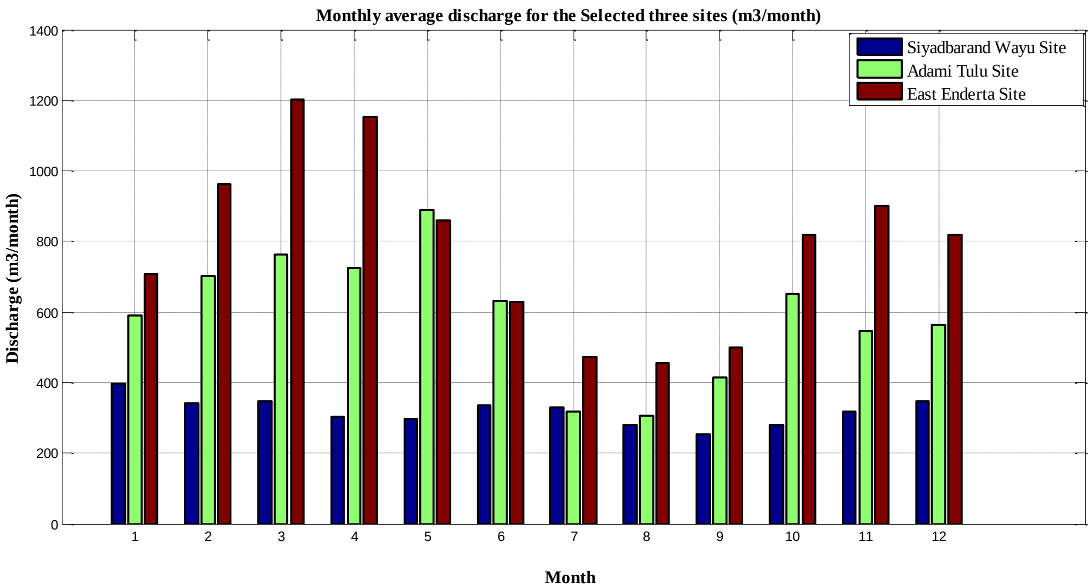

Figure 5. Monthly average discharges (m^3/month) for the selected three sites.

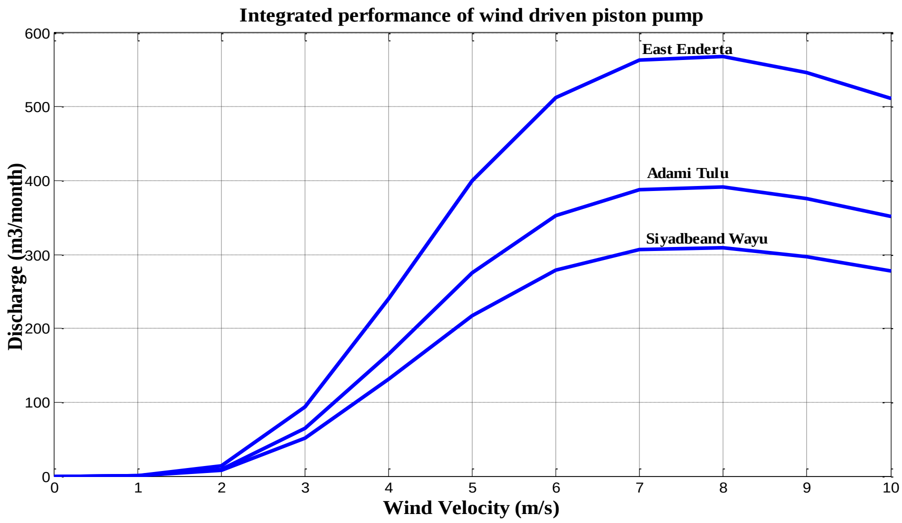

Figure 6. Integrated discharge within a given period of time for selected three sites.

Figure 6 shows the integrated discharge of wind driven piston pump for the three sites at a given period of time. As can be observed from the graph, the integrated discharge curves are similar for all sites with a higher discharge rate for the site that has a higher water demand per day.

Table 6 shows the monthly average water discharge (m^3/month) for the three sites. According to the simulation result, the annual discharges for the sites are 3830.42, 7098 and 9477 m^3 for Siyadberand Wayu, Adami Tulu and East Enderta sites, respectively.

Table 6. Monthly average discharges for the sites (m^3/month).

Months	Siyadberand Wayu Site	Adami Tulu Site	East Enderta Site
Jan	395.5322	590.887	707.2
Feb	342.6349	701.317	962.1
Mar	346.5323	761.794	1203.1
Apr	302.931	725.375	1151.1
May	297.4014	888.152	858.2
Jun	335.3538	632.295	628.6
Jul	329.8755	317.259	471.8
Aug	280.1304	307.367	455.4
Sep	254.1291	413.735	500.8
Oct	280.1304	650.886	819.7
Nov	319.2343	544.965	901.8
Dec	346.5323	564.396	817.3

5. Financial comparison between wind and diesel water pumping systems

In the financial comparison between windmill and Diesel water pumping, the main question is how the financial costs of both systems can be calculated. The whole costs of a pumping system have a certain life expectancy in years that is made up of the capital cost, operating cost and maintenance and replacement cost (M & R), costs that refer to the life cycle cost LCC. Table 7 shows assumptions that are made for financial comparison between WPS and DPS.

Table 7. Economic assumptions for all selected sites.

Parameters	Values
Interest rate (%)	5
Discount rate (%)	10
Life time of windmill (years)	20
Life time of submersible pump (years)	10
Life time of Diesel generator (years)	10
Diesel fuel cost ($/l)	0.77
Salvage value for windmill (%)	20
Salvage value for Diesel (%)	20

Assuming 6 hours/day working time for the system to provide the required daily water demand, 2190 hrs will be considered within the years.

$$\text{Annual fuel cost} = \text{Specific fuel consumption} * \text{Total operating hours in a year} * \text{Fuel rate}$$

$$= \frac{0.23\text{liter}}{\text{hr}} \times \left(\frac{6\text{hr}}{\text{day}} * 365\,\frac{\text{day}}{\text{year}}\right) \times 0.77\,\frac{\$}{\text{liter}} = 387.85\ \$/\text{year}$$

$$\text{Fuel Cost of Diesel Generator for 20 years} = 20\ \text{Year} * 387.85\ \$/\text{year} = 7757\ \$$$

Table 8. WP and DP system cost comparison using LCC for Adami Tulu site.

Costs	WP[$]	DP[$]
Capital Cost (CC) of windmill heads completed with tower and pump	2329.38	250
Maintenance cost (MC) :	1. For windmill and tower 313.2 $ is required within 20 years 2. For maintenance of pump, pump rod, delivery pipe 1100 $ is required within 20 years	500
Fuel/Energy cost (EC) for 20 years	None	7757
Replacement cost (RC) for generator	None	500
Replacement cost for submersible Pump	None	400
Total cost	3742.58	9407
Salvage value (SC)	Negligible	40
Life Cycle Cost (LCC)	3742.58	9367

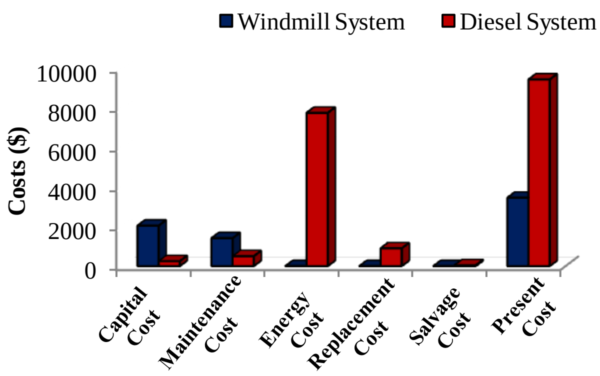

Figure 7. Life cycle cost analysis of windmill and Diesel water pumping system for Adami Tulu site.

As shown in Figure 7, the capital cost of Diesel water pumping system is lower than the windmill water pumping system. However, the fuel cost of Diesel water pumping system is higher than the windmill system. If, however, the windmill water pumping system is compared with the Diesel water pumping system based on their present cost, windmill water pumping system is more economical.

5.1. Cost of pumping water

The cost of water pumped by windmill and Diesel water pumping systems can be calculated using the cost annuity method [14]. Equation (20) can be used to calculate the cost of water pumped by windmill and Diesel systems in m^3.

$$Cost\ of\, m^3 of water\ pumped\ = \frac{Annualised\ life\ cycle\ cost\ of\ the\ system}{Total\ pumped\ water} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(20)$$

Table 9 shows the cost of pumping m^3 of water using Windmill and Diesel water pumping systems for the three sites. Based on the annual life cycle cost, the Windmill water pumping system is more economical than the Diesel system.

Table 9. Annuity and water cost calculation for the windmill and Diesel systems.

Pump	Siyadberand Wayu	Adami Tulu	East Enderta
			Windmill
Annualized capital cost	240.4	273.7	273.7
Operation and maintenance cost	70.66	70.66	70.66
Annualized life cycle cost for windmill	311.06	344.36	344.36
Water cost for Windmill system ($/$m^3$)	0.08	0.05	0.036
			Diesel
Annualized capital cost	52.875	52.875	52.875
Operation and maintenance cost	25	25	25
Replacement cost	27.625	27.625	27.625
Annual Fuel cost	337.26	387.85	306.9
Annualized life cycle cost for Diesel system	442.76	493.35	412.4
Water cost for Diesel system ($/$m^3$)	0.12	0.07	0.044

5.2. Comparison of cost of pumping water for the selected sites

In this section, the same total head and flow rate are assumed for all selected site to calculate the unit cost of water for each sites.

Based on this assumption, annual discharge of the sites are 4850 m^3, 6110 m^3 and 7040 m^3 for Siyadberand Wayu, Adami Tulu and East Enderta site respectively.

Table 11 shows the cost of pumping water using Windmill systems and annual average wind speed for three sites. Cost comparison for pumping water indicates that higher cost for Siyadberand Wayu as compared to Adami Tulu and East Enderta .The result shows that there is an inverse relationship between wind speed and cost of pumping water.

Table 10. Monthly average discharges of the sites assuming the same head and flow rate (m^3/month).

Month	Siyadberand Wayu	Adami Tulu	East Enderta
Jan	500.82	441.16	525.30
Feb	433.84	425.23	714.68
Mar	438.78	404.98	893.73
Apr	383.57	440.36	855.05
May	376.57	561.22	637.46
Jun	424.62	762.85	466.95
Jul	417.69	747.06	350.46
Aug	354.70	606.25	338.28
Sep	321.78	380.08	372.03
Oct	354.70	402.95	608.89
Nov	404.21	461.29	669.90
Dec	438.78	476.67	607.10
Annual Discharge	4850.04	6110.10	7039.85

Table 11. Annuity and water cost of selected sites.

Pump	Siyadberand Wayu	Adami Tulu	East Enderta
Windmill			
Annualized capital cost	240.4	273.7	273.7
Operation and maintenance cost	70.66	70.66	70.66
Annualized life cycle cost for windmill	311.06	344.36	344.36
Water cost for Windmill system ($/$m^3$)	0.064	0.056	0.049
Annual Average Wind Speed (m/s)	3.534	3.851	4.397

6. Conclusion

In this paper, the feasibility of a wind-powered water pumping system is conducted for three selected sites in Ethiopia. The designed system has a capacity to supply a daily average drinking water of 10, 12 and 15 m^3/day for 500, 600 and 1000 peoples in Siyadberand Wayu, Adami Tulu and East Enderta sites, respectively, with average per capital water consumption of 20 liters per day per person. The cost of pumping water is determined as 0.08, 0.05 and 0.036 $/$m^3$ for Siyadberand Wayu, Adami Tulu and Enderta sites, respectively.

If Diesel generator is used for the designed system in Siyadberand Wayu, Adami Tulu and East Enderta sites, with average per capital water consumption of 20 liters per day per person, the cost of pumping water, without any subsidy, are approximately 0.12, 0.07 and 0.044 $/$m^3$, respectively for the particular sites.

The life cycle cost analysis of pumping water shows that the wind powered water pumping system is more economical and feasible as compared to the Diesel-based system. The results indicate that replacing the existing expensive Diesel-based systems by wind-powered systems will play a significant role in achieving the country's MDG targets.

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Conflict of interest

All authors declare no conflict of interest in this paper.

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