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Photovoltaic Water Pumping System Modelling At Varying Total Dynamic Head (TDH)

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***Abstract:** In the design of photovoltaic water pumping system, the exact estimate of the water flow is a prerequisite for optimized implementation and system performance. In this study, an empirical mathematical model is developed and presented to characterize the photovoltaic water pumping subsystems used in pumping installations. The developed model is made to express the water flow output (Q) directly as a function of the electrical power input (P) to the motor-pump, at varying total dynamic head. Development of the actual model was made using the experimental results obtained by the use of a selected motor-pump system. Model validation was done by means of the experimental tests to cater for height variation. The results obtained from the models showed a high level of relation between the test results and the simulated values with minimal root mean square error. Based on the motor-pump subsystem model, a method is proposed to estimate the amount of carbon dioxide (CO_2) emissions saved by the use of water pumping facilities powered by a photovoltaic array instead of diesel fueled generators. By means of carbon emission coefficient for diesel, the results show mitigation potential of 337.58 tons of CO_2 annually. The overall analysis shows that the adoption of PV water pumping systems contributes to improved living conditions in rural communities and is environment friendly.*

***Keywords:** Photovoltaic, water pumping system, water flow, mathematical model, dynamic head, improved living condition.*

I. INTRODUCTION

In recent times, research on renewable energy resources such as solar energy for electricity generation and related technologies has been on the increase. Also, the use of photovoltaics as power source for pumping water is one of the most promising areas in photovoltaic applications. Solar energy is cheap, and naturally remains a clean source of energy. It does not risk human lives and it is devoid of environmental and economic disaster like pipe explosions, oil spillage, nuclear accidents etc. Its utilization promotes good health through reduction in coal and fossil fuel emissions (Chandel et al., 2015; Eihab et al., 2022). Additionally, the advantages of PVWP system include low maintenance, ease of installation, reliability and the matching between the power generated and the water usage needs (Ghoneim, 2006).

Nigeria is one of the countries in Africa that portable water and electricity supplies is inadequate. It is estimated that about 94% of businesses in Nigeria owned diesel generators while less than 60 % of the people do not have access to quality water supply (Babalola et al., 2022). The number of photovoltaic energy driven water pumps are quite low in Nigeria. This is predicated on high initial cost of investment and lack of adequate technology. However, the latter has become a global concern as workable solutions are on the pipeline by developed economies to meet these challenges

(Hrayshat and Al-Soud, 2004). At present, access to clean water in the rural communities has not been achieved by recent government due to lack of adequate supply of electrical energy. As a result, a reasonable size of the rural population still embarks on long trek just to fetch water at distant streams and springs. Others will have to wait for the rains so as to accumulate water for use. In addition to difficulties attached to this method of obtaining water, these water sources are most times polluted by the local activities. These problems can be completely averted by utilization of stand-alone solar photovoltaic water pumping systems with little maintenance over long time periods. In the light of the benefits of photovoltaic applications, detailed evaluation is necessary to predicting the PVWP system performance by consideration of the parameters governing its behaviour.

Past studies have been conducted on the feasibility of solar water pumping systems (Narvarte et al. 2006; Barlow et al. 1993; Montavon et al. 2004; Yue and Huang, 2011; Daud and Mahmoud, 2005; Elgendy, 2012; Yu et al. 2011), its performance and optimization (Ghosh et al. 2015; Betka and Moussi, 2004; Munzer et al. 2013; Mokeddem et al. 2011) and cost effectiveness (Whitfield, 1995; Campana et al. 2015). Consequently, this work it is intended to evaluate the feasibility of a dynamic water pumping system based on the local climatic conditions of Umudike, by correlating the discharge and the varying locations total dynamic head with selected water pumps. Additionally, for the utilization of photovoltaic water pumping system, the reduction of carbon dioxide emissions into the atmosphere is also considered.

II. OBJECTIVES

- ✓ To evaluate the feasibility of a dynamic water pumping system based on the local climatic conditions of Umudike, by correlating the discharge and the varying locations total dynamic head with selected water pumps.
- ✓ To reduce the carbon dioxide emissions into the atmosphere through the utilization of photovoltaic water pumping system.

III. METHODOLOGY

The performance of the PVWP system is a function of the location's solar irradiance and the corresponding quantity of energy obtained from it. The location's solar radiation data is evaluated with the methods developed below to obtain monthly averages of both solar energy density and the least power which will suffice to power an array of available pumps within the considered TDH.

A. SOLAR ENERGY DENSITY

Considering PV array losses, λ_p and other power conditioning losses, λ_c and the solar conversion efficiency, η_s, the monthly solar energy is written as:

$$E_{A,SUN} = (1-\lambda_P)(1-\lambda_C)\eta_s H_t \quad 1$$

The solar conversion efficiency, η_s with respect to real operating PV panels and their operating parameters is estimated with the relationship below (Evans, 1981):

$$\eta_s = \eta_r[1-\beta_p(T_c - T_r)] \quad 2$$

Where T_c is the PV module average temperature, β_p is the temperature coefficient for module temperature (%/°C), T_r is the reference temperature, and η_r is the PV module efficiency at reference temperature.

The average module temperature is a function of the location's clearness index, K_t and the nominal operating cell temperature, T_{NOC} and is presented below:

$$T_c = (219 + 832K_t)\left[\frac{T_{NOC}-20}{800}\right] + T_\infty \quad 3$$

Where T_∞ is the ambient temperature

From equations 1, 2, and 3, the location's solar energy is obtained as:

$$E_{A,SUN} = (1-\lambda_p)(1-\lambda_c)\left\{1-\beta_p\left[\left([219+832K_t]\left(\frac{T_{NOC}-20}{800}\right)+T_\infty\right)-T_r\right]\right\}H_t \quad 4$$

B. VOLUME OF FUEL SAVED BY UTILIZATION OF PHOTOVOLTAIC WATER PUMPING

If a diesel generator was used for water pumping, the energy output can be estimated as,

$$E_{gen} = \eta_k K_d V_d \quad 5$$

Where V_d is the volume of diesel in liters, K_d is the calorific value of diesel in (kWh/lit), and η_k is the diesel generator conversion efficiency. Due to replacement of solar energy for water pumping, the two energy sources are assumed equal. So that,

$$E_{gen} = E_{A,sun} \quad 6$$

From equations 4, 5, and 6, the volume of diesel saved is expressed as:

$$V_d = \frac{(1-\lambda_p)(1-\lambda_c)\left\{1-\beta_p\left[\left([219+832K_t]\left(\frac{T_{NOC}-20}{800}\right)+T_\infty\right)-T_r\right]\right\}H_t}{\eta_d K_d} \quad 7$$

Where η_d is taken between 29% and 35%, while diesel calorific value, K_d is taken as 10.08KWh/lit (Ghosh et al. 2003).

C. QUANTITY OF CO_2 SAVED DUE TO PHOTOVOLTAIC WATER PUMPING

The quantity of CO_2 emitted at the atmosphere is avoided when photovoltaic water pumping is employed. In this arrangement, the equivalent mass of CO_2 avoided will be obtained from the volume of diesel saved as expressed in equation 7. Accordingly, with CO_2 which results from the burning of diesel, V_d the equivalent mass of CO_2 is expressed as,

$$m_{co_2} = K_{co_2} V_d \quad 8$$

Where V_d is as obtained from equation 7, and K_{co_2} is the CO_2 weight equivalent for diesel fuel (kg/liter).

D. MODELING OF PHOTOVOLTAIC WATER PUMPING

With an avalanche of experimental data comprising solar energy at different power output and corresponding discharge, all obtained at varying dynamic head, a logarithmic model is proposed to relate these variables to create a platform for easy

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utilization of water pumping with other electrical power sources. This arrangement is expressed in the relationship below:

$$Q(h,P) = a(h) + b(h)log_e P \qquad 9$$

$$Q(h,P) = a(h) + b(h)P + c(h)P^2 \qquad 10$$

Where $Q(h,P)$ is the discharge which is a function of the power input and the height, P is the power input, while $a(h)$, $b(h)$ and $c(h)$ represents the coefficients to be determined. The proposed model is purely empirical, and the results obtained from the preliminary observation follows both logarithmic and polynomial form.

IV. RESULTS AND DISCUSSION

The results are presented in three parts: first is the results which featured the arrangement for retrieving the sun's radiant energy for the location, which includes the quantity of the location's solar power strength for pump selection and the average monthly energy yield; second is the results obtained from the water pumping data at different TDH with corresponding logarithmic models fitted to establish relationships which correlates power input, water discharge rate, and the varying altitude; and lastly is the evaluation of the carbon dioxide emissions which apparently is avoided by consideration of an equivalent quantity of diesel utilization for the system. The photovoltaic module area altogether amounts to 68 m^2 from the PV modules.

A. LOCATION'S MONTHLY SOLAR ENERGY AND POWER

The location's capacity to support photovoltaic water pumping is shown on Fig. 1 where monthly energy and power output are presented. The power output, after consideration of losses ranged between 6.438 kW and 9.441 kW. This assessment is necessary so as to note the choice of pump selection based on their rated power and their performance regarding capacity factor considerations. The months of January, February, March and December have greater solar energy potential due to higher solar intensity for these months. For instance, 42.96 kWh/day of energy was obtained for the month of January. The results obtained in Fig. 1 shows that the location can support water pumps of up to 1 kW rated power at higher capacity factor when the PV exposed surface area is up to 60 m^2.

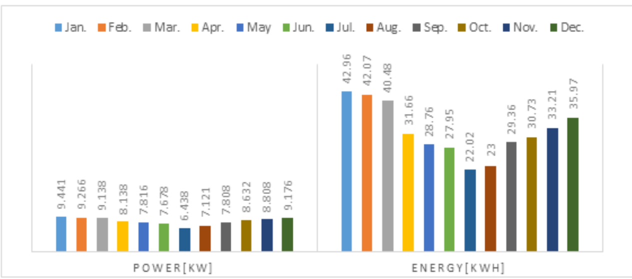

Figure 1: Monthly solar radiation energy and power

B. DISCHARGE AT VARYING ALTITUDE

The resulting data from the pumping routine and the fitted logarithmic curves are shown in the plots of Figs. 2, 3 and 4 for a number of altitude where varying power input resulted in different curve patterns. Results from TDH of 10m, 15m, and 20m as shown in Fig. 2 presents the relationship between the discharge, power, and altitude. At conditions of stability during the pumping exercise at 500 W, the maximum discharge recorded was 3.794 m^3/h, 3.053 m^3/h, and 2.492 at 10m, 15m, and 20m altitude respectively. The result shows that at constant power input to the water pump, there is a continuous reduction in discharge with increasing altitude. For instance, a 5m increase in altitude from 10m through 50m at 500 W, resulted to 19.53 %, 34.32 %, 49.16 %, 64.76 %, 72.01 %, 81.44 %, 88.25 %, and 96.36 % reduction in the discharge rates all referenced at 3.794 m^3/h (10 m altitude). Furthermore, the relationship between the discharge and pumping altitude, as expressed by the logarithmic models points to an empirical relationship between discharge and power input at varying heights.

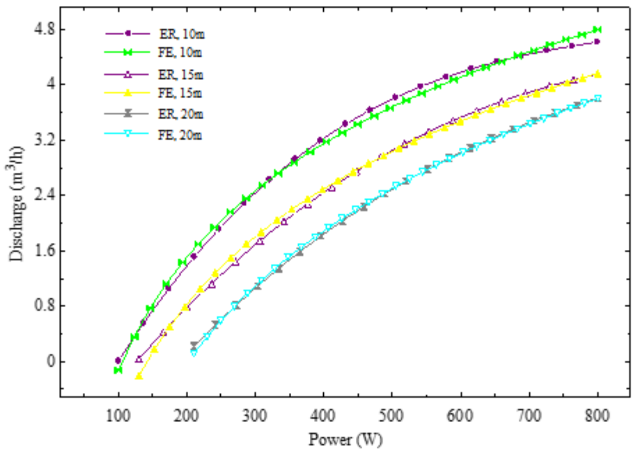

Figure 2: Experimental result and fitted result between power and discharge at 5m, 10m, 15m and 20m.

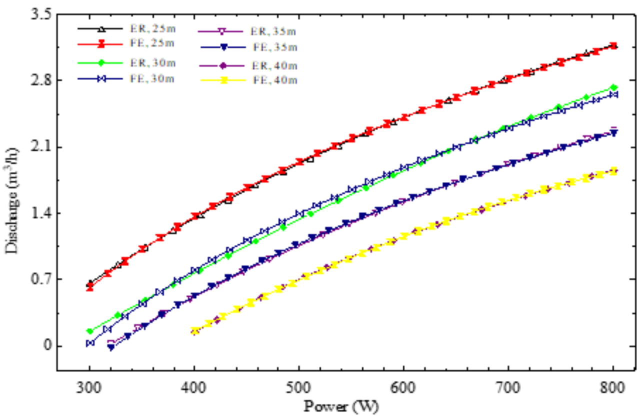

Figure 3: Experimental result and fitted result between power and discharge at 25m, 30m, 35m and 40m.

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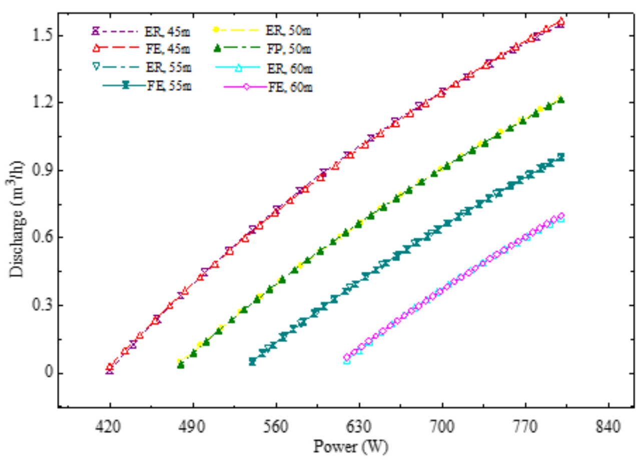

Figure 4: Experimental result and fitted result between power and discharge at 45m, 50m, 55m and 60m.

The trend of the relationship between the operating variables suggests different empirical relationships in terms of the modelling equations. This variation is seen in Table 1 where the empirical relationship fluctuates between second order polynomial and logarithmic equations. For experimental values at 40m, the relationship is a second order polynomial which fits properly in the values while a logarithmic relationship is evident at altitudes of 10m, 15m, 20m, 25m, 30m, 35m, 45m and 50m but with different experimental coefficients. The values of the root mean square errors are similarly presented. These values are as low as 1.6229 per cent at 25 m altitude suggesting very minimal variation in the model and experimental values obtained via both logarithmic and polynomial expressions.

Height (m)	Empirical Model	RMSE %
10	$Q = -11.0443 + 2.36951 log_e P$	9.6353
15	$Q = -11.9289 + 2.408141 log_e P$	8.5166
20	$Q = -14.6369 + 2.75827 log_e P$	3.7848
25	$Q = -14.1662 + 2.59258 log_e P$	1.6229
30	$Q = -15.227 + 2.67517 log_e P$	5.3964
35	$Q = -14.3192 + 2.47814 log_e P$	2.7537
40	$Q = -2.75445 + 0.00882468P - 0.000003844P^2$	5.7165
45	$Q = -14.3987 + 2.38849 log_e P$	9.7930
50	$Q = -14.1852 + 2.30409 log_e P$	4.0406
55	$Q = -14.4803 + 2.30965 log_e P$	1.9677
60	$Q = -15.7988 + 2.46805 log_e P$	6.1017

Table 1: RMSE and developed empirical models

C. QUANTITY OF CO_2 MITIGATED DUE TO SOLAR WATER PUMPING

In Fig. 5, the monthly values of tons of carbon dioxide emissions avoided by virtue of photovoltaic water pumping is evaluated. The quantity of carbon dioxide emissions has been linked with global warming and continues to serve as a major component of ozone depletion. In fact, between 2010 and 2011, carbon dioxide emissions increased by 3% in 2011, reaching an all-time high of 34 billion tonnes in 2011 (NEAA, 2012). These concerns can be addressed by the harnessing of renewable energy sources with photovoltaic water pumping being part of this broad alternative. This conclusion is drawn from the results of monthly emissions where the possibility of saving 337.58 tons per annum for a stand-alone is practical.

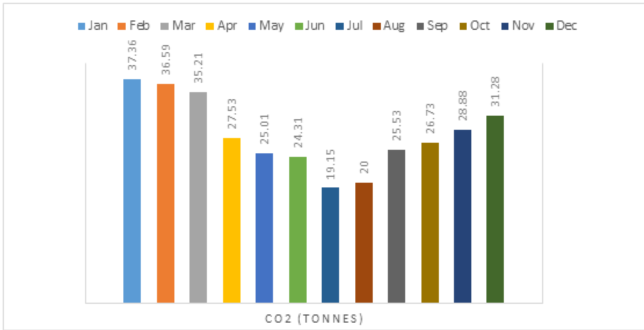

Figure 5: Average monthly mass of Carbon dioxide saved due to solar water pumping.

V. CONCLUSION

✓ In an attempt to adopt greener energy for sustainable development, the potential of photovoltaic water pumping, especially in rural communities, is an important objective. This is especially pertinent as global concern on energy efficiency and greenhouse gasses due to carbon dioxide emissions from the burning of fossil fuel have hit the front burner. These factors can be addressed with the adoption of PWPS technologies, where the water needs of the communities can be addressed while simultaneously fostering an ecofriendly environment.

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