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Analysis of off-grid hybrid wind turbine/solar PV water pumping systems

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Abstract

While many remote water pumping systems exist (e.g. mechanical windmills, solar photovoltaic, wind-electric, diesel powered), few combine both the wind and solar energy resources to possibly improve the reliability and the performance of the system. In this paper, off-grid wind turbine (WT) and solar photovoltaic (PV) array water pumping systems were analyzed individually and combined as a hybrid system. The objectives were to determine: (1) advantages or disadvantages of using a hybrid system over using a WT or a solar PV array alone; (2) if the WT or solar PV array interfered with the output of the other; and (3) which hybrid system was the most efficient for the location. The WT used in the analysis was rated at 900 W alternating current (AC). There were three different solar PV arrays analyzed, and they were rated at 320, 480, and 640 W direct current (DC). A rectifier converted the 3-phase variable voltage AC output from the WT to DC before combining it with the solar PV array DC output. The combined renewable energies powered a single helical pump. The independent variable used in the hybrid WT/PV array analysis was in units of W/m^2. The peak pump efficiency of the hybrid systems at Bushland, TX occurred for the 900 W WT combined with the 640 W PV array. The peak pump efficiencies at a 75 m pumping depth of the hybrid systems were: 47% (WT/320 W PV array), 51% (WT/480 W PV array), and 55% (WT/640 W PV array). Interference occurred between the WT and the different PV arrays (likely due to voltage mismatch between WT and PV array), but the least interference occurred for the WT/320 W PV array. This hybrid system pumped 28% more water during the greatest water demand month than the WT and PV systems would have pumped individually. An additional controller with a buck/boost converter is discussed at end of paper for improvement of the hybrid WT/PV array water pumping system.
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Keywords: Wind; Solar; Hybrid; Water pumping; PV; Wind turbine

1. Introduction

Water has been pumped using wind energy for centuries (Nelson et al., 2004; Nelson, 2009), and by solar energy for the past half century (Foster, 2009; Odeh et al., 2006). Remote locations have primarily used mechanical windmills for pumping water; however, many farmers and ranchers have switched to solar PV water pumping systems. For remote water pumping systems greater than 10 kW, diesel is the predominant energy source for water pumping systems in Egypt (Kamel and Dahl, 2005). Small wind turbines[2] currently are not used for many remote water pumping systems compared with mechanical windmills and solar PV arrays. Potential improvement in reliability (e.g. not dependent on wind or solar resources alone) and increased daily water volume could be realized by utilizing

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[2] Small WT's are defined by the American Wind Energy Association (AWEA) as having a blade rotor swept area less than 200 m^2 or approximately 50 to 60 kW power rating.

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hybrid WT/PV array systems which would also increase the number of small WT's used for water pumping.

The USDA-Agricultural Research Service Conservation and Production Research Laboratory (CPRL), Bushland, Texas, in collaboration with the West Texas A&M University – Alternative Energy Institute, Canyon, Texas, has conducted extensive research on renewable energy powered remote water pumping systems. The main criticism voiced to CPRL by farmers and ranchers in the Texas Panhandle concerning mechanical windmills is the high maintenance required for the piston pump (specifically the degradation of leather cups or poly vinyl cups which are used to seal the piston pump during the pumping action). This feedback led the CPRL to focus on the development of more reliable systems (e.g. less maintenance) using submersible turbine pumps for wells. These pumps were produced in great quantities (e.g. low cost) for rural utility connected systems and operate on single or 3-phase AC power. Small WT's with permanent magnet alternators output 3-phase variable voltage/frequency AC electricity. Therefore, WT's were a natural choice for powering the submersible turbine pumps. While small WT's/centrifugal pumps outperformed mechanical windmills/piston pumps at pumping depths of 20–30 m (Vick and Clark, 1997), the lower cut-in wind speed of mechanical windmills/piston pumps resulted in appreciably better performance at a 75 m pumping depth during the summer than the wind-electric centrifugal pumps (Vick et al., 1999). However, connecting a WT to a DC pump motor (via a rectifier that converted AC to DC) to power a helical pump (a positive displacement pump) resulted in pumping performance equivalent to or better than that of a mechanical windmill/piston pump during the summer months at a 75 m pumping depth (Vick and Clark, 2005). Modifying the controller of the WT powered helical pump system to include a controller load (could be used to heat water in the stock tank during the winter) also resulted in increased daily water pumped (Neal and Clark, 2007).

One major advantage of PV powered water pumping systems versus wind powered water pumping systems is that typically the solar resource matches the agricultural water needs, such as livestock watering or crop/vegetable irrigation, better than wind resource. This is because the solar resource is usually greatest during the summer when the water demand is also the greatest; whereas, the wind resource in the Southern Great Plains is typically the lowest in the summer. Solar PV powered diaphragm pump water pumping systems (a diaphragm pump is a positive displacement pump), are most often low volume (~800 L/day for a 70 m maximum pumping depth) or are limited in pumping depth (30 m for a ~5000 L/day water volume) (Vick and Clark, 2009). Since the pumping depth at the CPRL is 75 m, diaphragm pumps should not be used in the CPRL wells. There are also PV powered helical pump systems which are capable of higher daily water volumes (up to ~8000 L/day at 75 m pumping depth) and deeper pumping depths (~3000 L/day at a 150 m pumping depth) that require higher rated power than the PV powered diaphragm pump systems (Vick and Clark, 2009, 2011). The PV array rated power for typical diaphragm pump systems range from 75 to 150 W; whereas, the PV rated power for helical pump systems range from 200 to 1000 W. Reliability of solar PV powered helical pump systems is better than that of solar PV powered diaphragm pump systems for pumping depths greater than 30 m (Vick and Clark, 2011). A comparison was made between WT powered and solar PV powered helical pumps for livestock watering. The solar powered helical pump systems were found to be a better match to the livestock water requirement in the Southern Great Plains (Clark and Vick, 2008).

A number of locations have studied hybrid WT/PV array systems. Hybrid WT/PV array systems with battery backup have been shown to be reliable (e.g. as compared to using WT or solar PV alone) in certain locations (Zhou and Yang, 2008). At the CPRL we have a good wind/solar resource location since we are classified as a Class 4 wind site (WTAMU-AEI, 2011), and our annual daily average solar insolation is 5.8 kW h m^{-2} d^{-1} for a PV module at latitude tilt (Marion and Wilcox, 1994). Our renewable energy group developed a hybrid wind/solar/battery system[3] composed of a 300 W WT, 100 W PV array, and two 12 V 100 A-h deep cycle batteries to supply power to a remote data acquisition system with an electrical loading of 2 A/h (Vick et al., 1999). The final WT/PV/battery system has proven to be very reliable, and the only maintenance item has been to replace the batteries every 2 years. There are several models for the designing of hybrid wind/solar systems for on-grid or off-grid applications. Zhou et al. (2010) reviewed the more common optimizing models that can be used for hybrid wind-solar systems. Two of the models mentioned by Zhou were the Hybrid Optimization Model for Electric Renewables (HOMER, Lilienthal, 2005) and Hybrid2 (Baring-Gould, 1998) which are available in the public domain. Another model mentioned in Zhou et al. (2010) is the Hybrid Solar-Wind System Optimization Sizing (HSWSO, Yang et al., 2007). The HSWSO model is specifically for a hybrid solar-wind power system employing a battery bank. Renewable energy powered water pumping systems seldom use batteries for storage of energy because it is more cost effective to store the water. Also, most, if not all, of these models require electrical loading data to be input, but in water pumping for livestock most farmers/ranchers/agricultural extension personnel only know the daily water requirement for the livestock.

The objectives of our hybrid off-grid WT/PV array research were to determine:

1. advantages and disadvantages of using hybrid WT/PV system over using WT or solar PV array alone;
2. if the WT or solar PV portion of hybrid system interfered with output of the other components; and
3. which hybrid system was most efficient at our location.

[3] Hybrid systems developed by trial and error rather than a model.