Performance of Wind-Electric and Solar-PV Water Pumping Systems for Watering Livestock

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The water pumping performance of two wind-electric systems is compared to the water pumping performance of two solar-PV systems. The wind-electric systems were rated at 1.0 kW and 1.5 kW at a wind speed of about 12 m/s, and the rotor diameters were 2.75 m and 3.05 m, respectively. The solar-PV systems were rated at 0.1 kW and 0.9 kW at a radiation level of about 1000 W/m², and the total solar panel surface areas were 1 and 17 m², respectively. Both wind-electric systems powered three-phase 230 V a-c induction motors with centrifugal pumps. The smaller of the solar-PV systems powered a d-c motor with a diaphragm pump, and the larger one powered a single phase 230 V a-c induction motor with a centrifugal pump. Only a well pumping depth of 30 m was evaluated for both wind-electric and solar-PV water pumping systems. The 0.1 kW and the 0.9 kW solar water pumping systems can provide enough water for 25 and 75 cattle, respectively, if the incident solar radiation is similar to that of Bushland, TX. The 1.0 kW and 1.5 kW wind-electric water pumping systems can provide enough water for 300 and 400 cattle, respectively, if the wind regime is similar to that of Bushland, TX.

Introduction

Providing water for livestock in remote locations is still a major problem in the world. Many farmers and ranchers depend on mechanical water pumping systems to pump water for their livestock. Many of these mechanical water pumping systems are beginning to wear out and some farmers and ranchers are beginning to replace them with wind-electric or solar-PV systems. Also, some utilities are beginning to investigate stand-alone wind-electric and solar-PV water pumping systems because it is costing them too much to maintain rural transmission lines. Clark and Mulh (1992) showed that a wind-electric pumping system will pump twice as much water as a mechanical pumping system at a comparable price if the wind regime is similar to that of Bushland, TX, (annual average wind speed of 5.73 m/s @ 10 m height). While technical papers have been written on the pumping performance of wind-electric pumping systems (Clark and Vick, 1994, 1995) and solar-PV pumping systems (Clark, 1994), no comparison has been made of wind-electric pumping systems to solar-PV pumping systems showing actual test results.

The purpose of this paper is to compare two wind-electric pumping systems to two solar-PV pumping systems that have been tested at the USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX. This USDA-ARS Laboratory is located 16 km (10 miles) west of Amarillo in the Texas Panhandle. The wind energy and solar radiation at this laboratory are typical of that on much of the Great Plains. Both the wind-electric and solar-PV pumping systems were evaluated at a pumping depth of 30 m. The relative performance of these different pumping systems may vary depending on the pumping depth. The wind data used to evaluate the wind-electric pumping systems was gathered at a 20 m height in Bushland, TX, and was binned every minute over a one-year period from April 1, 1993 to March 31, 1994. The radiation data used to evaluate the solar-PV systems was gathered from a horizontal pyranometer in Bushland, TX, and was binned every hour over a 12-year period from 1983 to 1994. These data were corrected to fixed angles for spring/summer (25 deg) and fall/winter (45 deg) by the following equations:

spring/summer

$$\text{Corr. Rad.} = \text{Horz. Rad.} * \text{Abs}(\text{Cos}(25\text{-Optimum}))/\text{Cos}(25) \tag{1}$$

fall/winter

$$\text{Corr. Rad.} = \text{Horz. Rad.} * \text{Abs}(\text{Cos}(45\text{-Optimum}))/\text{Cos}(45). \tag{2}$$

These equations were used to correct horizontal data collected during winter and summer to prescribed fixed angles. These data were then compared to data collected by pyranometers at the same fixed angles. Since the data correlated very well (correlation coef. = 0.8); then the equation was assumed to be correct.

Description of Wind-Electric Water Pumping Systems

The two wind-electric water pumping systems chosen for this paper were the World Power Technologies[1] Whisper 1000 (Duluth, MN) and the Bergey Windpower[1] 1500 (Norman, OK). Information on these wind-electric systems is shown below.

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[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

Wind turbine	Whisper 1000	Bergey 1500
Rated power	1 kW @ 11 m/s	1.5 kW @ 12.5 m/s
Number of blades	2	3
Rotor diameter	2.75 m	3.05 m
Blade material	FRP (epoxy resin)	FRP (polyester resin)
Blade construction	Hand layup	Pultrusion
Rotor geometry	Varying chord/twist	Constant chord/twist
Airfoil	Wortmann	Bergey
Over speed protection	Vertical furling*	Horizontal furling**
Generator	Permanent magnet alternator	Permanent magnet alternator
Controller	Low frequency Cut-in (35 Hz) Cut-out (20 Hz)	Low/high frequency Cut-in (35 Hz, 65 Hz) Cut-out (30 Hz, 75 Hz) High amp cut-out (5 to 8 A)
Pump motor	0.75 kW, 230 V three-phase a-c	1.1 kW, 230 V three-phase a-c
Pump	0.36 kW, 9-stage centrifugal	0.75 kW, 10-stage centrifugal
Total system costs	$3566	$8196

* Furling wind speed varies with loading (pumping depth)
** Furling wind speed is 13.5 m/s unloaded

For both wind-electric water pumping systems, the electricity produced by the wind turbine is variable-voltage and variable-frequency, three-phase a-c electricity. This electricity will power off-the-shelf induction motors and pumps without the need of an inverter. Capacitors are usually added across the three phases of the pump motor, thereby balancing its inductive load and improving the power factor of the wind turbine generator, particularly at high operating frequencies. A controller is necessary to keep the pump motor disconnected from the wind turbine until a certain minimum alternator frequency is reached, otherwise the wind turbine would be braked by the load. Therefore, the controller must have a low-frequency cut-in and cut-out. The Whisper 1000 controller meets this criteria, and the Bergey 1500 controller has in addition a high frequency cut-out, a high frequency cut-in, and a high current cut-out. Additional information on the controllers can be found in Vick and Clark (1995). The motor used on the Bergey 1500 was recommended by Bergey Windpower. The pump used on the Bergey 1500 was selected by testing four different pumps at different pumping depths. For a deeper pumping depth and/or less windy site, a pump with more stages should be selected. The motor and pump used on the Whisper 1000 was recommended by World Power Technologies. Both of these wind turbines were evaluated assuming a tower height of 20 m and a wind regime similar to Bushland, TX. For a discussion of the instrumentation and experimental setup, see Clark and Vick (1995). The total system cost (as of May 1995) includes the cost of the wind turbine, controller, capacitors, motor, pump, pipe, and tower.

Description of Solar-PV Water Pumping Systems

The two solar-PV water pumping systems discussed in this paper are the Solarjack[1] (Safford, AZ) 0.1 kW d-c pumping system and the Golden Photon[1] (Golden, CO) 0.9 kW a-c pumping system. Although tracking data were collected on the Solarjack d-c pumping system, the data shown in this paper is based on a fixed position. Golden Photon manufactures a water pumping system with a motorized tracking system, but only the fixed position system has been tested at the USDA-ARS Laboratory in Bushland. Information on the solar-PV systems is shown below:

Solar pumping system	Solarjack	Golden photon
Rated power/panel	0.050 kW	0.018 kW
Number of panels	2	50
Solar cell material	Crystralline silicon	Cadmium telluride
Area of panel	0.478 m^2	0.338 m^2
Controller	Converter	Smart
Motor	24 Volt d-c	0.56 kW, 230 V phase a-c
Pump	Diaphragm	0.56 kW 12-stage centrifugal
Total system cost	$1423	$6976

A detailed description of the Solarjack pumping system can be found in Clark (1994). The Solarjack water pumping system takes the solar d-c generated electricity (12 volts) and converts it to 24-30 volts through the controller which in turn drives the 24 V d-c motor/diaphragm pump combination. The Golden Photon pumping system was installed on June 13, 1995, and data have been collected since June 24, 1995. The Golden Photon controller converts the d-c solar panel generated electricity into either one or three-phase a-c. The Golden Photon controller continuously monitors system performance to determine whether the solar radiation is high enough to engage a single or three-phase a-c induction motor which in turn drives a centrifugal pump. Current testing has been with a single-phase a-c motor, but changing one switch on the controller will give it the ability to power a three-phase a-c motor. The one-phase motor was selected since that is the predominant type of electricity supplied by the utilities in the Great Plains. The instrumentation and experimental setup for the solar pumping systems is similar to that used for the wind-electric systems. The total system cost (as of May 1995) includes: solar panels, solar panel racks, controller, motor, pump, and pipe.

Results of Wind-Electric Water Pumping

Figure 1 shows the flow rate of the Whisper 1000 and the Bergey 1500 for a pumping depth of 30 m. The motor used on

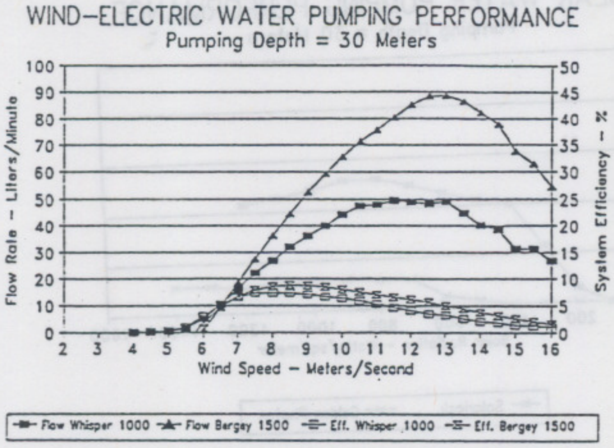

Fig. 1 Flow rate and system efficiency of two wind-electric water pumping systems

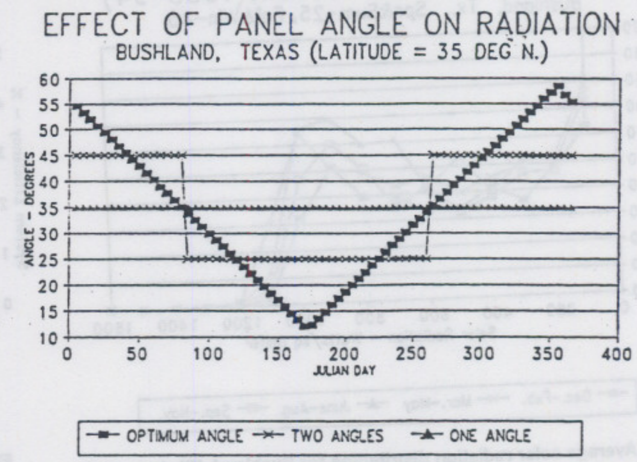

Fig. 3 Approximating the optimum solar panel angle for Bushland, TX (Lat. 35 = deg N)

the Whisper 1000 was a Franklin Electric[1] 0.75 kW (1 hp) 230 V, three-phase a-c motor. The pump used on the Whisper 1000 was a McDonald[1] 0.36 kW (0.5 hp) nine-stage pump. The amount of capacitance used on the Whisper 1000 was 35 microfarads/phase. The motor used on the Bergey 1500 was a Franklin Electric 1.1 kW (1.5 hp) three-phase 230 V a-c motor. The pump used on the Bergey 1500 was a Grundfos[1] 0.75 kW (1 hp) ten-stage pump. The capacitance used on the Bergey 1500 was 60 microfarads/phase.

Also shown in Fig. 1 are the system efficiencies of the Whisper 1000 and the Bergey 1500. The equation used for system efficiency for the wind-electric systems is

$$\text{System Efficiency} = \text{Water Power}/\text{Wind Power}. \quad (3)$$

Water Power is the change in potential energy of the pumped water with respect to time (the change in kinetic energy of the water pumped with respect to time is negligible). Wind power is the change in kinetic energy with respect to time of the air passing through a stream tube with the diameter of the wind turbine rotor and at the wind turbine hub height. The system efficiency of the Bergey 1500 is a little higher than the Whisper 1000 and reaches a maximum of nine percent at a 8.5 m/s wind speed.

Figure 2 shows the daily water volume for both the Whisper 1000 and the Bergey 1500 for each month of the year. The wind distribution used to calculate the volume was based on wind data binned every minute at a 20-m height from April 1, 1993 to March 31, 1994. The daily water volume over the entire year for the Whisper 1000 was 22,700 liters/day (6000 gallons/day) and the Bergey 1500 was 31,900 liters/day (8428 gallons/day). Additional information on the wind speed and air density during this period can be found in Clark and Vick (1994).

Results of the Solar-PV Water Pumping

Figure 3 shows the optimum panel angle for Bushland, TX, as a function of Julian day. The minimum optimum angle occurs on June 21 (11.5 deg), and the maximum occurs on December 21 (58.5 deg). Also shown is the angle the solar panels should be set to if the angle is only changed twice per year (during vernal and autumnal equinox). If the farmer or rancher wants to keep the incidence of the solar panels the same all year, the panels should be set to the latitude angle (35 deg for Bushland, TX).

Figure 4 shows the loss in radiation from optimum when the solar panel angle is changed twice during the year and when the panel angle is never changed. When the solar panel angle is changed twice a year then the radiation loss is never more than three percent. Even when the solar panel angle is set to the latitude and never changed during the year, the maximum loss in radiation is about nine percent. The solar-PV water pumping performance given in this report assumes the solar panel position will be changed twice a year to 25 deg during spring and summer and 45 deg in fall and winter. Figure 5 shows the solar frequency distributions which were determined by collecting solar radiation data over a 12-year period at Bush-

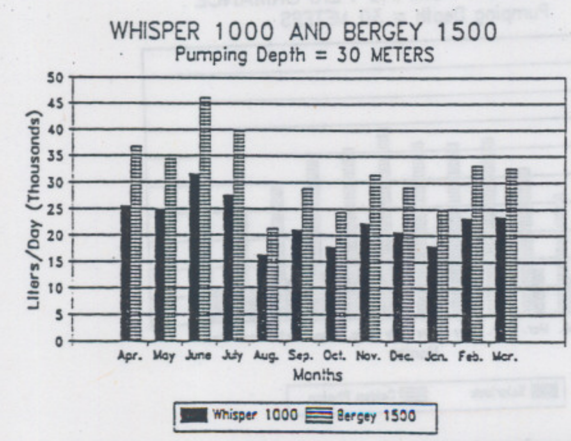

Fig. 2 Daily water volume for two wind-electric water pumping systems

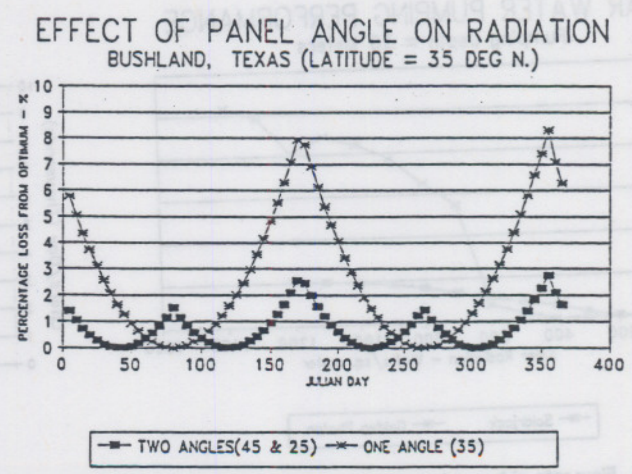

Fig. 4 Percentage loss in radiation when changing the solar panel angle twice per year or setting it to the latitude

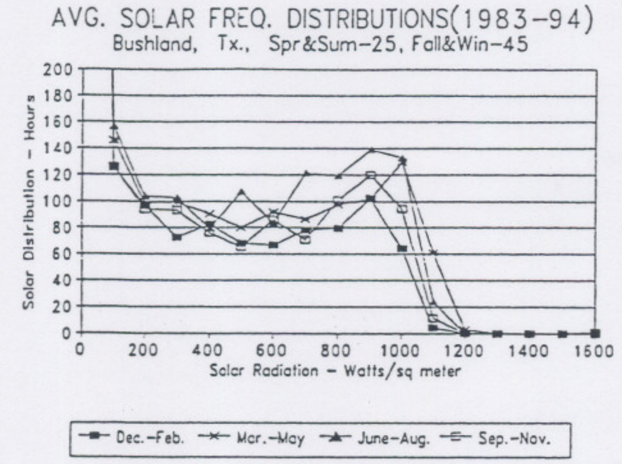

Fig. 5 Average solar radiation distribution for Bushland, TX, from 1983 to 1994

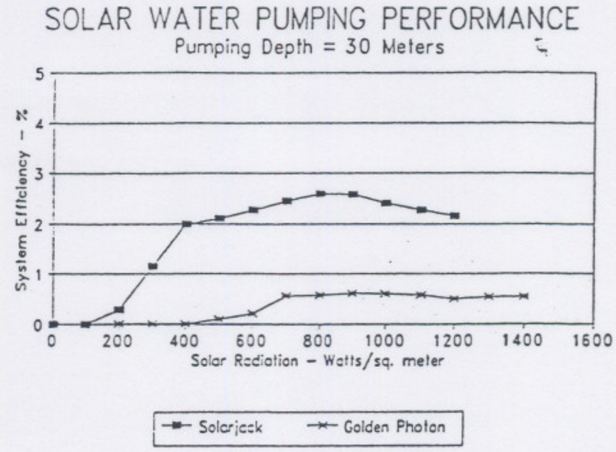

Fig. 7 System efficiency of two solar water pumping systems

land. The solar frequency distributions shown in Fig. 5 are grouped in periods of three months for clarity, although the daily water volumes were calculated using the 12-year average solar radiation for each month.

Figure 6 shows a comparison of the flow rate of the Solarjack 0.1 kW PV system compared to the Golden Photon 0.9 kW PV system. The 0.9 kW a-c system outperforms the 0.1 kW d-c system for a radiation level greater than 0.6 kW/m^2. However, the 0.1 kW d-c system begins pumping water at 0.3 kW/m^2 compared to 0.5 kW/m^2 for the 0.9 kW a-c system. The reason for the earlier cut-in for the d-c system is that the controller allows the motor and pump to immediately begin operating as soon as radiation is high enough to make the motor pump water. However, on the 0.9 kW a-c system the Smart controller has a programmed delay of about five minutes after experiencing a shut-off condition such as a drop in insolation. Therefore, on a partly cloudy day the 0.9 kW a-c system is off much of the time, and the 0.1 kW d-c system will be pumping water more often.

Figure 7 shows the system efficiency of both solar-PV water pumping systems. The equation used for system efficiency for the solar-PV systems is

$$\text{System Efficiency} = \text{Water Power}/\text{Solar Power} \quad (4)$$

where Solar Power = (number of panels) × Area of Panel (m^2) × Radiation (kW/m^2). The system efficiency of the 0.1 kW d-c system is much higher than that of the 0.9 kW a-c system.

Figure 8 shows the daily water volume which is expected for the Solarjack system and the Golden Photon system. Although the Golden Photon system has a power rating nine times that of the Solarjack system, it only pumps three times as much water at a 30 m depth. The annual daily water volume for the Solarjack 0.1 kW system and the Golden Photon 0.9 kW system was 1630 liters/day (431 gallons/day) and 5320 liters/day (1406 gallons/day), respectively.

Conclusions

Two wind-electric and two solar-PV water pumping systems were analyzed for a pumping depth of 30 m. The maximum system efficiency of the wind-electric pumping systems was much higher than the solar-PV pumping systems at this pumping depth. The maximum system efficiency was 7.5 percent and 9 percent for the Whisper 1000 and the Bergey 1500, respectively. The Whisper 1000 and the Bergey 1500 could provide enough water for 300 and 400 cattle, respectively, assuming a wind regime like that at Bushland, TX. The Solarjack 0.1 kW DC system and the Golden Photon 0.9 kW a-c system could provide enough water for 25 and 75 beef cattle, respectively, assuming the incident solar radiation is the same as that at Bushland, TX. The solar-PV a-c system pumped about three times the amount of water that the solar-PV d-c system although the maximum system efficiency of the solar-PV d-c system was about 2.5 percent compared to the 0.5 percent of the solar-PV a-c system. Golden Photon believes the low system efficiency of the 0.9 kW system is due to degradation of the cadmium telluride solar

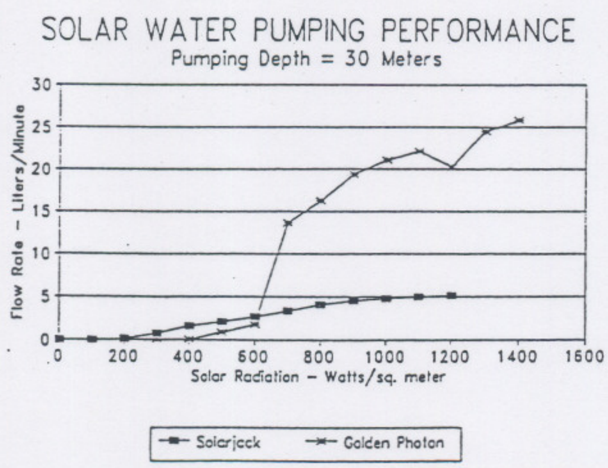

Fig. 6 Flow rate of two solar water pumping systems

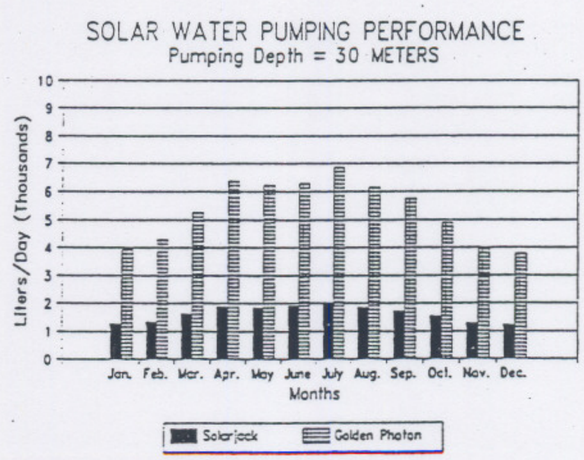

Fig. 8 Daily water volume for two solar water pumping systems

panels. Golden Photon is currently investigating the reasons for the low system efficiency. The water pumping performance of the Golden Photon system would also be improved if a three-phase motor was used instead of a single-phase motor. The annual system cost per cubic meter of water pumped at a 30 m pumping depth ($\$/m^4$) for the wind-electric and solar water pumping systems were

Whisper 1000	$0.014/m^4
Bergey 1500	$0.023/m^4
Solarjack 0.1 kW	$0.080/m^4
Golden Photon 0.9 kW	$0.120/m^4

The above numbers assume an availability of 100 percent for all systems. Additional data need to be collected to determine reliability, maintenance costs, and finally lifetime cost/m^4.

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