Water Pumping Performance of a Solar-PV Powered Helical Pump

Brian D. Vick
USDA-Agricultural Research Service
Bushland, TX 79015
E-mail: bdvick@cprl.ars.usda.gov

R. Nolan Clark
USDA-Agricultural Research Service
Bushland, TX 79015
E-mail: rnclark@cprl.ars.usda.gov

ABSTRACT

A solar-PV powered helical pump was tested at three different pumping depths (50, 75, and 100 meters) and two different solar-PV array power ratings (480 and 640 Watts). This testing began in Feb, 2004 and has been performed continuously since that time at the USDA-ARS Laboratory near Bushland, TX. So far this solar-PV water pumping system has performed very well and reliably and it should be a good economical system for many livestock watering applications. For all pumping depth/PV power ratings tested, a relatively high total system efficiency of 5 to 7% was achieved and a low cut-in irradiance of 100 to 300 W/m^2 was demonstrated. For Bushland, TX (annual average of 5.5 to 6 kWh/m^2/day at latitude inclination) the amount of beef cattle that could be watered ranged from 60 cattle (100 m pumping depth/480 W PV array) to 150 cattle (50 m pumping depth/640 W PV array).

1. INTRODUCTION

1.1 Background

For the past fifteen years, solar-PV (photo-voltaic) water pumping systems have been installed with either diaphragm, centrifugal, or piston pumps. The diaphragm pumps have been used successfully for small daily water volumes and shallow pumping depths (500 to 1,500 liters/day and 5 to 30 meter pumping depths). The centrifugal pumps have been used for larger daily water volumes and moderate pumping depths (2,000 to 10,000 liters/day and 5 to 75 meter pumping depths). Lastly, the piston pumps (with a pump jack) have been used to pump water for small to moderate daily water volumes and deep pumping depths (500 to 5,000 liters/day and 100 to 300 meter pumping depths). At the USDA-ARS Conservation and Production Research Laboratory (CPRL) near Bushland, TX, we have been testing various solar-PV powered diaphragm and centrifugal pumps at different pumping depths for about a decade (1-6). Our current 5-year project plan, which began Oct., 2004, also includes testing solar-PV powered piston pumps with pump jacks in the near future.

For daily water volumes of 5,000 to 10,000 liters/day at pumping depths in the 50 to 100 meter range, there really has not been a good reliable, economical solar-PV system for pumping water. However, we have been testing a helical pump which appears to meet these specifications. This helical pump was developed about 3 years ago by a pump manufacturer who specifically designed it to be powered by solar-PV modules. At the time we installed our system, these systems used amorphous-silicon modules, but we elected to use 160 W/ 24 V multi-crystalline silicon modules instead. Currently no PV manufacturer is making amorphous-silicon PV modules, and the pump manufacturer is now recommending using 65 W/ 12 V multi-crystalline silicon modules with their helical pump.

1.2 Test Setup, Instrumentation, and Data Acquisition

The solar-PV water pumping system we tested was powered by either three or four 160 W/ 24 V multi-crystalline silicon modules which were connected in series. The submersible motor powering the helical pump was a single-phase 120 V AC motor. Most of the controller operation (determining if electricity input to motor was DC or AC, converting DC electricity to single phase AC electricity, determining if well water level was too low to pump water) was installed in the submersible motor metal casing. There was also a ground level control unit which served as: a junction box between the motor and solar modules, a switch to turn pump on or off, and a display for various error codes if no water pumping occurred. The helical pump (including motor) was installed under the floor in a 15 foot deep water filled sump which was located in a building at the USDA-ARS Laboratory. The pump outlet was connected to pressure valve, which is necessary in order to consistently simulate different pumping depths. In addition, a flow meter for measuring the water flow rate and a pressure transducer for measuring the water pressure were included. Wires from the pump motor were connected to the ground level controller which in turn was connected to the solar PV array. The PV modules were installed on a pole mount at the south end of the building. Although the solar modules were in a fixed position (e.g. not tracking system), the solar array incidence was changed twice per year at the spring and autumnal equinoxes (45 degree incidence during fall and winter, 25 degree incidence during spring and summer – Bushland latitude is 35.18° North). DC voltage and current transducers were connected between the solar PV array and the ground level controller. The irradiance was measured with a pyranometer mounted in the plane of the PV modules and although this pyranometer only had a 5% accuracy, it was calibrated with a pyranometer with a 1% accuracy. In addition, a thermocouple was mounted to the back of one of the solar PV modules to measure the solar module temperature. All the measured data was sampled every second and recorded every minute on a data logger. The data recorded were:

1. Julian Day
2. Hour/Minute
3. DC Voltage (Volts)
4. DC Current (Amps)
5. Flow rate (gallons/minute)
6. Water pressure (psig)
7. Irradiance 1(W/m^2)
8. Irradiance 2(W/m^2) – for calibration
9. Solar module temperature (deg F)

The data from the data logger was stored in a storage module and once a week that data was down loaded to a PC computer. A Quick Basic computer program was written to bin the data in terms of irradiance level and it also displayed graphs of the measured data versus irradiance. This computer program helped in determining if problems existed with the instrumentation or pumping performance. Also, a "Log Book" was kept on the experiment where observations, calibrations, daily water volumes, flow rates, etc. were recorded.

2. RESULTS

2.1 Electrical Analysis of Solar-PV Water Pumping System

The solar-PV powered helical pump was tested at three different pumping depths (50, 75, and 100 meters) and at two solar-PV array power ratings (480 and 640 Watts) for a total of six configurations. The measured DC Voltage for all six configurations is shown in Fig. 1. The 160 W PV modules are rated at an irradiance of 1,000 W/m^2 and a module temperature of 25°C (77°F). For the 640 W PV array, four of the 160 W modules (rated at 24 V/module) were connected in series while only three of these same modules were connected in series for the 480 W PV array. Although each module is rated at 24 V, each module actually outputs 32 to 40 V depending on irradiance level and pumping depth. The helical pump motor optimum input DC voltage was 120 V according to the pump manufacturer. The pump manufacturer stated the input voltage from the solar PV array could vary as much as 30 V without the motor efficiency decreasing more than a few percent.

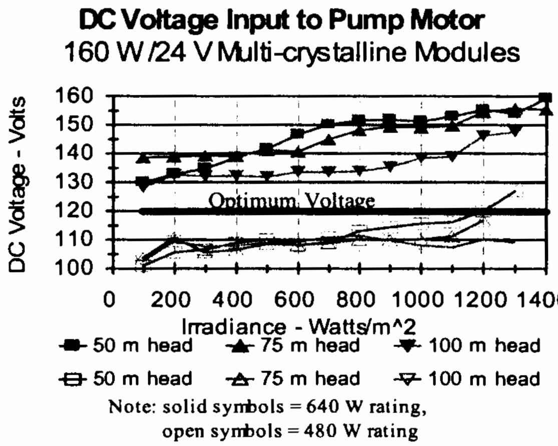

Fig. 1. Measured Voltage at Three Pumping Depths for Two PV Array Power Ratings.

Fig. 2 shows the measured DC current and Fig. 3 shows the calculated DC power (e.g. Voltage x Current) for all 6 configurations. The measured DC current for the motor is fairly independent of the pumping depth and number of PV modules for irradiance levels below 600 W/m^2 and levels out for higher irradiance levels when no more current is needed at a particular pumping depth. For irradiance levels below 600 W/m^2, the 640 W PV array has higher DC power than the 480 W PV array. For the 640 W PV array, the DC power levels out at 600 W/m^2, 800 W/m^2 and 1000 W/m^2 for 50, 75, and 100 meter pumping depths respectively. For the 480 W PV array, the DC power levels out at 800 W/m^2 and 1,000 W/m^2 for 50 and 75 meter pumping depths, respectively. For the 100 m/480 W case, the DC power did not level out even at an irradiance of 1,300 W/m^2.

2.2 Efficiency of Solar-PV Water Pumping System

Fig. 4 shows the average solar energy distribution for each season (winter, spring, summer and fall) at Bushland, TX.

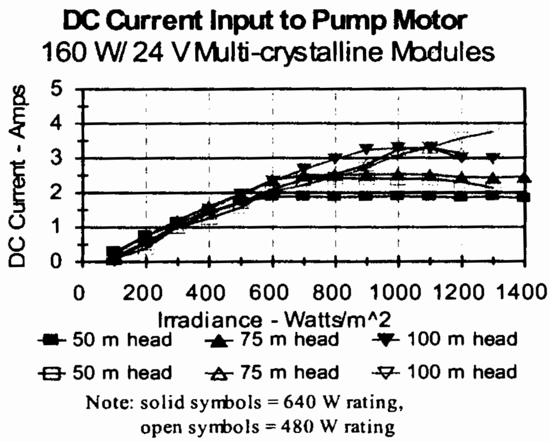

Fig. 2. Measured Current at Three Pumping Depths for Two PV Array Power Ratings.

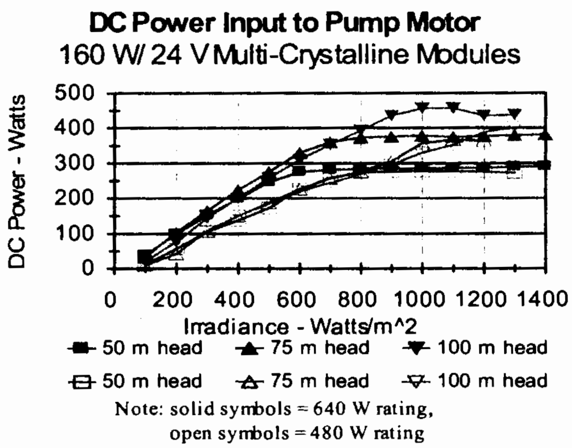

Fig. 3. Calculated Power at Three Pumping Depths for Two PV Array Power Ratings.

This graph indicates that for Bushland, what the PV pumping system is doing in the 800 to 1,100 W/m^2 irradiance range is most important. Figs. 5-7 show the various efficiencies (pump, solar panel, and total system) calculated from the measured data. The pump (actually pump & motor & electrical converter) efficiency varies between 50 and 60% for all configurations except for the 100 m /480 W case where there is a significant drop due to insufficient power for the 100 m pumping depth. The peak PV panel efficiency for the multi-crystalline silicon modules was 12.4 % while the measured peak for a water pumping system with an amorphous-silicon PV array (5) was only 3.9%. The peak total system efficiency for the helical pump system was between 5 and 7 % for all six configurations. As the pumping depth increased or the power rating decreased, the peak total system efficiency occurred at higher irradiance levels. For the Bushland solar resource

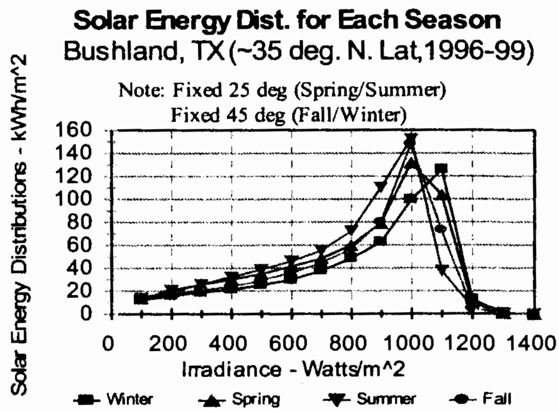

Fig. 4. Average Annual Solar Energy Distribution at Bushland, TX (1996-1999).

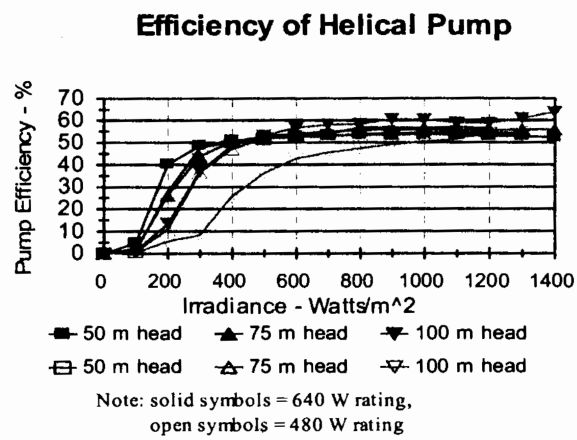

Fig. 5. Pump Efficiency at 50, 75, and 100 Meter Pumping Depths for Two PV Array Power Ratings.

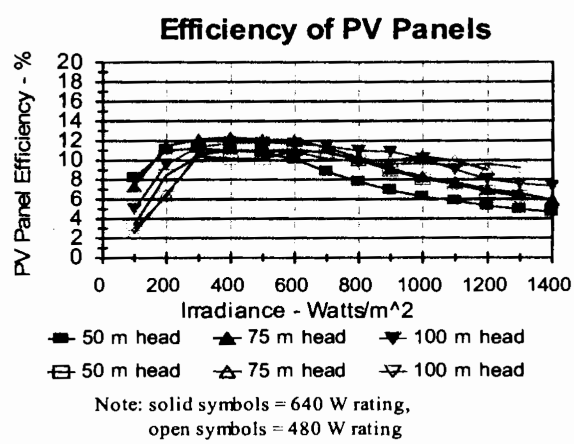

Fig. 6. PV Panel Efficiency at 50, 75, and 100 Meter Pumping Depths for Two PV Array Power Ratings.

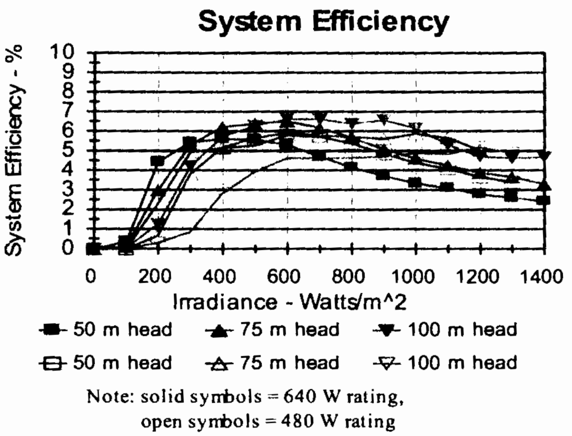

Fig. 7. System Efficiency at 50, 75, and 100 Meter Pumping Depths for Two PV Array Power Ratings.

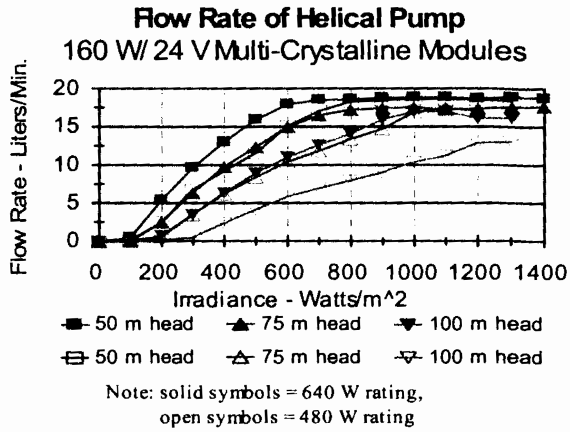

Fig. 8. Measured Flow Rate at Three Pumping Depths for Two PV Array Power Ratings.

and in terms of efficiency, the 480 W PV array was the best power rating for pumping depths of 50 and 75 m, but the 640 W PV array was the best for the 100 m pumping depth.

2.3 Water Pumping Performance of Helical Pump

The measured flow rate for all six configurations tested is shown in Fig. 8. The maximum flow rate for all but the 100 m/480 W case was between 17.5 and 19 liters/min or about 4.8 gallons/min. The cut-in irradiance varied between 100 and 300 W/m^2 for all six configurations tested. This cut-in irradiance is lower than that measured on solar-PV centrifugal pump systems (3). Low cut-in irradiance is important if several days at a location are cloudy. Using an average solar distribution for Bushland (assuming solar array incidence is changed twice a year at equinoxes) and the flow rates measured in Fig. 8, daily water volumes were calculated for each month of the year for all six configurations (Fig. 9 and Fig. 10). A rule-of-thumb for estimating the water needed for each beef cow is that each beef cow will need about 50 liters per day. Therefore, the average daily water volume and the number of cows that could be watered are:

1. 50 m/ 480 W – 7530 liters/day (151 Beef Cattle)
2. 75 m/ 480 W – 5770 liters/day (115 Beef Cattle)
3. 100 m/ 480 W – 3420 liters/day (68 Beef Cattle)
4. 50 m/ 640 W – 8480 liters/day (170 Beef Cattle)
5. 75 m/ 640 W – 7250 liters/day (145 Beef Cattle)
6. 100 m/ 640 W – 6040 liters/day (121 Beef Cattle)

We estimate the amounts above should decrease 9% if the solar array incidence is set at the latitude inclination. The number of cattle that could be watered with the 640 W PV array compared to the 480 W PV array increased by 20 and 30 cattle for 50 and 75 meter pumping depths, respectively.

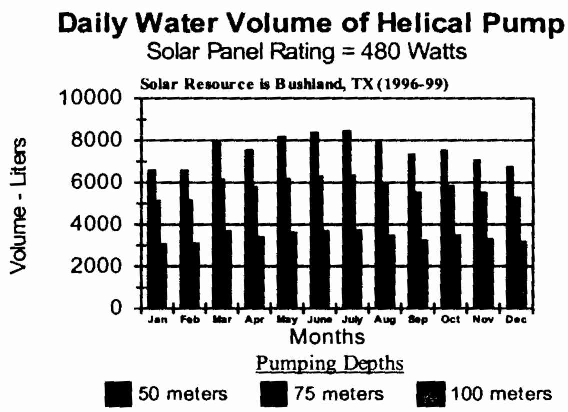

Fig. 9. Daily Water Volume at Three Pumping Depths for a 480 Watt PV Array Power Rating (Bushland, TX).

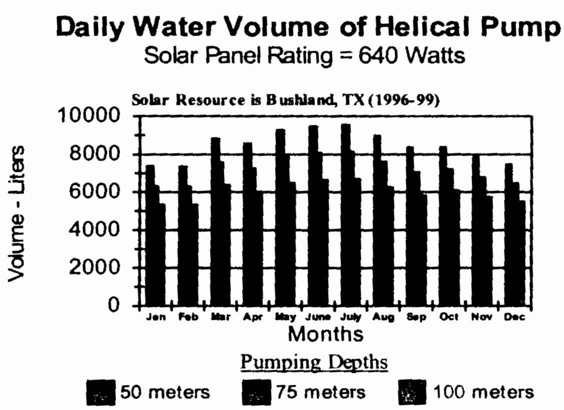

Fig. 10. Daily Water Volume at Three Pumping Depths for a 640 Watt PV Array Power Rating (Bushland,TX).

However, for the 100 meter pumping depth, the number of cattle that could be watered increased by 50 if the 640 W PV array was used instead of the 480 W PV array.

3. CONCLUSIONS

The solar-PV powered helical pump system performed well for pumping depths in 50 to 100 meter range and so far in the testing, this solar-PV water pumping system has been very reliable (no downtime has occurred). Since the cost of the helical pump, ground level controller, PV panel array, and pole mount was between $4,000 and $4,500, then the system should be very economical for most farmers and ranchers in developed countries. Using the more efficient multi-crystalline silicon modules instead of the amorphous-silicon modules makes the system less expensive and more reliable. For a solar resource similar to Bushland, TX, the 640 W PV array is preferable over the 480 W PV array for a 100 meter pumping depth, but the 480 W PV array is preferable over the 640 W PV array for 50 and 75 meter pumping depths. The low cut-in irradiance of this helical pump makes it very desirable for locations which have several cloudy days.

4. ACKNOWLEDGEMENTS

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