Direct-coupled PVWPS sizing using borehole hydraulic parameters

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Abstract. Photovoltaic water pumping systems (PVWPS) are a promising solution to improve water access in isolated rural areas in developing countries. Each system must be carefully sized to satisfy local demand while being as affordable as possible. In order to design a successful and sustainable system, the knowledge of solar radiation and groundwater resources availability is crucial. There are several steps that are followed to size and model a PVWPS. The current study used the borehole and solar radiation characteristics at Vuwani Science Resource Centre to determine the suitable pump and the size of the PV power system for a sustainable battery-less pumping of groundwater without depletion. The hydraulic characteristics, optimal flow-rate of 69.12 m^3/day and total dynamic head of 53 m were used as inputs for the sizing of the pump. Grundof on-line software was used to validate the sizing of a proper submersible water pump that can supply the water needs. With having the electrical load of the system, the excel was used to design a complete and optimized model of PV system. The proposed system consists of a PV, a submersible pump and storage tank. A system controller was also designed and analysed successfully.
Keywords: Direct-coupled; sizing; hydraulic; photovoltaic; pump-curve

1. Introduction

A direct-coupled photovoltaic water pumping systems (PVWPS) is one of the simplest methods which connect the pump direct to the PV array power converter without using batteries. The battery-less PVWPS is preferred for the fast recovery of investment in order to reduce the total system costs. Because there is no battery to store the energy for later use, it stores the energy in the form of water in the tank to be used when the sun on not shining. Figure 1 shows block diagram of the system which is consist of solar array, controller, DC submersible pump and water tank. As compared to AC drive which can be recovered in 8 years, DC drive can be recovered in 2.5 years [1]. Direct-coupled system provide both technically and economically feasible solutions. Unlike grid-tied, the system in this study is beneficial in remote and rural areas where there is no or limited access to electricity. The system functions by utilising the DC power generated from the solar array.

Properly designed systems involve the sizing individual components and the performance by using computer simulation to check the effect of climatic conditions on the peak power. Over- and under-design of the system should be avoided at all costs because it becomes expensive over time

[3]. One of the common PVWPS challenges is for the wells that are not sustainable, and dry up quickly due to the lack of proper assessment of the available groundwater. Sustainability of the system can be achieved by groundwater recharge-discharge rate balance through a well testing. This balance is a key factor for the determination of the suitable optimal pumping rate leading to a long life-cycle of the system. The current study is conceptualized for a sustainable system which is informed by the location characteristics. The idea is to design a system customised to the local available groundwater and the climatic parameters like the temperature and solar irradiation.

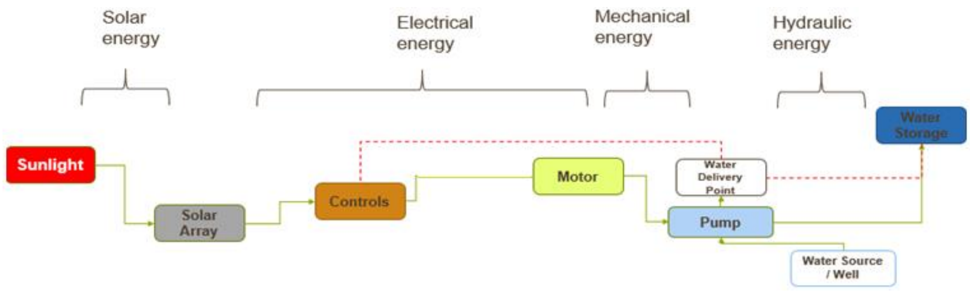

Figure 1. Block diagram of a direct-coupled PVWPS. [2]

The solar pumps available in the market can pump water from 5 m to over 200 m with outputs up to 250 m^3/day, being used in boreholes of 15 to 50 m of depth [4]. Most of the PVWPS have a water reservoir. The capacity of water reservoir (system autonomy) is determined by the type of supply (domestic, animal, and irrigation) and the financial constraints of the investor [5]. In order to ensure that the water supply service is not impaired during periods of low or absent solar irradiance, the presence of a reservoir is of great importance, and require an analysis of the stochastic nature of the energy resource, flow and periods needs to meet the full demand [6]. However, the water source must recharge the reservoir faster than the water pumping rate, avoiding a reservoir drought as it could damage the pump. The purpose of this study was to size and analyse a solar water pumping system which is customised to the borehole characteristics and the local climatic conditions. This multi-stage method includes the well and aquifer losses in order to calculate the hydraulic head. Adding to the head and flow rate, the method combines the effect of temperature and solar radiation on the peak power to be generated based on these parameters.

2. Methodology

2.1. System model

The sizing process of the system is to ensure that the groundwater in the well is sustainable and its exploitation matches the discharge-recharge rate [7]. This process is considered based on the parameters such as the pump power matching the site characteristics (depth of the wheel, hydraulic loop, and design flow rate), capacity of solar PV power, the running conditions and the reservoir dimensions [7]. The MATLAB simulations based on the design phase outputs are performed to evaluate the effects of climatic conditions and hydraulic parameters on the peak power of the system. The use of simulation programs allows solving problems of design and optimization of the PV systems [8]. The block diagram of the energy conversion model is presented in Figure 2. Detailed methodology is presented to achieve an adequate design of the proposed PVWP system utilized for irrigation purposes.

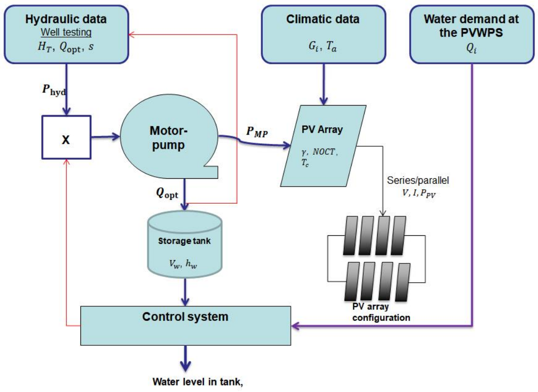

Figure 2. Operation model of the PV water pumping system.

2.2. Data collection

The proposed system is based on the local solar irradiation and groundwater characteristics at Vuwani location in the Limpopo Province, South Africa. Two sets of data were collected from the research and used as inputs to the sizing process and pump selection exercise. Figures 3 and 4 show the weather data collected from the study site and the well characteristics to be used for the sizing process. Figure 3 shows the graph of average temperature and solar irradiation data collected through USAid Venda (located at latitude: -23.13100052, longitude: 30.42399979 [9]), one of the South African Universities Radiometric Network (SAURAN) stations. The data was collected between 2018 and 2022, and shows that the lowest solar irradiation: 1231.63 Wh/day and the highest solar irradiation 1953.60 Wh/day were observed in June and February, respectively.

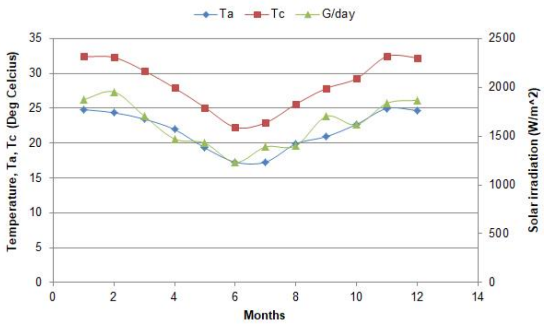

Figure 3. 4 years monthly average solar irradiation (green), ambient temperature (blue) and cell temperature (red).

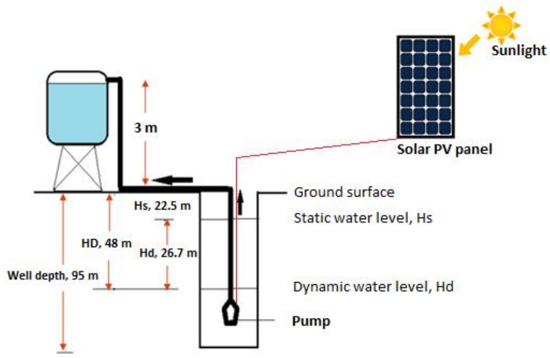

Figure 4. Adapted PV water pumping system with the hydraulic data from a well testing study.

Regarding the groundwater resources the hydraulic power varies from day to day or month to month, due to varying water table, the PVWPS was designed for the worst-case combination of solar radiation energy and water demand [10]. Figure 4 shows the well characteristics which was conducted to determine optimum pumping rate and total head through both the aquifer and the well losses. There are two fundamental hydraulic parameters that can be deduced from the information in the figure, i.e. total dynamic head and flow rate. The well characteristics show that a flow rate of 69.12 m^3/day is required to determine the peak power of the pump which is placed at the total dynamic head of 53 m.

2.3. Sizing of the components of the system

A basic power calculation is provided below for the design of a solar DC pump for the required capacity. With an average discharge rate of 2880 m^3/hour at the hydraulic head of 53 m in Figure 4, the pump's required hydraulic power (P_h) is estimated and the electric power needed to run the pump is expressed as equation 1 [11]:

$$P_{MP} = \frac{P_h}{\eta_{MP}} \tag{1}$$

where $P_h = (\rho g Q H_T/3600)$ is the hydraulic power, ρ is the water density (1000 kg/m^3), g is the acceleration due to gravity (9.8 m/s^2) and η_{MP}, efficiency of pump (60 %) is also taken into consideration [12]. Once the total dynamic head (H_T) and the flow rate (Q) of water and the borehole characteristics. The power required to run the given pump was produced from the solar panels with the total peak power (P_{PV}) based on the daily irradiance (G_{dm}) and the performance ratio of the panels (α) dependent on the installation conditions is given by equation 2 [13]

$$P_{PV} = \frac{P_{MP}}{\alpha \times G_{dm}} \tag{2}$$

The value of P_{PV} calculated in equation (2) is then used to determine the required total number and the unit power of the panels which vary depending on the voltage necessary for the operation of the pump. The number of panels multiplied by the unit power will give the total power supplied.

2.4. Simulations with MATLAB

To calculate the power peak of the array, the output power of a photovoltaic generator under standard condition of measurements which are solar irradiance (G_{ref}=1000 W/m^2) and cell temperature ($T_{ref} = 25°C$) were used. The peak power (P_p) that must be generated accordingly to the demand is calculated below:

$$P_{PV} = \frac{2.72}{f_m \times [1 - \gamma \times (T_c - T_{ref}) \times \eta_g] \times G_i \times \eta_{PV}} \times Q \times H_T \tag{3}$$

η_{PV} is the daily average efficiency of the generation in exploitation conditions. The γ is the temperature coefficient of the cell, for monocrystalline module, it ranges from 0.004 to 0.005 $/°C$. For polycrystalline silicon module, it ranges from 0.001 to 0.002 $/°C$ [12]. T_c is the daily average temperature of cell and G_T is the daily average irradiation on the module plane (Wh/m^2/day), and it is expressed in equation 4

$$T_c = T_a \left(\frac{NOCT - 20}{800}\right) \times G_T \tag{4}$$

3. Results and discussion

3.1. Sizing

Based on the well characteristics as indicated in Figure 4, the optimal pumping rate of 69.12 m^3/day at the head of 53.00 m, the sizing of the sustainable system which fits these parameters is presented in Table 1. The calculated daily required electricity to power a pump which is capable of pumping the water at a given rate was used to select the right pump. The pump needs 6 solar panels with 255 W each to guarantee the desired flow. The results also indicated that the required capacity of the water tank is 207.36 m^3, which allows autonomy for three consecutive days.

Table 1. PVWPS sizing results.

Well testing		**Pump**		**PV array**	
Parameter	value	Parameter	value	Parameter	value
H_T (m):	53.00	Type:	*DC-Subm.	Type:	Poly-Si
H_h (m):	95.00	P_{MP} (kWh/d):	16.95	P_{PV} (kW):	1.35
s_t (m):	26.70	P_{max} (kW):	3.39	PV stand:	fixed @ 45°
Q (L/h):	2883.75	-	-	P_{max} (kW):	0.26
-	-	-	-	No. of panels:	6 (series)

Given the daily pumping rate at the given head, Figure 5 show the H-Q curve (pumping curve) was generated from the manufacturer, Grundfos online tool to select the pump. A Grundfos SP3A-15 stainless-steel pump matched the sizing requirements of pumping the water from the well at a rate of 2880 m^3/hour at 53 m total dynamic head. The pump power peak of 1359.00 W was found to be very close to the calculated (sizing) peak power of 1348.45 W as indicated in Table 1. This pump is able to meet the desired pump rate of 69.12 m^3/day without depleting the groundwater in the well.

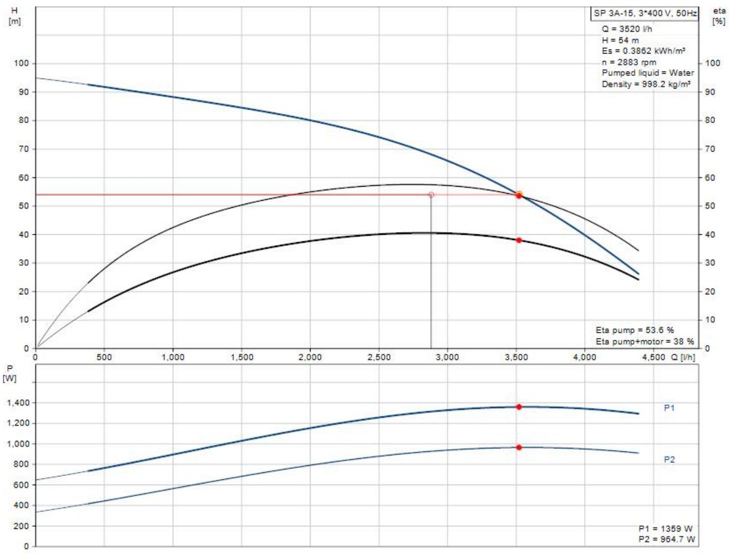

Figure 5. Illustration of pump curve to determination of the pump operating point.

3.2. Effect of hydraulic parameters on peak power

The MATLAB simulations results in Figure 6 show the effects of the pump rate, solar irradiation and ambient temperature variations on the peak power of the system. Graphs in Figures 6 (a), (b) and (c) represent the relationship between the peak power required to pump the water from the well at varying head, but constant pumping rate, solar irradiation and ambient temperature, respectively. In Figure 6(a) is related to hydraulic head and the optimum pumping rate which was determined through the well testing. It can also be seen that varying pumping rate (slopes) from 40 to 80 m^3/day, increased proportionally the peak power as well. Figures 6(b) and (c) represent the effect of two climatic conditions factors which are the solar irradiation and ambient temperature, respectively. An increase in solar irradiation shows that a lower power is required for the system to meet the hydraulic demands. On the other hand, the variation of temperature has negatively affected on the PV panel power production. This shows that the peak power on site should be increased in order to compensate for any possible loss of production due the variation of temperature. Therefore, ignoring these variations may lead into an under-sized system.

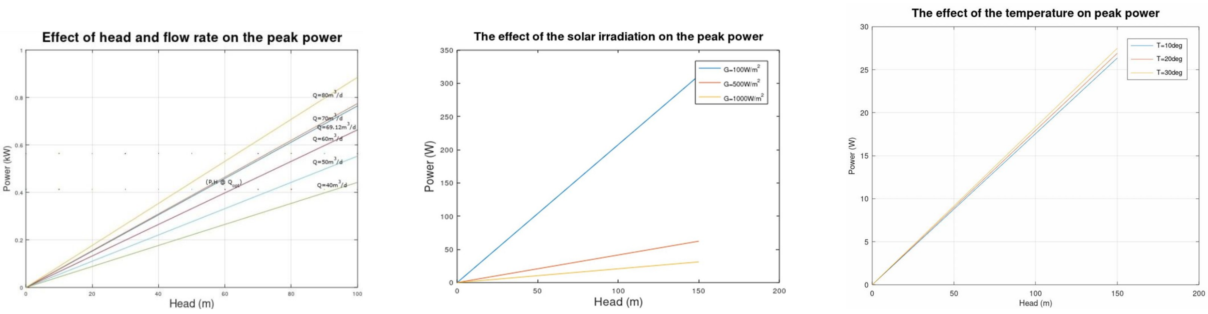

Figure 6. The effect of climatic conditions and hydraulic parameters on peak power; (a) flow rate, (b) solar irradiation and (c) temperature.

4. Conclusion

The proposed analytical sizing method of PVWPS based on the available groundwater such that the discharge rate match the recharge rate and the local meteorological data was achieved in this study. The system was designed to supply a daily average of 69,120 Liters/day at 54 m head in June with the lowest average solar irradiation. The PV array of 6 panels connected in series with the power unit of 255 W produced 1.35 kW under this winter condition which was enough to run a DC pump to pump the water from the well to the storage tank. Simulation results obtained with MATLAB shows the effect of variation temperature, solar irradiation and pumping rate on the peak power. The simulations were useful to avoid under-sizing or over-sizing of the system which always becomes very expensive. It was demonstrated that an increase in temperature do affect negatively the peak power while an increase of solar irradiation was proportional with the peak power. This method shows that well characteristics and local climate parameters are useful for a sustainable and reliable system to be designed.

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