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RESEARCH ARTICLE

Performance evaluation and simulation of a photovoltaic powered water pumping system

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ABSTRACT

One of most important application of solar energy is to utilize it in the field of water pumping. A PV powered water pumping unit was simulated and evaluated for its performance in this study. The system comprised a PV pumping unit (0.75 Hp) with a DC motor, electronic controller (DC-DC), solar modules (960 W_p) and a submersible pump in a deep well (20 m). The pumping unit started flow when solar radiation intensity was 100 Wm^{-2} and became smooth at 650W m^{-2}. The flow rate of the pump affected when the ambient temperature exceeded above 30°C. Pumping performance was best when it was operated at an angle, which was equal to the latitude of site (32°) where the solar pumping system was installed. The simulated results had a good match with the observed values and a correlation coefficient value of 0.944 was obtained. The results indicated that PVSYST simulation program is a good option for design and performance evaluation of a solar water pumping system.

INTRODUCTION

The fast development of a country depends very much upon water and energy availability. Pakistan is amongst the countries, which are rich with renewable energy resources like solar, wind and ground water resources. Due to the inaccessibility of fresh water in many areas of Pakistan, people drink water from ponds. These ponds come into existence after rainfall and hence cause many diseases due to bad quality of water. One of the reasons for the unavailability of fresh water is the lack of pumping power in rural areas. The current electricity shortfall of Pakistan in the month of May 2011 was 7200 MW as admitted by PEPCO (Pakistan electric power company) (Ammar, 2011). Pakistan is an agricultural based country and its rural areas are badly affected by energy shortfall. Pakistan has extensive canal irrigation system, but still there is water shortage. Approximately 0.8 million tube wells have been installed to fulfil water shortage, out of which 90% are diesel operated and 10% are operated using national grid connected electricity (Anonymous, 2008). Pakistan's government is heavily subsidizing the tube wells, which pump water for agriculture purposes and resulting in an additional burden on national exchequer increase. In Pakistan, it is very difficult to extend the electric grid to every location where it is needed and to collect dues from every farmer. These factors have led to the use of standalone power systems based on renewable resources usually backed up by a diesel generator (Akella et al., 2007). Many developing countries are choosing decentralized energy planning which means that in addition to the national electrical grid, small energy systems supply parts of the country separately (Hiremath et al., 2007).

Solar energy is available for more than 300 days a year in Pakistan with about 6-8 effective day light hours (Khalil et al., 2007). Solar powered water pumping plays a vital role to improve rural dwellings. The average net available radiations in Pakistan are in the range of 10-15MJ m^{-2} day^{-1}, and the sunshine time period is 12 hours per day from March to October. So, it may be the cheapest source of energy available in Pakistan and can fulfil our energy shortfall if managed properly.

The most of the grid energy used in agricultural farms is consumed for pumping water for irrigation purposes. If water-pumping system is converted from grid-connected supply to renewable electricity obtained from PV (Photovoltaic) panels, then a positive contribution can be made to the national grid electricity deficit and environment. As the PV solar pumping systems use photovoltaic plates which are cost effective, the farming community cannot afford the big solar pumping systems. So it is better to use the PV pumping system in a high efficiency irrigation system like drip irrigation to justify the cost of the system. It is considered that the solar water pumps may be used for irrigation purposes more optimally with high efficiency irrigation system because a small quantity of water is pumped. When PV pumping system is attached with drip irrigation system or laser levelled furrows with gated pipe water networks, it can provide water to 3-5 acre of orchard or vegetable under cultivation (Mehmood, 2010).

The main objective of the present research was to evaluate the performance of a PV water pumping system at different heads and inclination angles of the PV modules. For this purpose, data were recorded for water flow rate at different heads and different PV module inclinations. Simulation of photovoltaic pumping system was also carried out by using the site specific data using PVSYST model. In order to assess the validity of the model, a comparison was done for measured values of the actual flow rates from the solar pumping system and predicted values obtained from the PVSYST model.

MATERIALS AND METHODS

The experiments were conducted to simulate and evaluate the performance of PV system installed at University of Agriculture, Faisalabad (Pakistan). The photovoltaic pumping site is situated at latitude 31°N, longitude 73°E and at an elevation of 186 m above sea level. The pump was a submersible type and installed in a well of 20m deep. The system of pumping water comprised of a 500 W electric motor and eight PV modules; each having 120 Wp (Watt-peak) and a DC-DC converter. DC current operated the electric motor used in this system and the electronic controller used was a fixed DC-DC type. The output generated by PV array and electronic controller monitors input provided to motor in a well. Static water level is at approximately 19-20 m depth in the Faisalabad region.

The energy output from PV panels varied with the solar irradiance level. Output of the PV panels was used as input for pump. The flow rates from pump were measured at different solar irradiance intensities for performance evaluation of solar powered water pumping system. Pyranometer was used to measure solar irradiance of PV array during experiments.

The flow rates of pumping unit were measured at various irradiances, pumping heads, ambient temperatures and inclination angles of PV array for the performance evaluation of PV submersible pumping unit. PVSYST (Photovoltaic System Model of solar pumping) simulation model was used to compare the observed and predicted values.

Water flow rates were measured at different solar radiation intensities. Pyranometer was used to measure solar irradiance in $W.m^{-2}$ on a surface of PV array. The Pyranometer was adjusted on the same angle as that of modules. An Apogee Pyranometer with a silicon cell yields in milli-volts of output with conversion factor of 5. The data of solar irradiance were collected on hourly basis from 6:00 AM to 6:00 PM, from the month of January 2011 to May 2011. The data of solar irradiance falling on PV array tilted surface were measured from sunrise to sunset. The hourly discharge from pump was measured along with solar radiation data and the relationship between these two variables was determined using statistical techniques.

The effect of ambient temperatures on the pump discharge was measured. The flow rate of water was measured in graduated flask and the ambient temperature was measured using mercury glass thermometer on hourly basis.

The experimental system was deep well pump and discharge directly into field. The head was increased by providing the additional pipe to the discharge end. The discharge was measured at 20, 22, 25, 28 and 30 m heads. The effect of various inclination angles on the discharge was also measured. Various inclination angles adjusted for this study were 32º, 40º and 45º. The tilt angle was changed from latitude 32º, and its positions at 40º and 45º were adjusted and discharges at various inclinations were recorded.

PVSYST model

PVSYST, a PC software package was used to simulate the grid-connected, stand-alone, pumping and DC-grid (public transport) photovoltaic systems. This model was also used to determine the water flow rates, size of PV system and pump power, as well as the cost of the PV solar system by putting the site specific input data.

RESULTS AND DISCUSSION

Solar Irradiance

The monthly average of hourly-based values of solar irradiance from January to May is shown in Figure 1. The irradiance depended upon the time of day and weather condition i.e., cloudy or sunny day. Solar irradiance shows a parabola curve like trend through out the day starting from low values to maximum at noon and then decreasing in the evening. During morning and evening hours, the solar radiations have to travel a long way though the air column which convert most of the solar radiations to diffuse radiation and beam radiations component is reduced. Beam radiations are the solar radiations reaching the earth without being scattered by the atmosphere. It is also evident from Figure 1 that the values of solar radiations started in January and February from 8:00 AM. This was due to variation in solar declination; it varied from +23.45 in summer (Jun, 21) to -23.45 in winter season (Dec, 22). This solar declination variation changed the sun rise and sun set time and then forming different curves in different months as shown in Figure 1.

Pump Discharge

The discharge data were recorded with an interval of one hour during the sun shine hours. The water flow rate verses time is shown in Figure 2 with an interval of one hour. It is clear from the Figure that the water flow rates increased from January to May.

Figure 2 shows that the discharge increases with increase of solar radiation, it was zero at the start of day and increased with increase of solar radiation, attained maximum value at mid day then it decreased gradually till zero in the evening. It is also evident from the Figure 2 that the discharge figures during summer months are is more as compared with that of during winter months. In summer, day becomes longer and discharge time or pumping duration increased and reverse is the case in winter.

As the irradiance was low at start of day and increased with time proceeded for the mid of the day and after that it decreased and became zero when sun disappeared. So the discharge from solar pumping system is directly proportional to solar radiation at constant head.

Relation between Irradiance and Flow rate

From above data of time and irradiance, irradiance and discharge; the flow rate at various irradiance intensities were recorded. This data represented five months average flow at various irradiance intensities and the relationship between irradiance and flow rate is given in Figure 3.

The flow rate analysis with respect to solar irradiance showed that flow rate increases as irradiance increases and becomes constant at certain value of irradiance. When this specific irradiance level is reached, then there is no effect of water on flow rate. It was also observed that the solar pumping unit started at irradiation level of 100 W/m^2, below this level pump cannot contribute to flow as the available solar radiations are not strong enough to provide the required starting power to run the pumping system. At radiation level of 100 W/m^2, the discharge from pump was 0.5 m^3/hr. When irradiation level is at 200 W/m^2, the discharge from pump was recorded to be 1.5 m^3/hr and at 400 W/m^2 irradiance level, the discharge was recorded as 2.54 m^3/hr. At radiation intensity 600 W/m^2, the discharge from pump was recorded to be 2.9 m^3/hr. After irradiance level of 650W/m^2, the discharge from pump became constant (2.9 m^3/hr) throughout the experiments. About 1000-1100 W/m^2 solar radiations were available at UAF during summer, while pumping unit was run at its full capacity at 600 W/m^2, so pumping requirement in winter was fulfilled by this unit because winter potential of radiation was recorded between 500-600 W/m^2.

Results have shown that discharge increased with increase of solar radiation. It is also observed that as the radiation intensity increased to a certain limit, the voltage dropped due to increase in temperature. During the hot months, the discharge from pump was low and lower power output was obtained. The polynomial

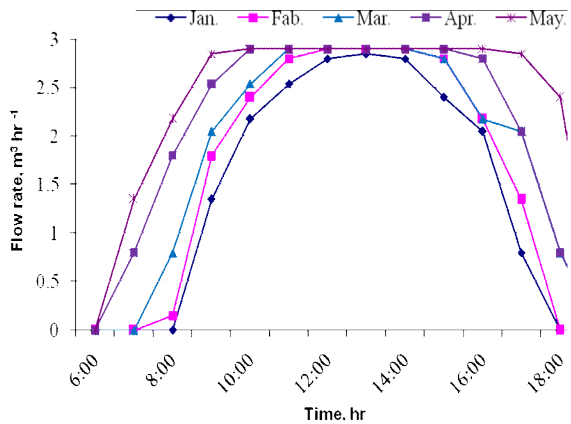

Fig. 1: Monthly average hourly based solar irradiance

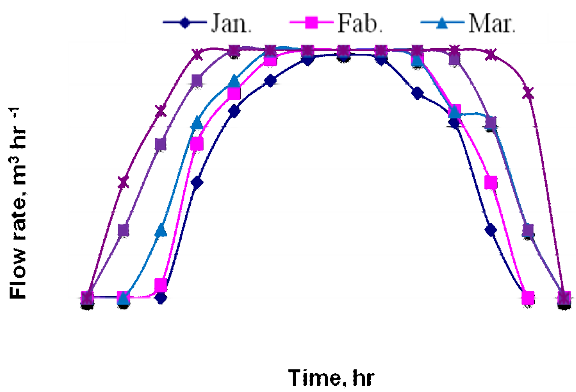

Fig. 2: Average water flow rate of PV pumping unit

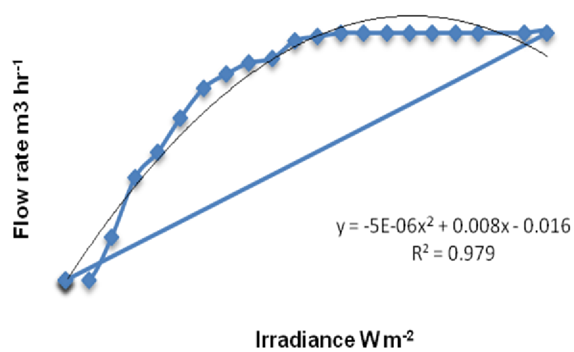

Fig. 3: Relationship between irradiance and flow rate

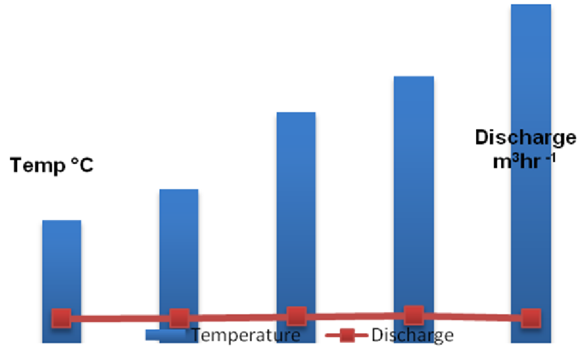

Fig. 4: Effect of temperature on discharge

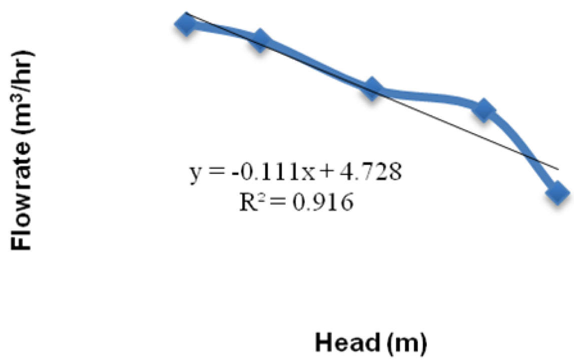

Fig. 5: Head- discharge relationship

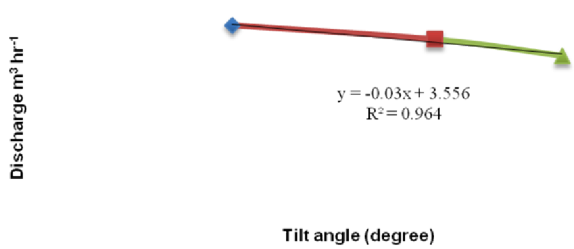

Fig. 6: Relationship between discharge and tilt angle of PV array (Head=22m , irradiance 500 W/m^2)

regression model fitted to the observed data to determine the mathematical trend. The coefficient of determination was found to be 0.966 indicating that there is a strong relationship between solar irradiance and the module temperature.

This was due to the reason that the PV modules are designed for specific temperature range (25-30°C) and perform efficiency in low temperature range. Under the tropical conditions of Pakistan, the modules are subjected to higher temperature than the optimum temperature which ultimately reduced the PV system efficiency. The research concluded that module temperature was also one of the vital parameters which affect the performance of PV pumping system. The relationship between monthly average ambient temperature and monthly average hourly flow rate is shown in Figure 4.

Figure 4 clearly depicts the effect of temperature on discharge. For month of January, average monthly temperature was recorded to be 12°C and monthly average hourly flow rate was found to be 2.45 m^3/hr. For February, the monthly average ambient temperature was 15°C and flow rate was 2.5 m^3/hr. For the month of March, the monthly average ambient temperature was recorded to be 22.5°C and monthly average hourly flow rate was found to be 2.61 m^3/hr, similarly for month of April, the monthly average ambient temperature was 26°C and average hourly flow rate was found to be 2.7 m^3/hr. In the month of May, ambient temperature was 33°C and average hourly flow rate was found to be 2.5 m^3/hr.

Figure 4 also shows that flow rate increases with increase of temperature up to 30°C, and after 30°C the flow rate decreased with the increase of temperature. With the increase of temperature, voltage dropped and the efficiency reduced and output power affected adversely. According to Sumathey et al. (1997), the efficiency of PV system was increased with the increase of ambient temperature up to 30ºC and then decreased with increase of temperature. The results obtained of the present research were in accordance with the results obtained by Sumathey et al. (1997).

Head of the Pump

The experimental system was deep well pump and discharged directly into field. The head was increased by providing the additional pipe and valves to the discharge end.

The flow rate was measured in m^3/hr for seven days and average value was taken. It is noted that average discharge was found to be 2.5 m^3/hr at 20 m head. When head was adjusted at 22, 28 and 30 m, then average flow rates were recorded to be 2.4, 1.98 and 1.2 m^3/hr respectively. The reason of the decreasing trend of the discharges with the increase in head is that the solar PV powered pump is designed for specific head. When head exceeded from the designed value, the pumping performance was decreased and ultimately the system efficiency decreased. The linear regression model fitted for head verses discharge and high value of coefficient of determination was found (0.916) which depicts a strong effect of head on flow rate.

These results confirmed the behavior of a centrifugal pump which needs a relatively high speed to overcome system head. In addition, the pump efficiency decreased with the increase of head (Betka and Moussi., 2003).

Relation between Discharge and angle of PV array

The plane tilt was defined as the angle between the plane and the horizontal. To check the influence of tilt angle of PV array on flow rate, the flow rate of pumping unit was measured at 32°, 40° and 45° tilt

Table 1: Balance and main results

Month	GlobEff kWh/m²	EArrMPP kWh	EPmpOp kWh	ETkFull kWh	HPump meterW	WPumped m³/day	W Used m³/day	W Miss m³/day
January	182.1	154.3	111.8	0	20.14	21.99	22.5	0
February	188.6	156.8	115	0	20.14	25.02	22.5	0
March	228.4	183.8	132.1	0	20.18	25.93	22.5	0
April	227.9	180.5	140.7	0	20.16	28.57	22.5	0
May	254.5	196.4	153.9	0	20.14	30.29	22.5	0
June	231.6	177.8	144	0	20.1	29.35	22.5	0
July	214.9	168.3	139.4	0	20.09	27.54	22.5	0
August	208	163.5	132.4	0	20.05	26.29	22.5	0
September	217.5	171.1	132.9	0	20.15	27.08	22.5	0
October	229.1	182.4	134	0	20.18	26.23	22.5	0
November	207.2	168.5	120.3	0	20.22	24.38	22.5	0
December	188.1	158.7	116.9	0	20.16	23.04	22.5	0
Annual	2577.9	2062.3	1573.5	0	20.14	26.31	22.5	0

GlobEff = effective Global, corr. For IAM & shading, W Missed = Missing water, EArrMPP = Array virtual energy at MPP, E pmpOp = Pump operating energy, ETKFull = Unused energy (tank full), H pump = Average total head at pump, W Pump = Water pumped, W Used = Water drawn by user

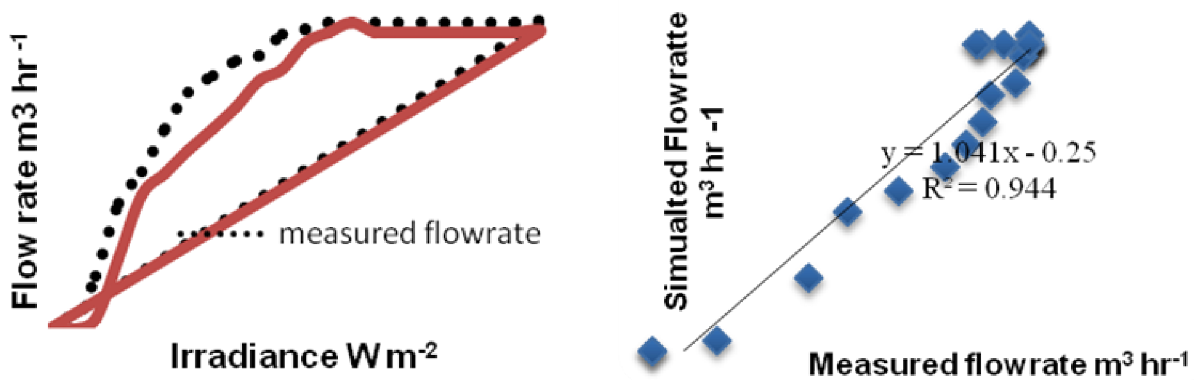

Fig. 7: Measured and Simulated discharge at various irradiances and relationship between measured and simulated flow rates

angles at constant value of head and solar irradiance. The seven values of flow rate were collected at tilt angle 32° when head was 22 m and irradiance level was 500 W/m^2. The relationship between average flow rate (m^3/hr) versus tilt angle was developed. In the graphical representation of tilt angle and discharge, the data of tilt angle 35°, average flow rate at irradiance 500 W/m^2 and head 22 m were taken. For the same condition of head and irradiance level, the average flow rate of seven readings at tilt angle 40° was also added in graphical representation of tilt angle and flow rate in Figure 6.

In the experimental unit, PV array was adjusted on East-West frame facing south. At tilt angle of 32°, which is latitude of Faisalabad, average flow rate found to be 2.58 m^3/hr at 500 W/m^2 solar irradiance level and 22 m head. For tilt angle of 40°, the average flow rate was 2.4 m^3/hr at 22 m head and 500 W/m^2 solar irradiance. For the same value of head and irradiance level, the flow rate at tilt angle 45° was found to be 2.18 m^3/hr. When tilt angle was increased from 32° and adjusted at 40° and 45°, the discharge decreased with increase of tilt angle of PV array.

For maximum utilization of solar radiation, an array full-tracking unit should be used. But the addition of such unit results in a significantly higher cost. Gad (2009) investigated that fixed tilt angle array (south facing) yields maximum output all over the year if its tilt angle is adjusted equal to the latitude of the site; and the results obtained in present research are well according to his statement

Simulation of the Results by using PVSYST

The complete one-year simulation results by PVSYST model are shown in Table 1. The whole year analysis was done. Table 1 shows that water pumping system meets the design requirements. The system pumped water at a head of about 20 m. The water flow rate in month of January was found to be 22 m^3/day. While in month of February and March, the daily water flow rates were 25 m^3/day and 26 m^3/day respectively. In month of May, water discharge was determined to be 30.5 m^3/day, which was maximum flow rate during the year on monthly basis.

Figure 7 represents the comparison of measured and simulated flow rate and shows good relationship. The flow rate wass over predicted by the model from 200 to 800 W m^{-2} irradiance levels. This slight variation was due to the undetermined losses in the pumping system which is normally not taken into consideration. Model was fit for the performance evaluation of pumping unit due to high value of coefficient of determination (R^2=0.944). The comparison of measured and simulated flow rate at different irradiance is very close. The simulation of system checked at a head of 25 m at geographic location of Faisalabad area. The flow rate of pump obtained at varying intensity of solar irradiance by PVSYST model, thus flow obtained is simulated flow rate at varying intensity of solar irradiance. The results concluded that PVSYST model can be successfully to predict flow rate, power and other parameters.

Conclusions

From the study the following results were obtained:

The irradiance has a significant effect on the average discharge of the pump from January to May as the irradiance increased, the discharge of the pump also increased. But with the increase in temperature the discharge of the pump reduced. It was also noted that at irradiance level of 650 W/m^2, the pump gave its maximum discharge and the system can work smoothly even in winter season. The discharge reduces significantly with the increase in head. At a head of 20, 22, 28 and 30 m, the average flow rates were found to be 2.5, 2.4, 1.98 and 1.2 m^3/hr respectively. The angle of inclination also has a significant effect on the pump discharge. From the study it was observed that the best suited inclination angle of the PV array was the latitude of the place where the solar PV system was installed.

It was found that the observed and predicted values were found quite similar in terms of pump discharges and power using PVSYST simulation. This concluded that PVSYST simulation model can be successfully used to assess the solar pumping system at different sites.

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