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Performance Evaluation of A Photovoltaic Pumping System in Funaab Community

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***Abstract*— The need for constant renewable supply of electricity for effective pumping of water at low cost is highly needed to provide a constant supply of water for FUNAAB community. It is important to understand the source of water and consumption pattern to ensure the sustainability of water supply, and also to reduce its costs.**

The Design, Installation, and Performance evaluation of a photovoltaic pumping system in FUNAAB community was carried out. The water demand for the site and daily solar insolation data obtained using 'Meteonorm' software were determined. The Component parameters for the PV pumping system were designed to include the pump flow rate and the hydraulic power, the hydraulic head, power rating of the PV module, orientation, and direction of the PV module. Experiments to acquire a relationship between Photo-voltaic pump system outputs and solar-radiation intensity at different times during the day were carried out to determine periods of maximum pumping efficiency. The maximum discharge logged 0.162m^3/h was obtained between 11 am to 2 pm at the PV power output of 727.5W/m^2 with a 300W solar module connected to a DC pump discharging at 24.5 m water head. The system operated approximately 8 hours in the month of October. Although the initial cost to set up a PV pumping system is high, but with the little maintenance cost for years, it is revealed that PV based water pumping system is a suitable and feasible option for domestic use and farm irrigation systems in Funaab community.

***Keyword*— PV module, DC pump, power consumption, solar insolation, pump discharge.**

1. INTRODUCTION

Like most other communities in Nigeria, the energy situation in FUNAAB community is extremely critical, so the electricity generation from alternative sources has become a much-focused need. FUNAAB community is blessed with renewable energy resources and the availability of alternative energy creates opportunities for utilization in the power sector. Among different renewable energy sources like solar, wind, biomass, and others, the abundant availability of solar energy makes it the most promising one for FUNAAB community. FUNAAB community is located in Ogun State at the state capital Abeokuta 7°9′39″N 3°20′54″E Nigeria which is an ideal location for abundant solar radiation with average solar radiation of about 4.5kWh/m2/day (16.2MJ/m2/day). The utilization of the photovoltaic system for water pumping is appropriate as there is often a natural relationship between the availability of solar energy and the water requirement. The water requirement increases during hot weather periods when the solar radiation levels are highest and the output of the solar array is at a maximum. Photovoltaic water pumping systems are particularly suitable for water supplies to the irrigation system used in FUNAAB farmlands, and also for other domestic uses. Therefore renewable solar energy-based off-grid electrification can be an alternate option for providing electricity in FUNAAB community where no reliable constant electricity supply is available.

Given an average solar radiation level of about 4.5kWh (m2 per day) and the prevailing efficiencies of commercial solar-electric generators, then if solar collectors or modules were used to cover 1% of FUNAAB's land area of 100km2, it is possible to generate 1850x103GWh of solar electricity per year, which is over one hundred times the current grid electricity consumption level in the country.

Though the installation cost of a solar-powered pumping system is more than that of gas, diesel, or propane-powered generator based pumping system it requires far less maintenance cost [9]. However, by comparing installation costs (including labor), fuel costs, and maintenance costs over 10 years with other conventional fuel-based pumping systems, the solar PV water pumping system can be a suitable alternate option [8]. This system has the added advantage of storing water for use when the sun is not shining, eliminating the need for battery, electricity, and reducing overall system costs.

2. MATERIALS AND METHODS

2.1 Water Demand Design.

The building consists an average of 30 occupants per day with an approximate water usage of 14 liters per person. Assuming increase in occupants by 25%, total number of occupants = 30×1.25 = 37.5 = 38

Therefore design population = 38 persons

The daily water demand was calculated using the formula:

$$Q = CP \times DP \quad (1)$$

Where:

Q = daily water demand (liters)

CP = per capita consumption per day

DP = design population

Substituting a daily water requirement of 14liters per person per day in equation above, we have;

Q = 14 x 38 = 532 liters per day = 0.53m^3/day

2.2 Water Storage Design

The purpose of the battery-less PV water pumping system is storing water instead of electrical energy. The disadvantages of employing battery storage is requiring a complex control system, considerably increases in the cost of implementing the system and more maintenance burden of PV water pumping system. The water tank size was designed to be three-times of peak water demand [16].

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Water storage size would be = 3×532liters = 1596 liters = 1.6m^3

2.3 Pump Design

Pump Flow Rate

The pump flow is estimated via dividing daily water demands by PSH. PSH represents peak sun hours every day. Using the sunshine data from the area the peak sun hours is 4.5 hours, which is used in the design [16]. The pump flow rate Q is then determined as follows:

$$Q=\frac{Daily\ water\ demnd\ Dwd}{number\ of\ PSH\ per\ day} \quad (2)$$

$$=\frac{532}{4.5} = 118.2\text{liters/hour} = 1.97\text{liters/minute} = 0.1182\ m^3/\text{h}$$

Pump Total Dynamic Head

The Total Dynamic Head (TDH) for a pump is the sum of the vertical lift, pressure head, and friction loss. Friction losses apply only to the piping between the point of intake (inlet) and the point of storage (i.e. the storage tank). Therefore, friction losses between the storage tank and the point of use are independent from the pump and do not need to be accounted for when sizing the pump [16].

TDH = Vertical Lift + Pressure Head + Friction Losses (3)

Vertical lift = vertical distance between the water surface at the intake point and the water surface at the delivery point (the tank's water surface).

Vertical Lift = 80 ft = 24.3 m

Pressure head = Pressure at the delivery point in the tank. There is no pressure at the delivery point (the water surface in the tank), so:

Pressure Head = 0 ft

Friction loss is the loss of pressure due to the friction of the water as it flows through the pipe. Friction loss is determined by four factors: the pipe size (inside diameter), the flow rate, the length of the pipe, and the pipe's roughness. Due to the relatively close proximity of the intake point and the storage tank, the total friction losses in the pipeline would be minimal. As such, approximately 360 inches of $\frac{1}{2}$-inch diameter PVC pipe will be used to convey water from the source to the tank. The friction loss for $\frac{1}{2}$inch pipe conveying 1.11 gpm is approximately 1.14 feet of head loss per 100 ft of pipe.

Therefore, the total estimated friction loss for 30 ft of pipe is calculated below

$$\frac{1.14ft}{100ft} \times 30\text{ ft.} = 0.342\text{ ft. friction head}$$

Total Dynamic Head TDH = 80ft + 0ft + 0.342ft = 80.342ft = 24.5m

Pump Power Requirement

The hydraulic energy required of the pump can also be calculated as in below.

$$E=\frac{\rho g\ H\ V}{3.6\times10^6}$$

(4)

Where,

E = hydraulic energy required (kWh/day)

ρ = density of water (1000kg/m^3)

g = gravitational acceleration (9.81ms^{-2})

H = total hydraulic head (24.5m)

V = volume of water required (1.5m^3/day)

By putting above all values, equation reduces as shown below;

$$E=\frac{1000kgm^{-3}\times9.81ms^{-2}\times24.5m\times1.5m^3/day}{3.6\times10^6} = 0.10014\text{ kWh/day} = 100.1\text{Wh/day}$$

2.4 Sizing of P-V Panel

Sizing and Selection of PV Panels

The size of panels to be used depends on the amount of power that is required (in watts) the time it operates (in hours) and the amount of energy available from the sun in a particular area. The first two parameters are based on the project requirement, while the third depend on the location. The size of a PV array was calculated by using the equation below

The solar array power required (kWp-kilowatt peak)

$$=\frac{Hydraulic\ energy\ required\ (kWh/day)}{Average\ solar\ daily\ irradiation\ (kWh/m^2/day\times F\times E)} \quad (5)$$

Where,

F = array mismatch factor = 0 .85 on average

E = daily subsystem efficiency = 0.25 - 0.40 typically

Table (1) shows the monthly average solar radiation of FUNAAB Community (Meteonorm)

Month	Average Solar Radiation (kWh/m^2/day)
January	5.45
February	5.64
March	5.57
April	5.27
May	5.01
June	4.49
July	3.93
August	3.73
September	4.05
October	4.65
November	5.06
December	5.30

From Table 1 it is clear that for the month of August the solar radiation was lowest therefore solar radiation of 3.73 KWh/m^2/day will be considered for optimum solar array sizing calculations.

$$\text{Solar array power} = \frac{0.10014kWh/day}{3.7Kwh/m^2/day\times0.85\times0.35} = 0.09897\text{kW} = 98.9\text{W}.$$

Orientation and Direction of the PV Array

Orientation of the PV array is one of the most important aspects of the site assessment. For any surface the maximum available radiation is obtained when the sun's incidence is normal to the plane of the plate. This is approximately so at the noon of the location. In order not to be tracking the sun every now and then it is necessary to find a fixed value of tilt that will absorb radiation higher than that possible were the surface horizontal through the day, though not as high as when hourly tracking of the sunrays is adopted. For optimum tilt angle, 0+10° for locations with latitude <8.5° N. Therefore the optimum possible tilt angle for Abeokuta is approximately 17.2° [1]. Therefore the solar PV array will be tilted at this angle with the help of Clinometer.

Incident solar radiation to the PV array gives the input power (Watts) to the system given by

$$P_i = I_s \times A_c \quad (6)$$

The D.C. output power from the photovoltaic array is given by

$$P_o = V \times I \quad (7)$$

The hydraulic power output of the pump

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$P_h = \rho \times g \times Q \times H$ (8)

Array efficiency (E_a) is the measure of how efficient the PV array is in converting sunlight to electricity.

$E_a = P_o/P_i$ (9)

Subsystem efficiency (E_s) is the efficiency of the entire system components (inverter, motor, and pump).

$E_s = P_h/P_o$ (10)

Overall efficiency (E_o) indicates how efficiently the overall system converts solar radiation into water delivery at a given head

$E_o = P_h/P_i$ (11)

It can be written in the form of efficiencies as:

$E_o = E_a \times E_s$ (12)

2.5 Materials Used**.**

The Table 2: shows a list of the materials used for the installation of the PV pimping system.

Materials	**Quantity**
100W Monocrystalline solar panel Digital Flow Meter	1 1
PWM Charge Controller	1
Battery	1
'On/Off' Switch	1
30m PVC pipe 0.5 inch 1500liters Storage Tank DC water pump	1 1 1

Installation Process

The installation process is shown in plates 1-5. The PV panels is mounted on a erected metal frame support facing a location where it receives maximum sunlight throughout the year avoiding trees or other obstructions that could cast shadows on the solar panel and reduce its output. The PV panel is connected directly to the PWM charge controller that was nailed to the wall. The charge controller is connected to the battery regulator, and the output of the charge controller is connected to a switch box which is also connected to the pump. A 12 volts positive displacement submersible DC pump was selected to pump water from the reservoir at a depth of 1.8m below ground surface. The pump was connected to the ½' PVC pipe. The PVC pipe other end connects to a digital flow meter to allow the pumped water flow through the flow meter leaving through the PVC pipe and dumped into the tank. The pipes used for the water transfer between the Reservoir and the tank are ½' PVC..

Plate 1. (a) The mounting rod in the concrete hole (b) The Mounting frame attached to the rod

Plate 2. Installed solar panel

Plate 3 Installed PWM charge controller with Switch box

Plate 4::Installed Battery

Plate 5: Flow Meter Installation

3. RESULTS AND DISCUSSION.

3.1 Results.

During the course of testing, the following parameters were recorded to evaluate the performance of the photovoltaic pumping system and determine the pump discharge rate at every pumping hour.

Day Hour	Power Consumption, watt	Pump Discharge, m^3/h	Solar Radiation, w/m^2	Array Efficiency, Ea	Subsystem Efficiency, Es	Overall Efficiency, Eo
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	2.4	0	0	0
7	0	0	173.2	0	0	0
8	26.2	0.072	430.3	0.68	0.11	0.11
9	30.8	0.094	452.2	0.68	0.17	0.15
10	34.6	0.117	552.5	0.69	0.21	0.19
11	38.4	0.126	603	0.70	0.19	0.17
12	40.2	0.147	727.5	0.71	0.18	0.16
13	41.1	0.162	688.5	0.71	0.19	0.17
14	40.4	0.152	592.3	0.70	0.17	0.15
15	39.7	0.138	501.2	0.68	0.18	0.1
16	36.2	0.122	390.2	0.66	0.15	0.13
17	28.2	0.107	285.6	0.67	0.12	0.09
18	0	0	0	0	0	0
19	0	0	0	0	0	0
20	0	0	0	0	0	0
21	0	0	0	0	0	0
22	0	0	0	0	0	0
23	0	0	0	0	0	0
24	0	0	0	0	0	0

Fig. 2 shows the motor power consumption at pumping discharge rate during a selected day in the month of October.

It could be seen that 8hrs of the day, the solar radiation was 430, the power delivered to the pump was 26.2 watts. The solar radiation increases gradually to maximum value of 40.2 at the mid-day, this is followed by decrease in solar intensity to a value of 28.2 at 17 hr of the day

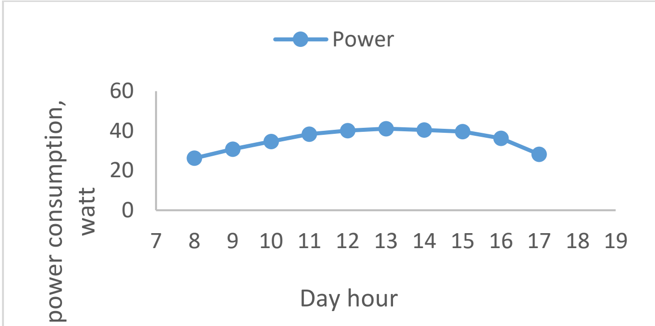

Fig. 2: Power consumption through a selected day in the month of October.

Figure 3 shows the variation of pump discharge during the selected day in the month of October when solar radiation was highest for FUNAAB community.

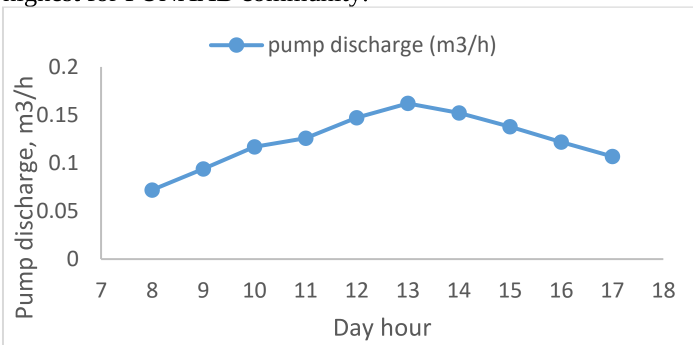

Fig. 3: Pump flow rate through a selected day in the month of October.

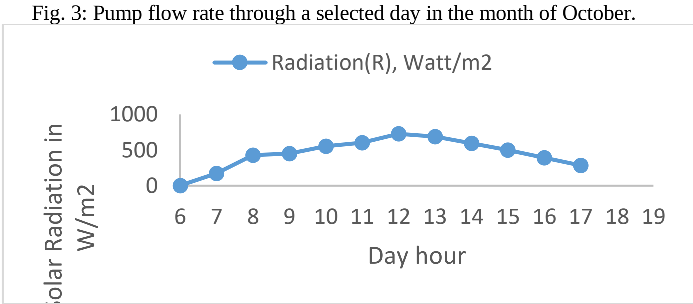

Fig. 4: Hourly average radiation (derived from Meteo-Norm software) through a selected day in the month of October

The graphical representation of solar radiation and discharge with respect to time shows that the discharge has been increased from morning to middle of the day or noon after that discharge will be decreasing. It clearly indicates that the peak solar radiation in October will provide sufficient energy for maximum discharge. This discharge is higher than the prescribed 0.1182 m^3/h.

Hourly solar radiation average was derived from "MeteoNorm" database for area under investigation. Hourly solar radiation is shown in graphical Figure4.3. The highest solar radiation 727.5$W/m^2$is found at mid of day and variation in the pattern shows the absence of clear sky condition. The sufficient radiation availability shows the sufficient running power availability for the PV array generation which fulfil the energy requirement of submersible pump.

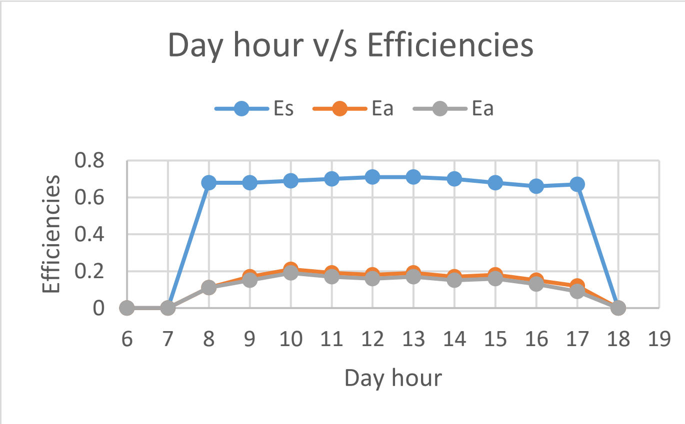

Figure 5: Day hour v/s efficiencies

Figure 5 represents time v/s array efficiency (Ea), subsystem efficiency (Es) & overall efficiency (Eo). It shows that all efficiencies will be increased from morning time approximately 8 AM to 9 AM and it is constantly up to 5:00PM after that abruptly decreases it means system is designed for constant efficiency and it is clear that these efficiencies are depends on the solar radiation intensity availability or availability of solar radiation for maximum power output from the PV array.

Linear relationships concerning solar radiation values (W/m2) with both pump discharge (m3/h) and DC motor power consumption (Watt) were obtained using curve fitting equation (150≤R≤750) as illustrated in Fig. (4.5, 4.6) respectively

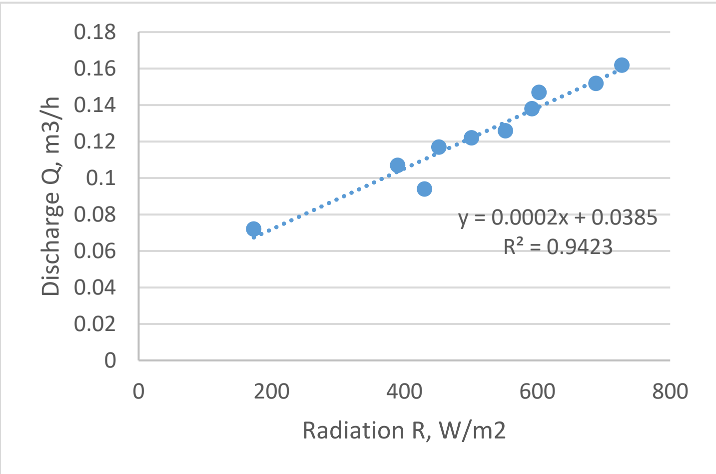

Fig. 6: Pump delivery correlated to solar radiation.

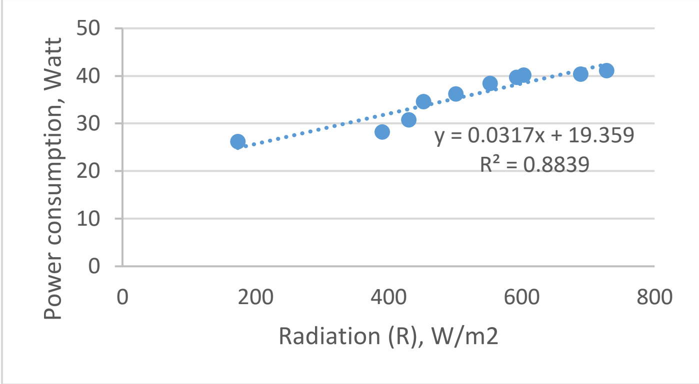

Fig. 7: DC motor power consumption (Watt) with different solar radiation values.

4. CONCLUSION

The conclusions of this study are found as follows.

- The system is economically feasible in interior areas where no electricity or it is an alternate source of electricity.
- The initial cost is high but with the little cost of maintenance over the years, it becomes the best option compared to other methods of water pumping system.
- It is a good alternate because the demand is in the face of solar radiation availability.

Although this study could not correctly predict the degree of sub-optimal performance of all the sub-systems due to limitations of data acquisition methods, it highlights the critical need to operate the PV system at its design parameters. Other than physically creating the extra head, reducing the total array power utilized for pumping appears another plausible solution for improving the overall system efficiency. The excess power could be diverted to some other operations. However, for any such design change, a few aspects need careful consideration. The PV systems are designed taking into account the daily and mostly hourly variations in solar related parameters. The pumping systems are designed such that water is available for maximum hours of sunshine during the day. It is possible that excess power is available during certain hours of the day and the reduced array power may not always be adequate to pump water at times when the irradiance is low.

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