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Modelling the Photovoltaic Pump Output Using Empirical Data from Local Conditions in the Vhembe District

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***Abstract*—**The mathematical analysis on radiation obtained and the development of the solar photovoltaic (PV) array groundwater pumping is needed in the rural areas of Thohoyandou for sizing and power performance subject to the climate conditions within the area. A simple methodology approach is developed for the directed coupled solar, controller and submersible ground water pump system. The system consists of a PV array, pump controller and submerged pump, battery backup and charger controller. For this reason, the theoretical solar radiation is obtained for optimal predictions and system performance in order to achieve different design and operating parameters. Here the examination of the PV schematic module in a Direct Current (DC) application is used for obtainable maximum solar power energy for water pumping. In this paper, a simple efficient photovoltaic water pumping system is presented with its theoretical studies and mathematical modeling of photovoltaics (PV) system.

***Keywords*—**Renewable energy sources, solar groundwater pumping, theoretical and mathematical analysis of photovoltaic (PV) system, theoretical solar radiation.

I. Introduction

PROVIDING sufficient water of appropriate quality and quantity in rural areas has been one of the most important issues in human life [1], [2]. Due to the inaccessibility of proper water resources, rural communities face challenges in collecting and transporting water from far and other locations in their communities, as the result, a new technological method is needed to overcome the sacristy of the water supply. Stand-alone photovoltaic systems are the best solutions for water pumping and low power appliances in rural areas. From the renewable energy resources, the energy due to the photovoltaic (PV) effect can be considered the most sustainable resource because of the ubiquity, abundance, and sustainability of solar radiation. Regardless of the intermittency of sunlight, solar energy is widely available and is free. Hence, the output characteristic of PV module depends on the solar radiation directly absorbed by the cells, so it is necessary to determine the maximum power point for stand-alone PV systems [3].

An option of using the renewable solar photovoltaic (PV) arrays for groundwater pumping is highly desirable and sustainable.

In addition, sustainable energy provision is regarded as a major challenge, especially in Africa, where large proportions of (rural) population do lack access to (basic) energy services. This is particularly prominent in the Sub-Saharan Africa and has prompted several donors, multilateral organizations and states to pay specific attention to improving the situation on the lack of access to modern energy services [2].

Recent studies and analysis of water systems around the world indicate that most remote populations experience difficulties accessing safe and clean drinking water [3], [4].

Water resources are essential for satisfying human needs, protecting health, and ensuring food production, energy and the restoration of ecosystems, as well as for social and economic development and for sustainable development [1], [5], [11]. There is a great and urgent need to supply environmentally sound technology for the provision of drinking water. Remote water pumping systems are a key component in meeting this need.

II. Site Characteristics

The Limpopo Province has significant water challenges in the rural areas, especially since only 40% of the entire province has access to safe drinking water [5]. Ground water is the principal source of fresh water for domestic, industrial and agricultural use in many parts of the world.

The district is one of the second lowest on access to infrastructure development, has a high unemployment rate of 53%, poverty rate stands at 32% and is the lowest socioeconomic area in the Limpopo Province. The municipality is mainly rural in nature and the citizens are dependent on agriculture as the main economic activity to sustain and improve their livelihood [5].

The demand for water and energy access has grown. The government has sought alternative methods of power generation for its industrial development, community up-lifting and sustainable development especially in the remote areas. Hence the option of using renewable energy resources is increasingly being sought and implemented [1], [6].

The success of implementation of solar energy systems at micro-generation scale would involve a lot of intelligent decision making, planning and monitoring by the local

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authorities [7], [8]. Since the approach is at a micro-generation scale, the use of mathematical tools and analysis of the strategically sizing of the solar panels, its energy predictions (power outputs) for the submersible pump flow rate and demand is needed.

Several experiments and theoretical analyses of groundwater pumping systems have been published. The choice is the direct coupled solar (PV) array pumping system as being suitable for use in these conditions, since it is simple and affordable and easy for installation. The area is of preference as it has adequate solar radiation and large water resources.

III. Graphical Representation of the Environmental Conditions

The diagrams showed Figs. 1–5 and Table I demonstrate the characteristics of the environmental conditions and climate in the area.

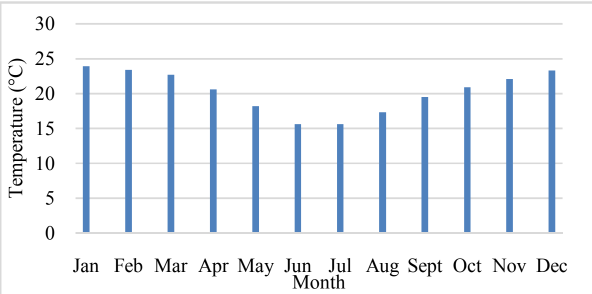

Fig. 1 The monthly temperature measurement (Average - 20 °C)

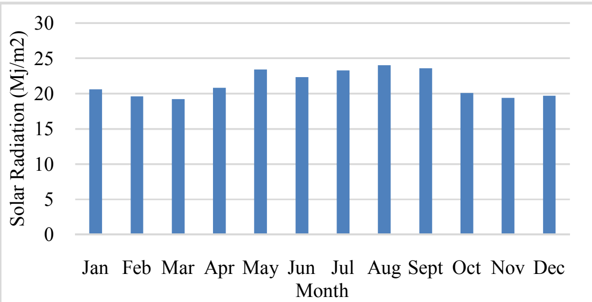

Fig. 2 The monthly direct solar radiation (Energy – MJ/m^2) Annual direct solar radiation = 21.3MJ/m^2

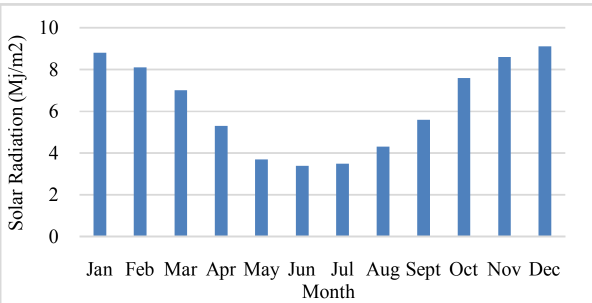

Fig. 3 The monthly diffused solar radiation (Energy – MJ/m^2) Annual diffused solar radiation = 6.3MJ/m^2

TABLE I
AVERAGE ENVIRONMENTAL CONDITIONS FOR THE REGION

Month	Air Temp. (°C)	Dew Point (°C)	Rel. Hum. (%)	D.S.R. - Direct (MJ/m²/d)	Length of Day (Hrs)
Jan	23.9	17.4	67.2	20.6	13.8
Feb	23.4	17.7	70.2	19.6	13.2
Mar	22.7	17	70.4	19.2	12.6
Apr	20.6	14.7	69	20.8	12.6
May	18.2	11.2	63.6	23.4	11.4
Jun	15.6	8.1	60.8	22.3	11.2
Jul	15.6	7.7	59.4	23.3	11.3
Aug	17.3	8.6	56.5	24	11.7
Sept	19.5	10.4	55.6	23.6	12.4
Oct	20.9	12.9	60.3	20.1	13
Nov	22.1	15.1	64.5	19.4	13.6
Dec	23.3	16.7	66.4	19.7	13.9
Annual	20.3	13.2	63.7	21.3	12.5

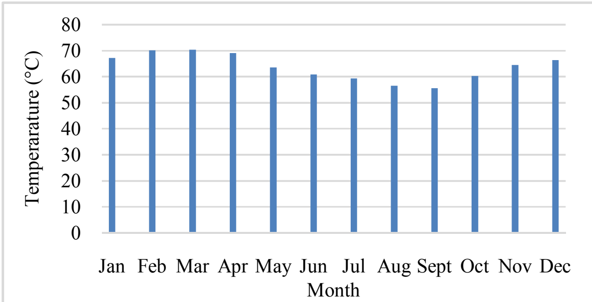

Fig. 4 The relative monthly humidity (Average - 63.70%)

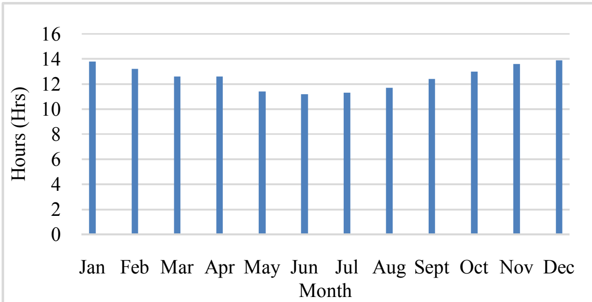

Fig. 5 The monthly length of the day measured (Average - 12.5Hrs)

The area is known for its abundance in radiation. The determined available solar resources greatly have an influence on the design, configuration, and the cost of power system developed. Monthly average solar insolation data for the area are shown in Figs. 1–4. It is noticed that the highest values of the solar insolation are during the summer months (Jan, Feb, Mar, Apr, Sept, Oct, Nov and Dec) and the lowest values are during the winter months (May, Jun, Jul, and Aug).

IV. Solar Radiation Expression for Sizing of the Photovoltaic (PV) Array

The mathematical modeling of the PV pumping system includes the solar radiation data, PV array and the pump. The pump controller function is also considered for operational purposes and flow supply to successfully monitor the power output from the PV array and the pump motor. Solar radiation data is essential for design and sizing the PV pumping system since the power output of the PV array depends on its value.

In designing and properly sizing of the PV groundwater pumping system depends mainly on the solar radiation absorbed since the produced power depends on its value. In order to estimate this value, the global solar radiation intensity on the PV array tilted at specific angle surface, the total hourly value of solar radiation, $G_c$is obtained from the Duffie and Beckman [6], [21], neglecting the solar radiation reflection component from the PV array.

$$G_c = (R_b.B_h) + (R_d.D_h) \quad (1)$$

where, B_h and D_h are the beam and diffuse solar radiation component intensities on a horizontal surface respectively. This means that, tilt angle is referenced at zero (0) degrees. Also R_b and R_d are the beam and diffuse solar component intensities at tilted angle factors respectively.

By using 25°C tilted angle and the Latitude angel (L = 22°C) and solar hour angle is defined by (h = (12 – t)x15°), where t (hrs.) is the local time for the day and δ, the solar declination angle is obtained [2], [9], [18]-[20]:

$$R_b = \frac{\cos(L-\beta).(\cos\delta.\cos h)+\sin(L-\beta).\sin\delta}{\cos L.\cos\beta.\sinh + \sin L.\sin\delta} \quad (2)$$

From Table I, the local time, t = 12.5hrs, hence

$$h = (12 - 12.5) \times 15° ; \qquad h = 7.5 \quad (3)$$

$$\delta = 23.5 \sin\left[\frac{360}{365}(N + 284)\right] \quad (4)$$

where N is the number of days in a year starting from the 1st January. In this case, N = 360days.

$$\delta = 23.5 \sin\left[\frac{360}{365}(360 + 284)\right]; \quad \delta = -23.4 \quad (5)$$

Therefore

$$R_b = \frac{\cos(22-25).(\cos 35.\cos(-23.4)) + \sin(22-25).\sin(-23.4)}{\cos(22).\cos(25).\sin(-23.4) + \sin(22).\sin(-23.4)}$$

$$R_b = -1.595 \quad (6)$$

and

$$R_d = \left(\frac{\delta}{2}\right) = \left(\frac{-23.4}{2}\right) = \qquad R_d = -11.7 \quad (7)$$

Using, formula by Meinel and Mainel [7], [8], [14], [19], the hourly global solar radiation intensity on a horizontal surface can be expressed by, ($G_h = B_h + D_h$) in the clear sky model is given by

$$G_h = G_{oh} \times 0.7^{m^{0.678}} \quad (8)$$

and G_{oh} is the extraterrestrial irradiance on horizontal surface given by Markvart formula [8], [13], [18], [19]; G_{sc} is the constant solar radiation = 1367W/m^2 and m, air mass ration obtained from the clear sky conditions expressed by Kreith and Kreider [10], [11], [20];

$$m = [1229 + (614 \sin\alpha)^2]^{0.5} - 614 \sin\alpha \quad (9)$$

where, α is the sun altitude angle obtained from,

$$\sin\alpha = \cos L \times \cos\delta \times \cos h + \sin L \times \sin\delta \quad (10)$$

$$\sin\alpha = \cos 22 \times \cos\delta \times \cos 7.5 + \sin 22 \times \sin(-23.4)$$

$$\alpha = 52.3°C \quad (11)$$

$$G_{oh} = \left[1 + 0.033\cos\left(\frac{2\pi N}{365}\right)\right] \times (\cos L\cos\delta\cos h) + \sin L\sin\delta)]$$

$$G_{oh} = 2.3 \quad (12)$$

$$m = [1229 + (614\sin(52.3))^2]^{0.5} - 614\sin(52.3)$$

$$m = 1.3 \quad (13)$$

Therefore G_h is

$$G_h = G_{oh} \times 0.7^{1.3^{0.678}} \qquad G_h = 1.5 \quad 14)$$

By obtaining these constant and values from the equation, the solar energy required can be determined.

V. Photovoltaic (PV) Panel Specifications

Ground water pumping for irrigation and water supply at rural communities is an important area for the stand-alone PV systems [11], [12], [16], [21]. The solar radiation is very important in computing the amount of electricity produced by PV modules. The PV module chosen is a 72 multi-crystalline silicon solar cells in series capable to deliver 140W/ 12Vof maximum power shown in Fig. 6.

Fig. 6 Solar (PV) array component of the groundwater pump

The long term statistical data on solar sunshine hours are also very important in deriving an equation to calculate the solar radiation, and use in the design of the PV energy generation system. However, the solar radiation could be generated by the mathematical model which is developed based on the meteorological sunshine hour data as shown in Table I.

The amount of solar radiation incident on the surface of the earth measured on a horizontal surface is referred to the total or global solar radiation measured in kWh/m^2/day. It is therefore necessary to approximate the amount of useable solar radiation from the data captured as available parameters such as; sunshine hours, relative humidity, maximum and minimum temperature and geographical conditions of the area. With the monthly average solar irradiation found; 6.3–21.3MJ/m^2 with the monthly average daily sunshine duration of 12.5hours, then the energy output from the system is determined by the following relationship [9], [13], [20].

The expression to be used to calculate the radiation on the PV plane array would be [14], [20], [21]:

$$E = G_d \times A_{pv} \times \eta \tag{15}$$

where, E is the PV electricity production in MJ/d, G_d is the sum (Σ) of the available solar radiation in MJ/m^2.d. The A_{pv} is the PV surface area (m^2), and η is the efficiency of the PV panel. Knowing the panel specification, as given in Table II, the energy is determined.

TABLE II
PV PANEL TECHNICAL SPECIFICATION

Max power	140Wp
Optimum voltage	17.6V
Optimum current	7.95A
Open circuit voltage	22.2V
Open circuit current	8.43A
Number of cells (PCS)	36(4 * 9)
Size of module (mm)	1480 * 870 * 35mm
Maximum system voltage (V)	1000VDC
Temperature coefficients of I_{sc} (%)	(0.055± 0.01)%/k
Temperature coefficients of V_{oc}	(%)-(78± 10) MV/k
Temperature coefficients of Pm (%)	-(0.48± 0.05)%/k
Temperature Range	-40° C+80° C
Tolerance	+/-3%
Output tolerance (%)	+/-5%
Cell Efficiency (%)	17%
Module Efficiency (η)	15%

Many research investigations have been carried out to determine the optimum tilt angle for solar PV modules and are presented in many literatures. For the values G_d = 255.6Mj/m$^{2;}$ A_{pv} = 1.2876m^2 and η = 15%, therefore E is computed as

$$E = G_d \times A_{pv} \times \eta$$
$$E = 21.3\text{Mj/m}^2 \times 1.2876\text{m}^2 \times 15\%$$
$$E = 4936.65\text{MJ/d} \tag{15}$$

For the maximum power delivery the V_{max} and I_{max} is used.

VI. DC POWER MOTOR PUMP

For groundwater pumping, the Total Dynamic Head (TDH) is a very important and essential factor in system design as determining the operational pressure of the pump. This is measured in meters (m) or feet (ft) as the sum of the total vertical lift (m), friction loss (Mj/m^2) and tank pressure (kPa) [15], [21].

Most common PV groundwater pump systemsemploy DC motor as are they could be directly coupled with the PV arrays and that makes very simple system installation [1], [16]. Among different types of DC motors, a permanent magnet DC (PMDC) motor, Shurflo 9300 Series is chosen (Fig. 7) as it provides higher starting torque.

Fig. 7 Solar Groundwater Submersible Pump and under test

The pump is the heart and soul of the solar groundwater pumping system. For the given power input, the pump produces a unique combination of flow and pressure during the operation which gives its performance characteristic. Solar pumps are rated according to the voltage of electricity that should be supplied. A 24VDC, 120W/4A, pump is tested for the installation. Other accessories such as filters, float valves and switches are included to optimal performance. The pump to be installed must be a heavy duty type motor to withstand harsh operation under severe conditions with its nominal regulated voltage [17], [21].

The average daily load of the hydropower (kWh/day) needed by the pump [18], [21], is computed using:

$$E_H = \frac{g \times \rho_a \times Q_a \times TH}{\eta_p \times 3600} = \frac{C_H \times Q_a \times TH}{\eta_p} \tag{16}$$

where, g is acceleration of gravity (9.81 m.s^{-2}); ρ_a is water density (1000 kg/m^3); Q_a is daily water needs (50m^3/day); TH is the total head (55m) and the η_P is pump system efficiency (50%)

The energy for the PV module to generate a tank capacity of 200m^3 is expressed by the formula used. The daily water needs and the autonomy of the system is determined by the tank capacity. E_H as the hydraulic energy needed is expressed [15], [19], [21] by

$$E_H = \frac{9.81 m.s^{-2} \times \frac{1000kg}{m^3} \times 55m}{50\% \times 3600} = \frac{539550}{1800} = 299.97kWh \tag{17}$$

The Total Dynamic Head (TDH) is the required energy needed to raise the daily required volume of water per day by the pump from the water source to the storage tank in meters.

It's also important to establish the overall system efficiency Generally, to have a well-designed PV solar water system, the system should have an overall (η_o) efficiency in the range of 3-5% determined by the hydraulic energy and the solar radiation energy [17]-[21]. Where V_w is the daily required volume (m^3/day), G_T is the global daily solar radiation on tilted surface

($kWhm^{-2}$). This also expressed by multiplying the typical standard pump efficiency with the PV efficiency. In order to achieve the optimal overall system efficiency, the minimum (30%) is chosen for computation [20], [21].

$$\eta_o = \frac{\rho_g \times TDH}{A_{pv} \times G_T} = \eta_{pv} \times \eta_s = 15 \text{ x } 30 = 4.5\% \qquad (18)$$

where η_{pv} is the PV efficiency (15%) and the η_s is the wire-to-wire efficiency (30%). With the hydraulic energy (E_H) and daily required volume of water (V_W), the Total Dynamic Head (TDH) [19], [20] is expressed as

$$E_h = C_h \times V_W \times TDH \qquad (19)$$

where; $C_h = \frac{\rho \times g}{3600} = 2.725$; p is the water density ($1000Kgm^{-3}$) and g, is the acceleration due to gravity ($9.81ms^{-2}$).

Therefore the TDH = 36.23.

VII. Mechanical Power Design Requirement

The figure and character of individual solar modules that will be used to power the water pumping scheme is dependent on the power requirements of the system's mechanical components. Before the proper solar modules can be selected it is necessary to produce an applied science model that delineates the essential parameters of the scheme so that the mechanical components can be chosen. The choice of piping materials and pumps is based along the mechanical constraints imposed on the organization by the engineering model, goals for improvement over the existing pumping system and the goal of long-term reliability of the organization with minimal care.

VIII. Conclusion

This study contributes to answering the theoretical analysis and practical questions on providing sufficient drinking water for rural communities by using PV system. However, interesting subjects for further research on the application underlies on the field conditions remaining.

Despite the remaining questions to be answered, the results form part of the practical assessment of the system and the use of solar energy installations can be taken with more confidence and consideration during the design. Hence the need for the field data is required for monitoring the performance and its capacity to deliver.

With choice of the pump used, consideration should be made of climate conditions and demand capacity of the water together with other losses of testing model.

An evaluation of the groundwater PV system is currently being developed for testing at selected location operating for a period of one year in order to determine its performance and efficiency. This will finally be re-evaluated and adjust the system to operate at its optimal design considerations and factors obtained during the experiments.

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