Determining the Optimum Solar Water Pumping System for Domestic Use, Livestock Watering or Irrigation

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ABSTRACT

For several years we have field tested many different types of solar powered water pumping systems. In this paper, several steps are given to select a solar-PV water pumping system. The steps for selection of stand-alone water pumping system were: deciding whether a wind or solar water pumping system would be best, determining the type of PV module, how controller can affect the decision, selecting pump type (diaphragm, piston, helical, or centrifugal), and analyzing the monthly water demand requirement. Three case studies are also included to demonstrate how to determine PV array size, motor/pump rated power, and type of pump.

1. INTRODUCTION

For stand-alone (no utility interconnection) water pumping systems there have been papers published comparing diesel powered water pumping systems to solar-PV water pumping systems (1, 2). There are also papers on modeling and field testing of solar pumps in different locations in the world (3, 4, 5). However, there are very few papers on the following topics with regards to stand-alone water pumping:

1. Choosing between a wind or solar powered system.
2. Advantages and disadvantages of PV module types.
3. Controller characteristics (efficiency, reliability, price) for different systems.
4. Choosing the best pump based on daily water volume requirements and pumping depth.

This paper will focus on the list of items above to help the reader in the selection of the best stand-alone water pumping system. Fig 1 shows a typical solar-PV water pumping system containing a PV array, disconnect switches, controller, submersible motor with pump, and storage tank.

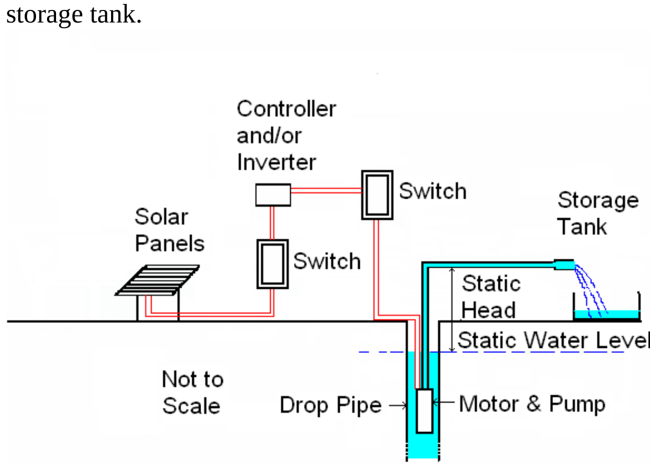

Fig. 1. Schematic of Solar-PV Water Pumping System.

At the USDA-ARS Conservation and Production Research Laboratory (CPRL) near Bushland, TX, research has been conducted on wind powered watering pumping systems since 1978 and solar powered water pumping systems since 1992. Since our facility is in a semi-arid climate with a declining underground aquifer, our main focus has been to determine the most efficient way of pumping underground water for livestock, domestic use, and irrigation through use of wind energy, solar energy, or a combination of both. Several papers have been written on the performance of PV water pumping systems at CPRL including the following:

1. Performance of PV powered diaphragm pump (6, 7).
2. Comparison of wind to solar powered water pumping systems (8).
3. Fixed versus passive tracking PV panels (9, 11).
4. Performance of PV powered centrifugal pump (10).
5. Comparison of amorphous-silicon (a-Si) to cadmium-

telluride (CdTe) PV modules in water pumping (12).
6. Effect of PV module temperature on pumping performance (13).
7. Performance of a PV powered helical pump (14).

2. DISCUSSION

2.1 Choosing between a wind or solar powered system.

To determine whether a wind or solar water pumping system is the best one to use, the first step is to evaluate the wind or solar energy resource at the location. Fig 2 and 3 show the wind and solar resource of United States (U.S.). (www.nrel.gov). The wind resource in U.S. is best in the Great Plains in the middle part of the country and also off shore along the Atlantic and Pacific Coast lines The solar resource is good for a larger portion of U.S. land area than that of the wind resource, and the solar resource is very good to excellent for southwestern part of U.S.

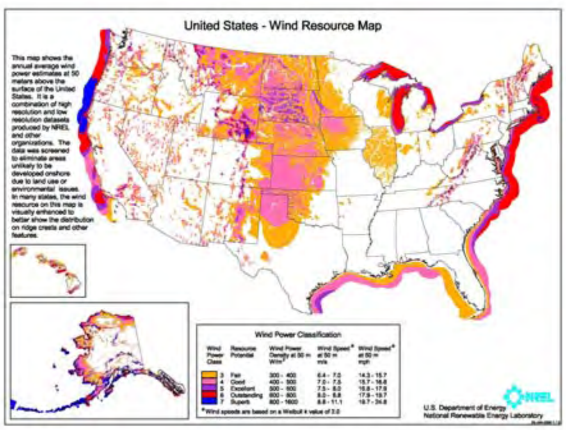

Fig. 2. Wind Resource in U.S.

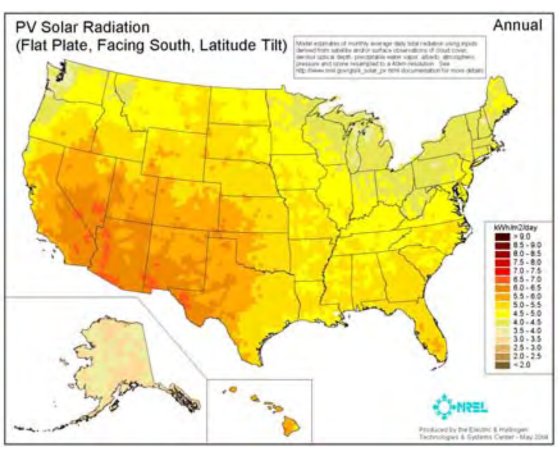

Fig. 3. Solar Resource in U.S.

One note of caution, when evaluating solar resource for PV water pumping, it is important to make sure the solar map is based on pyranometers measuring global solar irradiance and not normal irradiance pyranometers (NIP) which measure direct normal irradiance (DNI) – DNI is used for evaluating solar hot water heating systems or concentrated solar thermal power plants. For solar resource terminology – see www.bom.gov.au/sat/glossary.shtml

The USDA-ARS-CPRL facility is located near Bushland, TX (Latitude = 35.184° North, Longitude = 102.083° West), and since all of the data shown in this paper were gathered at this location, the wind and solar resource of Texas is shown in Fig 4 and 5. While the solar resource is good near Bushland (PV array tilt angle = latitude setting, ~ 5.75 kWh/m^2/d), the wind resource is excellent with a class 4 rating (400 to 500 W/m^2 at a 50m height).

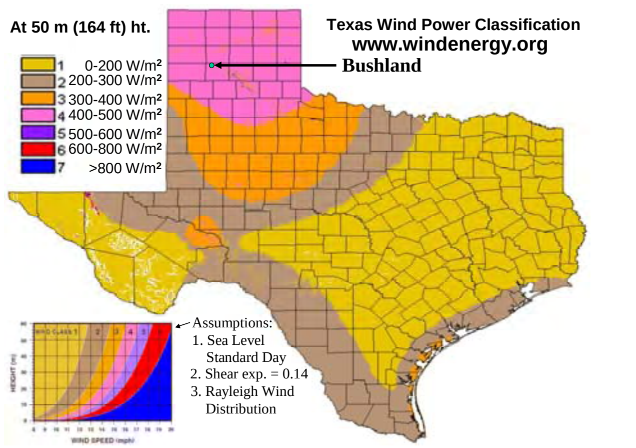

Fig. 4. Wind Resource in Texas.

Texas Annual Average Solar Resource (Latitude Tilt)
kWh/m^2/day

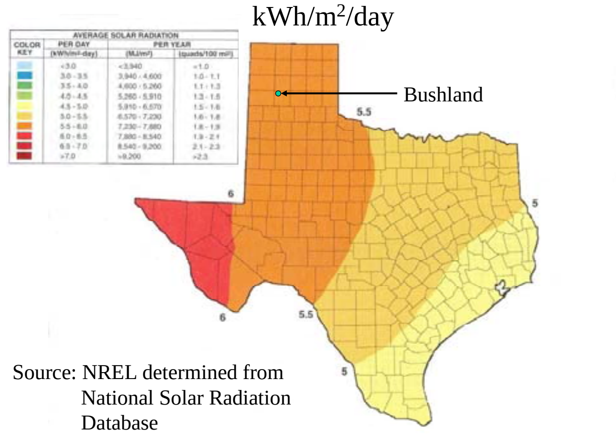

Fig. 5. Solar Resource in Texas.

Unfortunately the units are different when showing wind resource maps (W/m^2) or solar resource maps (kWh/m^2/d), but in Fig 6 the wind and solar resource is depicted in the same units for Bushland, TX. All windmills and most wind turbines used for water pumping are on towers 30m or less, so despite the class 4 winds at Bushland, the solar resource is better than the wind resource during most of the year. The solar resource shown in Fig 6 is better than latitude tilt due to changing the PV array incidence at the equinoxes (25 deg during spring and summer and 45 deg during fall and winter) – see Fig 7 and 8.

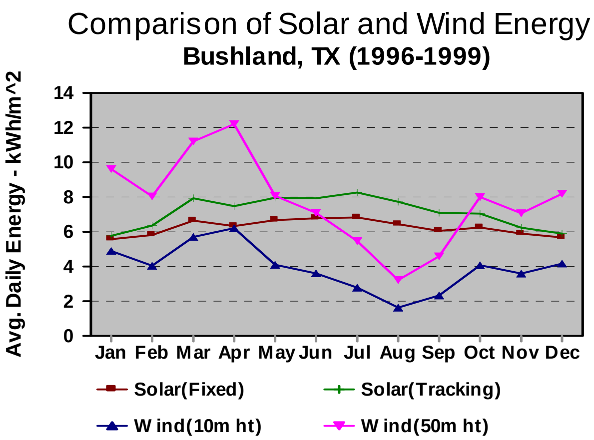

Fig. 6. Comparison of Wind and Solar Energy at Bushland, TX.

Fig. 7. PV Array tilt angle in fall and winter at Bushland, TX.

Fig 9 shows how the daily average solar insolation changes monthly at Bushland for global, latitude tilt, and varying PV array tilt angle twice a year for fixed and passive tracking. For solar resource at other locations in U.S. states and territories see http://rredc.nrel.gov/solar/old_data/nsrdb/. Although resource assessment is the first step in determining whether to choose a wind or solar powered pumping system, there are more things to consider like: does the resource match the daily water requirement for each month, what are the maintenance requirements, what is the reliability, and finally what is the life cycle cost (15). A comparison was made between wind-electric and solar-

Fig. 8. PV Array tilt angle in spring and summer at Bushland, TX.

PV water pumping systems in 1996 (8), but solar water pumping systems have become much more efficient, more reliable, and less costly than shown in that paper, and the fact that small wind turbine manufacturers have concentrated mainly on the grid-tie electricity market has resulted in the choice for stand-alone water pumping systems less than 2 kW being predominantly between using mechanical windmills or solar-PV. As the power requirements get higher though (e.g. multi-acre irrigation), hybrid systems using wind turbines and solar-PV are more likely since wind turbines become more cost effective for larger power requirements compared to solar-PV systems.

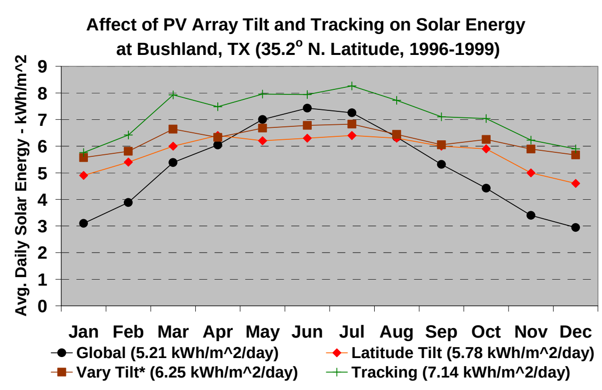

Fig. 9. Measured Daily Solar Radiation at Bushland, TX.

2.2 Type of PV Modules and Fixed Versus Tracking

Currently there are two types of PV modules that are used for solar-PV water pumping: multi-crystalline and thin film (thin film modules used so far are amorphous-silicon and cadmium-telluride). The advantages of using multi-crystalline modules for water pumping are:

1. Currently 85% of PV modules manufactured in world are multi-crystalline, so less worry on being

able to find replacement modules or adding additional modules to array.
2. Module efficiency is higher than thin film (12 to 14% versus 3 to 9%), so less modules are required for a specific power (takes up less space).
3. Lifetime over 30 years has been demonstrated and warranties up to 20 years are obtainable (thin film modules have only been around since 1988, and major problems with performance degradation with time for early models of thin film modules).
4. Can be disposed of in landfills while the thin film cadmium-telluride (CdTe) can not (e.g. CdTe is toxic).
5. Only slightly declining power output with time (~1% per year) while amorphous-silicon (a-Si) thin film modules experience about a 20% decrease in power output during first 6 months when exposed to sun, but performance decrease similar to multi-crystalline after initial 20% decrease (16).
6. Less likely to break since use tempered glass (manufacture of thin film modules currently requires the glass not to be tempered).

The advantages of thin-film modules are:

1. Can generate higher voltage modules than multi-crystalline (high voltages important in water pumping applications above 200 Watts).
2. Since most of the multi-megawatt PV installations in world are cadmium-telluride, the price per Watt for thin film is cheaper for large PV installations.
3. Less percentage power loss for increased panel temperature for thin film compared to multi-crystalline.

High voltage PV modules are only an advantage if the pump motor requires high voltage. Diaphragm pump motors are rated at 24V, so they don't require high voltage modules. Helical and centrifugal pump motors (< 1 kW) usually are designed for voltages from 100 to 250 Volts, so higher voltage multi-crystalline and thin film modules have been used for these pumps.

Fig 10 compares the pumping performance at a 75m pumping depth of 35V/160W PV BP Solar[a] modules to 65V/110W PV Grundfos modules (both multi-crystalline silicon). The 160W PV modules are rated at 24V, but actually output close to 35V. At a 75m pumping depth a single 160W module could not pump any water (due to low voltage) while a single 110W module and two 110W modules (220W) could pump water at this pumping depth. The lower voltage 160W PV modules at 320W and 480W power ratings were able to pump water at the 75m depth, but at comparable PV power ratings of 330W and 440W, the higher voltage 110W PV modules could pump more water. However, for PV power ratings of 440W and 660W (110W higher voltage modules) and 640W (160W lower voltage modules), the pumping performance was the same due to the maximum pumping rate being reached by the helical pump. Fig 11 shows the daily water volume as a function of insolation for all cases shown in Fig 10 except for the lowest power cases (e.g. 110W and 220W). While these graphs show in terms of pumping performance the higher voltage PV modules are better, currently the 110W PV modules have been discontinued due to not enough demand, so any 110W modules broken can't be replaced, so for now, the more common lower voltage modules are the better choice.

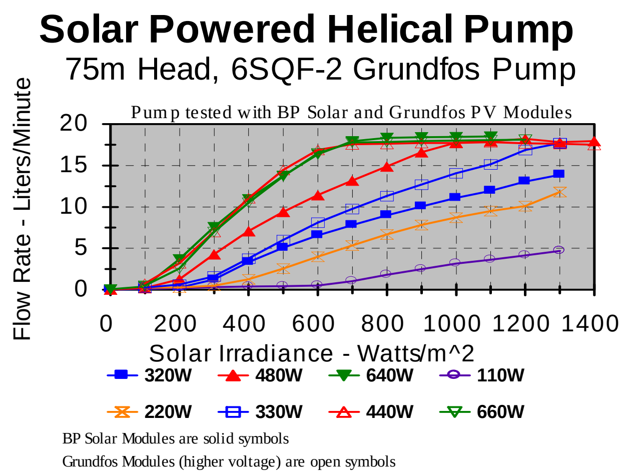

Fig. 10. Affect on Flow Rate of Same Type of Modules but at Different Voltage Ratings.

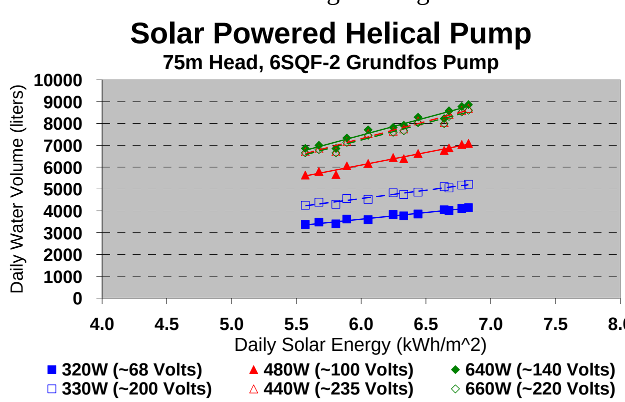

Fig. 11. Affect on Daily Water Volume of Same Type Modules but at Different Voltage Ratings.

During testing at CPRL some thermal cracks occurred in a-Si thin film modules (BP Solar was manufacturer) due to the glass not being tempered. Although our testing of CdTe PV modules (Golden Photon was manufacturer) showed significant degradation (50%) over a 4 year period, another

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[a] 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.

manufacturer of CdTe modules (First Solar) claims much higher efficiency (9% versus the 3% measured by CPRL of the Golden Photon modules). First Solar also claims degradation similar to multi-crystalline silicon (i.e. less than 1% per year). Another important point to add is that whichever modules selected, it is important that they are certified by the Underwriters Laboratory (UL).

At USDA-ARS-CPRL we have tested fixed versus passive tracking systems and the results were reported most recently in 2002 (11). Several of the performance deficiencies reported in this paper (morning wake up, inability to point the modules correctly on windy days) have been improved on by the passive tracker manufacturer. Whether a passive or motorized tracking system is used, it is usually better to just add more PV modules in a fixed array than installing a tracking system unless the PV array is rated higher than 500W.

2.3 Controller

Controllers for PV water pumping systems can range from not using any controller to sophisticated smart controllers. For diaphragm pumps, the simple controllers can perform many tasks such as:

1. limiting power to diaphragm pump motor in order to keep it from being damaged
2. adjusting voltage and current to improve pumping performance at lower solar radiation levels
3. providing manual disconnect switch between PV modules and pump motor
4. having a float switch to allow automatic disconnect of PV modules to pump motor when storage tank full.

Fig 12 shows the affect on a diaphragm pump of either using a controller or not using a controller. Since diaphragm controllers are usually less than $200 (less than 10% of total cost), and they have proven to be very reliable, there will not be many situations when it would be better to not use a controller.

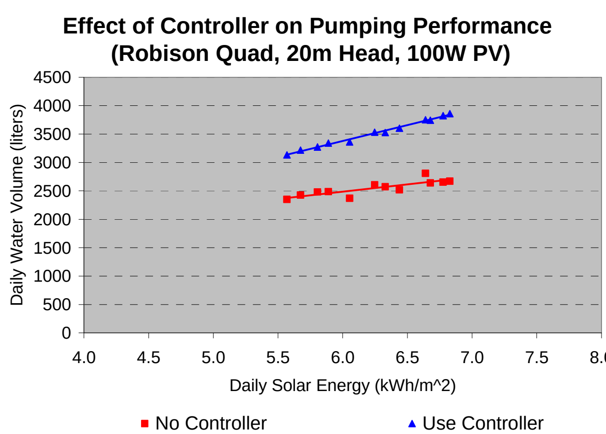

Fig. 12. Affect of Use of Controller on Daily Water Volume of a Solar Powered Diaphragm Pump.

The controllers used for helical pumps are more complicated than those used for diaphragm pumps, but they usually still are very reliable. One helical pump manufacturer (Grundfos) has embedded most of the controller function inside the submersible motor casing. This enables this controller to protect the motor from running dry via a wire sensor attached to motor which determines when water level is below pump intake. This embedded controller also has the capability of determining if input power is DC or single phase AC and if single phase AC, it is rectified to DC electricity before connecting to DC motor. This means that water can be pumped on cloudy days by switching from PV array to a gasoline generator. Fig 13 and 14 show how an update to this helical pump controller improved the pumping performance significantly.

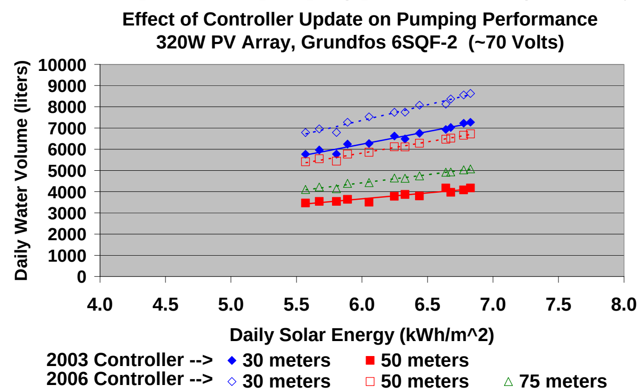

Fig. 13. Effect of Controller Update on Solar Powered Helical Pump System (320W PV).

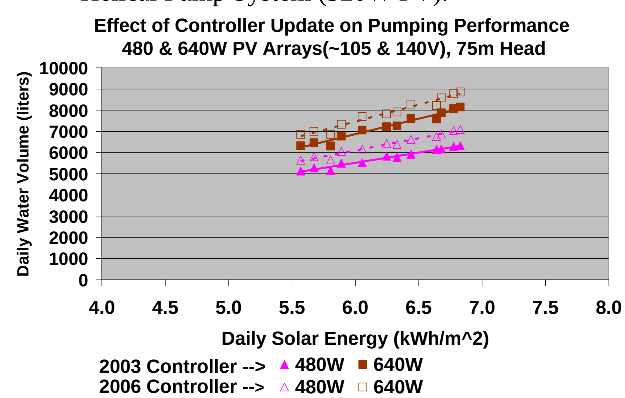

Fig. 14. Effect of Controller Update on Solar Powered Helical Pump System (480 & 640W, 75m Head).

The controllers used on solar AC water pumping systems are more complex than helical pump controllers since the DC electricity from the PV array has to be converted to single or three phase AC electricity. This is big advantage in terms of motor/pump price since it enables standard off-the-shelf motors and pumps to be used whose prices are usually cheaper due to huge volumes of this pumps being sold, but this advantage for smaller (<1.5 kW) systems is negated since the controllers are much more expensive.

2.4 Selection of Pump Type

There are four types of pumps which have been powered by solar-PV: diaphragm, piston, helical, and centrifugal. The first three pumps in the list above are referred to as positive displacement. Positive displacement pumps have the characteristic of being able to pump well at deeper pumping depths, but the flow rate is restricted. The characteristic of the centrifugal pump is opposite, it has higher flow rates, but not as good at pumping from deeper pumping depths unless the power rating is higher. Diaphragm pumps come in two types – high head (able to pump water from 70m pumping depth) and Quad (capable of flow rates up to 16 l/m but limited to 30m pumping depth). At USDA-ARS-CPRL we have seen these pumps survive over 6 years, but manufacturer usually recommends that pumps be pulled from well after 2 years and retrofitted with new parts (cost of retrofit only about $100 while replacement of pump is in $600 to $800 range). Fig 15, 16 and 17 show typical daily water volumes that these pumps are capable of.

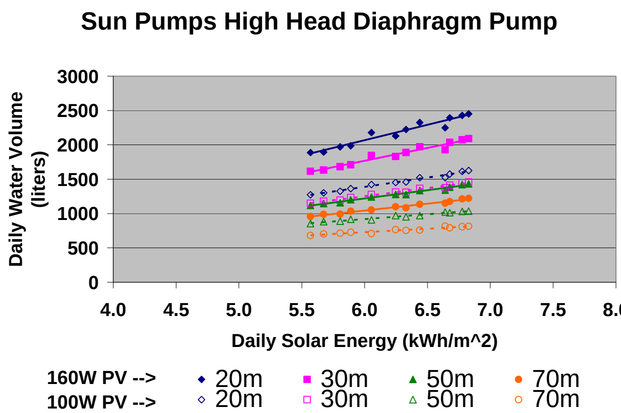

Fig. 15. Measured Sun Pumps High Head Diaphragm Pump Daily Water Volume.

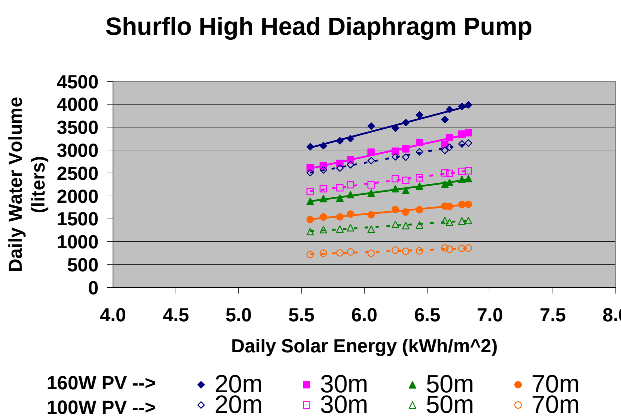

Fig. 16. Measured Shurflo High Head Diaphragm Pump Daily Water Volume.

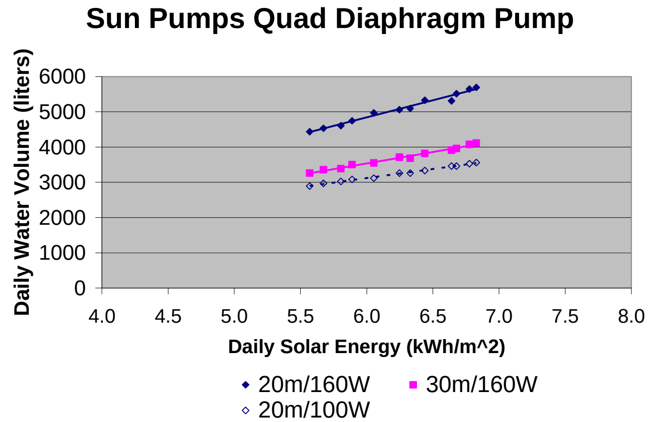

Fig. 17. Measured Sun Pumps Quad Diaphragm Pump Daily Water Volume.

The 30m/100W PV case is not shown for Sun Pumps quad pump because the PV power was too low to pump water. The Sun Pumps has demonstrated good reliability since it has pumped at maximum design pumping depth (70m) for over 2 years. However, the Shurflo high head pump quit at this same pumping depth after 1.25 years. The Shurflo high head pump did exhibit better performance than the Sun Pumps high head pump at lower pumping depths.

The piston pumps are usually driven by solar powered pump jack, and are predominantly used for very deep pumping depths (> 150 meters). The technology (borrowed from oil field) of balancing the long column of water with counter weight of pump jack allows these solar-PV systems to pump water from very deep pumping depths. We have not tested these systems at USDA-ARS-CPRL because it is not possible to simulate deep pumping depths with pressure (e.g. the sucker rod gets stuck in tight pressure seal), and wells this deep were not close by for testing.

There has been a tremendous growth in the use of helical pumps since 2002. They are predominantly used for livestock watering at pumping depths ranging from 50 to 150 meters. Previous figures (10, 11, 14, 15) have shown the pumping performance of Grundfos helical pumps, but Fig 18 shows a comparison between the Grundfos 6SQF-2 pump and the Lorentz HR07-2 pump. While the Grundfos pump showed no signs of performance loss after 3 years of testing, the Lorentz HR07-2 pump did degrade significantly in performance (~50%) after less than one year of testing.

The centrifugal pump is definitely the pump of choice for PV power requirements above 1.5 kW, but can also be the best pump at low pumping depths with high daily water requirements. Fig. 19 shows approximately the maximum pumping depth for a centrifugal pump with a PV array of 0.75 kW. A three phase motor is preferable over single phase motor since pumping performance is higher and cost of the two motors is about the same.

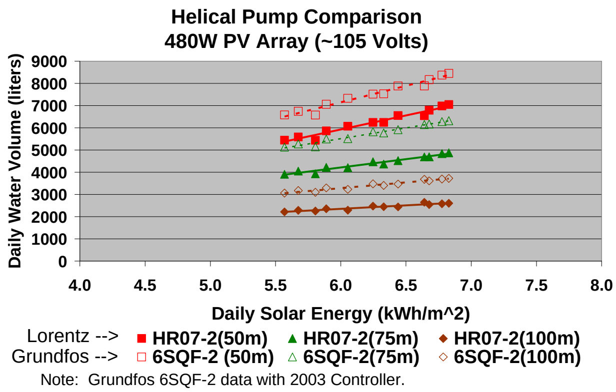

Fig 18. Comparing Daily Water Volume of Two Different Helical Pumps.

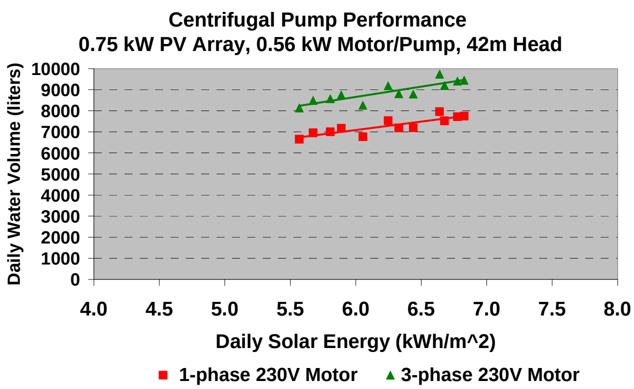

Fig. 19. Effect of AC Motor Phase on Daily Water Volume of Solar Powered Centrifugal Pump System.

Fig 20 shows the daily water volume versus pumping depth for all pumps which have been powered by solar-PV. Because most of the USDA-ARS-CPRL testing has been with helical and diaphragm pumps, then the boundaries for these pumps are known with the most accuracy. Due to cost restrictions (cost of equipment and required labor) we were not able to define where the boundaries for the centrifugal and piston pumps occurred, but the general regions for these two type pumps are shown. It is very important that whatever pump is used, the static level pumping depth should not exceed the maximum design pumping depth since we have seen the lifetime of a pump shortened significantly (as much as 80%) when the maximum design pumping depth is exceeded by as little as 15m.

2.5 Case Studies

Because the water demand can vary significantly for different water uses (domestic use, livestock watering, crop or orchard irrigation) and different locations (variation of solar resource, temperature, rainfall amount, etc), then we

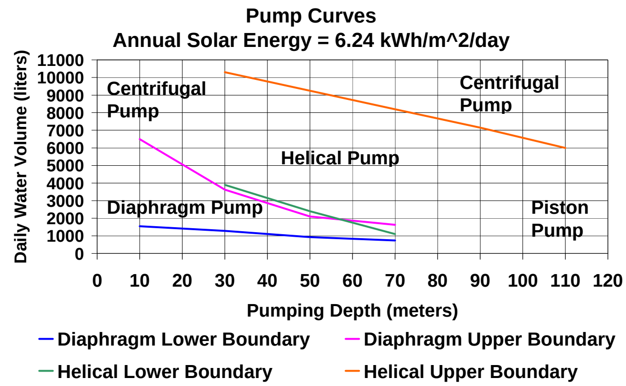

Fig. 20. Determining Type of Pump for Different Daily Water Volume/Pumping Depth Combinations.

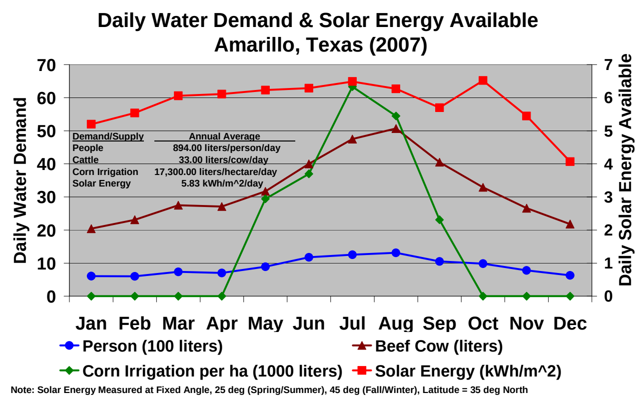

Fig. 21. Monthly Water Demand for Different Uses in Amarillo, TX (2007).

decided to select 3 specific cases of water demand for a specific year. Fig 21 shows for Amarillo, TX during 2007 the water requirements for 3 different uses (people, beef cattle, and corn) and also the solar resource.

Since the diaphragm pumps are limited to 70m pumping depth and the pumping depth at Amarillo is 75m, diaphragm pumps should not be used. Assuming a 4 person household, the type pump required is the helical and the PV power required is 0.5kW (24V rated PV modules). Assuming 150 beef cattle, the type pump required will again be helical but the PV power required is 0.64kW (24V rated PV modules). For 50 hectares (126 acres) of corn (center pivot on a 1/4 section), the type pump required will be centrifugal with 200hp motor (depending on amount of water that can be pumped at well, may need lower horsepower pump motors for more than one well). The PV power required will be 263 kW. This last case demonstrates the problem with using solar energy to irrigate in the Great Plains. For single crop irrigation in the Texas Panhandle, the solar-PV generated electricity is not needed during 7 months of the year. Combining a summer crop (corn, cotton, sorghum) with a winter crop (winter wheat) helps in utilizing solar-PV generated electricity more of the time, but PV modules are not being used during winter because of water freezing in irrigation system and dormancy of crop. Crops or orchards in regions closer to the equator which require irrigation water year round will have a shorter payback when solar energy is used.

3. CONCLUSIONS

Solar-PV water pumping systems less than 1.5 kW are more likely to be used in U.S. than wind powered water pumping systems due to a better match to water demand, less maintenance requirements (e.g. fewer moving parts), and a larger area of land with a good solar resource than with a good wind resource. As power requirements increase however, a wind only or a hybrid wind/solar water pumping system is desirable unless the price per Watt for solar-PV modules can be decreased significantly and/or efficiency of Solar-PV modules can be improved significantly. For helical and centrifugal pumps, standard 24V multi-crystalline silicon PV modules will likely be a better choice than high voltage multi-crystalline or thin-film modules due to supply problems if modules damaged in array. However, if worldwide production increases for the high voltage modules, these modules would be better due to better motor/pump efficiency with higher voltage. For diaphragm pumps, using a controller is nearly always the best option instead of directly connecting PV array to pump motor.

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