EFFECT OF WIND SPEED ON PERFORMANCE OF A SOLAR PV ARRAY

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ABSTRACT

Thousands of solar photovoltaic (PV) arrays have been installed over the past few years, but the effect of wind speed on the predicted performance of PV arrays is not usually considered by installers. An increase in wind speed will cool the PV array and the electrical power of the PV modules will increase as the temperature decreases. Data were collected on a grid connected 2.4 kW PV array (ground mounted, fixed and two-axis tracking) at the USDA Conservation and Production Research Laboratory near Bushland, TX. The data collected were: AC power, DC voltage and current (e.g. DC power), PV module and air temperatures, solar irradiance in plane of PV array, and wind speed at 2 and 10 m heights. For clear (cloudless) days with approximately the same air temperature and irradiance, it was shown that an average wind speed increase of 4.5 m/s (10 mph) resulted in a 4 to 5% increase in system efficiency. However, the average AC power only increased 2.5%. The AC power increase was only half the system efficiency increase due to a 2 % reduction in solar irradiance for the higher wind speed days. The solar irradiance may have decreased with an increase in wind speed due to increased amount of particulates (dust) in the atmosphere.

1. INTRODUCTION

Improving PV array performance in order to obtain a cost effective hybrid wind/solar crop irrigation system would provide a sustainable solution for farms in the Great Plains (1). One significant way of improving the PV array performance is to cool the temperature of the PV array since PV modules produce more power at lower temperatures. Using the pumped irrigation water, at a temperature of 15^{o}C (59^{o}F) appears promising, but understanding how other factors affect the temperature of the PV modules (e.g. increased wind speed) are also being analyzed. The power of a PV module is rated at standard test conditions (STC) which are: a PV module temperature of 25^{o}C (77^{o}F), a spectral distribution of AM 1.5, and a solar irradiance of 1000 W/m^2. For most PV module types, power output decreases/increases ~0.5% for each degree C (1.8^{o}F) increase/decrease in PV module temperature. The temperature of a PV module is mainly a function of solar irradiance, air temperature, and wind speed (2). Six years of PV module temperature of a fixed PV array (thin-film cadmium telluride) were collected at Bushland, TX, and the PV array performance at 1000 W/m^2 was predicted to be 1% above rated during winter but 6.5% below rated in the summer (3). In addition, daily water volume of an off-grid solar powered water pumping system was shown to decrease 2% for a low wind speed day compared to a moderate wind speed day on hot days in the summer (3). Similar performance results were obtained in this paper for the grid-tied PV array when comparing a moderate wind speed day to a high wind speed day. A simple equation for estimating PV module temperature was developed specifically for Bushland (3), but a more robust procedure for many locations was developed in (2). The objective of this paper is to quantify the increase in wind speed necessary to cool a grid tied mono-crystalline PV array (fixed and tracking) and determine the percentage increase in the power output.

2. EXPERIMENTAL SETUP

Figure 1 is a map of the solar resource in the U.S. for PV array systems with latitude tilt. The data presented in this paper were collected at the USDA-ARS Conservation and Production Research Laboratory (CPRL, 35.184° N. Lat, 102.083° W. Long, elev. 1160 m) which is located near Bushland, TX. The solar resource for this semi-arid location is very good.

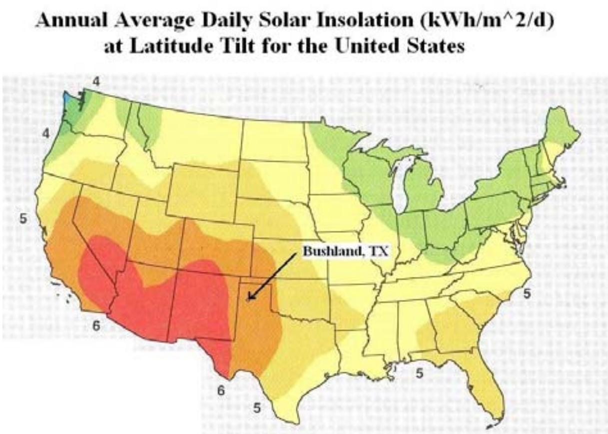

Fig. 1 Solar resource map of United States for latitude setting of PV array with Bushland, TX location shown (data shown on map based on (4)).

2.1 Solar PV Grid-Tie System Details

The installation of a 2.4 kW PV array at CPRL was completed on Nov. 15, 2011 and began generating electricity to the grid. The PV array is composed of 10 Solar World[*] Sunmodule mono-crystalline modules rated at 240 W per module for a rated power of 2400 W at standard test conditions. The maximum power point voltage of this PV module is 30.2 V and all 10 PV modules were connected in series for a measured PV array DC voltage range of 250 to 280 V. The maximum power point current of this PV module is 7.87 A, while the measured PV array DC current range, at a measured irradiance of 1000 W/m^2, was 8 to 8.3 A. The temperature sensitivity, according to the Solar World Sunmodule technical specification sheet, is minus (-) 0.45% in power per degree C increase in PV module temperature.

[*] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the USDA or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

The solar PV array was mounted on a WattSun (Array Technologies) AZ 228 two-dimensional tracking system. The solar sensor for determining sun location for the tracking controller is located on the top of 3rd strut (counting left to right) exposed in Fig. 2. The pyranometer was mounted on the bottom of the 2nd strut exposed (e.g. behind the student intern's left elbow). A picture of the motorized tracking system (e.g. picture of backside of Fig. 2) is shown in Fig. 3.

The PV array was connected to the utility grid via the SMA Sunny Boy 3000 inverter. According to the specifications, the efficiency (e.g. conversion of DC power to AC power) should be ~96%, and our measurements of DC/AC power indicated that the efficiency varied between 96 to 98%.

Fig. 2. Solar PV array rated at 2.4 kW (Bushland, TX).

Fig. 3. Two-dimensional motorized tracker (also includes disconnect switch and instrumentation enclosure).

2.2 Instrumentation and Data Acquisition of Solar PV Grid-Tie System

The data measured on the 2.4 kW Solar PV grid-tied system were:

1. Solar irradiance in plane of PV array (W/m^2)
2. PV module temperature near center of PV array(C)
3. DC voltage of PV array (V)
4. DC current of PV array (A)
5. AC power output from inverter (W)

The solar irradiance was measured with a LI-COR (Lincoln, NE) LI200 pyranometer. The temperature of a center PV module in the array was measured with a thermistor (Model CSI 107) made by Campbell Scientific Instruments (Provo, UT). The DC voltage and current were measured with CR Magnetics (St. Louis, MO) CR5210-500 and CR5310-10 transducers, respectively. Both the voltage and current transducers required a very precise DC voltage power supply (24 +/- 0.02 V) which was also made by CR Magnetics and the model was CRPS24VDC-120. The AC power was measured with an Ohio Semitronics (Hilliard, OH) Model GH004x5 transducer. AC power was also displayed on the inverter and periodic comparison of the Ohio Semitronics AC power to that shown on the inverter appeared to be the same. A PV array tracking system will improve the power output of a PV array (5, 6, 7) compared to a fixed system, but the average PV module temperature will also likely be higher than that of a fixed system due to greater average solar irradiance (2). Therefore, the accuracy of the motorized tracker was measured on Aug. 8, 2012 and is shown below in Table 1.

Table 1.Measurement accuracy of two-dimensional tracker.

Time (Standard)	Azimuth error	Elevation error
9:00	0	-9.5°
9:30	0	-7.6°
10:00	0	-7.6°
10:30	0	-7.6°
11:00	0	-6.7°
11:30	0	-3.8°
12:00	0	0.0°
12:30	0	0.0°
13:00	0	-2.3°
13:30	0	0.0°
14:00	0	+2.0°
14:30	0	+3.8°
15:00	0	0.0°
15:30	0	0.0°

Obviously the Azimuth error (e.g. east – west) on this tracker is very good, but the elevation error could be as much as 10 degrees (e.g. negative indicates the PV array was pointed too low while positive indicates the PV array was pointed too high). The solar irradiance decrease due to 5° and 10° elevation errors is estimated to be 0.5% and 1.5%, respectively.

In addition to the data measured on the 2.4 kW Solar PV grid-tie system, additional data were collected at the CPRL – Weather Pen (located 158 m WSW from PV array). The data obtained from this system were:

1. Air Temperature (C)
2. Wind speed at 2 m height (m/s)
3. Wind speed at 10 m height (m/s)
4. Wind direction (deg)
5. Barometric pressure (mB)

The air temperature was measured with a CSI Model 107 thermistor. The wind speeds were measured with Met One (Eugene, OR) 014 (mini) cup anemometers at 2 and 10 m heights. The barometric pressure was measured with a Met One 092 transducer. All the data collected on both Campbell data loggers were sampled every second, and averaged and stored every minute. The one-minute data were imported into Microsoft Excel spreadsheets to calculate hourly and daily averages.

The amount of daily solar energy incident on the PV array could be calculated by equation [1].

$$E_{sun} = \sum I_i \times (A_{pv} / 1000)\ dt \qquad [1]$$

Where,

E_{sun} = Solar Energy (kWh)
I_i = Avg. Solar Irradiance for each i_{th} hour (W/m^2)
A_{pv} = Area of PV array (m^2)
dt = time increment (h)

The amount of daily electricity generated by the PV array could be calculated by equation [2].

$$E_{pv} = \sum P_i / 1000\ dt \qquad [2]$$

Where,

E_{pv} = AC energy generated by PV array (kWh)
P_i = Avg. AC power generated for each i_{th} hour (W)
dt = time increment (h)

The daily system efficiency of the PV array was calculated by eqn. [3] using calculations from equations [1] and [2].

$$Eff_{system} = (E_{pv} / E_{sun}) \times 100 \qquad [3]$$

Where,

Eff_{system} = Daily system efficiency of PV array (%)

In addition, the hourly system efficiency was also calculated with the time increment being one minute.

3.0 RESULTS AND DISCUSSION

Although the 2.4 kW PV array produced power, when there was solar radiation, from Nov. 15, 2011 to present (with the exception of short periods to install instrumentation or replace sensors of tracking system), some data listed in Section 2.1 (1 and 5) were recorded starting on Apr. 1, 2012 while other data (2-4) were not recorded until July 3, 2012. The two-dimensional tracking system would intermittently track until July 26, 2012 when the system was overhauled. The pyranometer measuring the solar irradiance ceased working on Sep. 12, 2012 during a thunderstorm, but was not replaced until Oct. 19, 2012. The WattSun PV tracking system ceased tracking on Oct. 11. On Oct. 17, 2012 the 2.4 kW PV array was fixed at a 45 degree inclination facing south. Therefore, the 2.4 kW PV array was analyzed to determine the effect of wind speed for:

1. a two-dimensional tracking system (Aug. 2012),
2. a fixed system (Nov. 2012).

3.1 Effect of Wind Speed on Performance of a Two-dimensional Tracking PV Array (Aug. 2012).

Figures 4 and 5 present one-minute data on two days which demonstrates that increased wind speed improves the AC power of a motorized tracking grid-tied PV array. On a clear day with moderate wind speed (Aug. 9, 2012), the solar irradiance, AC power, PV module temperature, and wind speed at a 2 m height are graphed with time (Fig. 4). The solar irradiance and AC power reached a maximum at 10:00. The solar irradiance remains fairly flat until 17:00 when it begins to decrease. However, the AC power begins a steady decline from 10:00 to 15:00 while the PV module temperature increases from 51°C to about 61°F. During this period the wind speed varies from 3 to 6 m/s†.

Figure 5 depicts an almost clear day (Aug. 11, 2012) with wind speed varying between 7 and 10 m/s from 8:00 to 18:00. The AC power is noticeably higher and the peak PV module temperature decreased from about 61°C to 51°C (a 10°C decrease in temperature with higher wind speed).

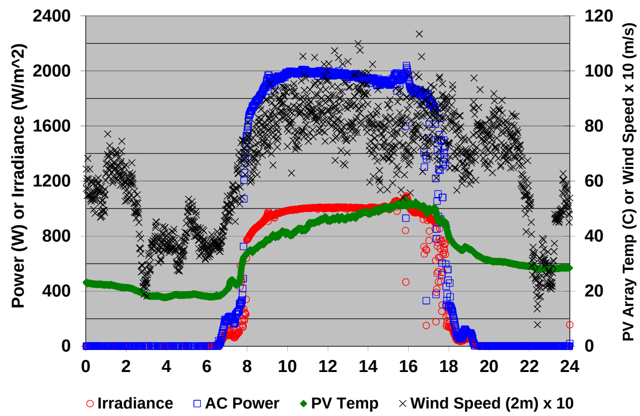

Fig. 5. Effect of higher wind speed on PV module temperature and AC Power at Bushland, TX (Bushland, TX, 8/11/2013).

Table 2 is the hourly average of the one-minute data for Aug. 9, 2012 (moderate wind speed day) and Aug. 11, 2012 (higher wind speed day). The average solar irradiance was not recorded ("NR" in Table 2) during the 8:00 hour although all other variables were recorded. The system efficiency could not be calculated ("NC" in Table 2) during the 8:00 hour either since the solar irradiance was not recorded. The average wind speed increase from Aug. 9 to Aug. 11 was 4.5 m/s, and the average temperature decrease was 9°C. The system efficiency improved from 11.8 to 12.3% which was a 4.2% improvement. However, the AC power percentage improvement (excluding last 2 hours when clouds occurred on higher wind speed day) was 2.8%. The higher wind speed day had a reduction in solar irradiance of 1.7% (excluding first hour and last two hours of the day). The AC power did not increase the same as the system efficiency for the higher wind speed day due to the lower solar irradiance on the higher wind speed day.

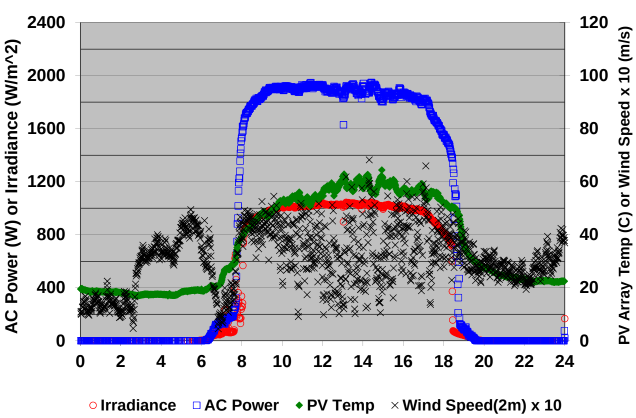

Fig. 4. Effect of moderate wind speed on PV module temperature & AC Power at Bushland,TX (8/9/2012).

† Note that to obtain the correct value of wind speed, divide values shown by 10.

Table 2. Comparison of Higher Wind Speed Day (HWD) on Aug. 11, 2012 to a Moderate Wind Speed Day (MWD) on Aug. 9, 2012 for a two-dimensional solar tracking 2.4 kW PV array (Bushland, TX).

	MWD	HWD	MWD	HWD	MWD	HWD
	8/9/2012	8/11/2012	8/9/2012	8/11/2012	8/9/2012	8/11/2012
	Hourly Avg.	Hourly Avg.	Hourly Avg.	Hourly Avg.	Hourly Avg.	Hourly Avg.
	Air Temp	Air Temp	PV Temp	PV Temp	Irradiance	Irradiance
Time	deg. C	deg. C	deg. C	deg. C	W/m^2	W/m^2
800	27.7	23.9	37.8	31.6	NR	NR
900	31.1	26.9	46.9	38.3	951.9	926.5
1000	33.6	29.8	51.9	41.0	1005.0	981.8
1100	35.2	32.1	53.4	43.5	1014.2	1001.7
1200	36.2	34.1	55.9	46.0	1027.2	1005.5
1300	37.5	36.0	58.6	46.7	1027.3	1006.2
1400	38.0	38.1	59.2	48.6	1031.2	1002.6
1500	38.3	39.7	59.1	50.3	1019.2	1015.2
1600	37.9	40.1	56.7	51.5	1002.8	1005.5
1700*	37.3	39.6	56.0	49.5	962.2	842.4
1800*	36.4	37.9	52.5	40.9	759.2	311.7
Daily Avg.	35.4	34.4	53.5	44.4	980.0	909.9
	MWD	HWD	MWD	HWD	MWD	HWD
	8/9/2012	8/11/2012	8/9/2012	8/11/2012	8/9/2012	8/11/2012
	Hr. Avg. 2m	Hr. Avg. 2m	Hourly Avg.	Hourly Avg.	Hourly Avg.	Hourly Avg.
	Wind Speed	Wind Speed	AC Power	AC Power	System Eff	System Eff
Time	m/s	m/s	W	W	%	%
800	3.7	6.9	1229	1192	NC	NC
900	4.3	8.0	1849	1887	12.2	12.8
1000	3.9	8.4	1907	1974	11.9	12.6
1100	3.6	8.6	1909	1991	11.8	12.5
1200	3.1	8.6	1906	1980	11.6	12.4
1300	3.0	8.5	1887	1971	11.5	12.3
1400	3.4	8.4	1893	1939	11.5	12.1
1500	3.0	7.4	1862	1926	11.5	11.9
1600	4.0	7.8	1857	1892	11.6	11.8
1700*	3.9	8.2	1789	1619	11.7	12.1
1800*	3.8	8.0	1533	619	12.7	12.5
Daily Avg.	3.6	8.1	1784	1726	11.8	12.3
	HWD-MWD	HWD-MWD	HWD-MWD	HWD-MWD	HWD-MWD	HWD-MWD
	Hourly Diff.	Hourly Diff.	Hourly Diff.	Hr. Diff. 2m	Hourly Diff.	Hourly Diff.
	Air Temp	PV Temp	Irradiance	Wind Speed	AC Power	System Eff
Time	deg C	deg C	W/m^2	m/s	W	%
800	-3.8	-6.2	NC	3.2	-36.4	NC
900	-4.2	-8.6	-25.4	3.7	38.3	0.6
1000	-3.8	-10.9	-23.2	4.6	66.8	0.7
1100	-3.1	-9.8	-12.5	5.0	82.3	0.7
1200	-2.1	-9.9	-21.7	5.5	74.5	0.7
1300	-1.5	-11.9	-21.2	5.5	83.4	0.8
1400	0.1	-10.6	-28.6	5.0	46.0	0.6
1500	1.4	-8.7	-4.0	4.4	64.3	0.4
1600	2.2	-5.1	2.7	3.8	35.2	0.2
1700*	2.2	-6.5	-119.8	4.4	-170.3	0.4
1800*	1.5	-11.6	-447.5	4.2	-914.1	-0.2
Daily Avg.	-1.0	-9.1	-70.1	4.5	-57.3	0.5

* - partly cloudy during 1700 and 1800 hours on 8/11/2012 (e.g. high wind day).

Table 3 shows how the wind speed, PV module temperature, temperature difference between PV module and the air, solar energy, AC energy, system efficiency, and type of day varied between 8:00 and 18:00 for each day in August. For all days the higher wind speed results in a reduction in the PV module temperature with respect to the air temperature for same type days. Also, on clear days the system efficiency and AC energy improve on the days with higher wind speed.

Table 3. Avg. 2m Height Wind Speed, Avg. PV Module Temperature (Tpv), Avg. Air Temperature (Tair), Avg. Tpv-Tair, Daily Solar Energy, Daily PV array AC energy, Avg. System Eff., and Type of Day for a two-dimensional tracking 2.4 kW PV Array during Aug. 2012 (Bushland, TX).

	800 to 1800	800 to 1800	800 to 1800			800 to 1800	
Day	Average 2m	Average	Average	Daily Total	Daily Total	Average	
of	Wind Speed	PV Temp (Tpv)	Tpv-Tair	Solar Energy	AC Energy	System Eff.	
Month	m/s	deg C	deg C	kWh	kWh	%	Type of Day
Aug. 01*	4.9	52.0	14.5	171.3	18.3	10.7	Clear
Aug. 02*	3.0	57.9	21.0	167.5	13.7	8.2	Clear
Aug. 03*	4.8	52.3	15.6	148.2	15.4	10.4	Mostly Sunny
Aug. 04	6.7	45.7	13.4	165.6	20.6	12.4	Clear
Aug. 05	2.9	51.1	20.4	152.5	18.5	12.1	Mostly Sunny
Aug. 06	5.2	45.7	10.9	121.4	14.6	12.0	Partly Cloudy
Aug. 07	3.6	50.3	14.6	130.4	14.0	10.7	Partly Cloudy
Aug. 08	4.4	46.0	15.2	151.6	19.1	12.6	Mostly Sunny
Aug. 09	3.6	54.5	18.7	166.5	20.0	11.8	Clear
Aug. 10	3.9	49.7	18.7	157.9	19.5	12.3	Clear
Aug. 11	8.2	45.5	10.7	155.4	19.2	12.3	Mostly Sunny
Aug. 12	6.7	39.1	8.2	99.9	12.8	12.8	Mostly Cloudy
Aug. 13	5.4	47.3	14.0	162.0	19.9	12.3	Mostly Sunny
Aug. 14	6.4	46.3	12.8	157.8	19.6	12.4	Mostly Sunny
Aug. 15	4.4	48.8	16.1	156.2	19.0	12.1	Mostly Sunny
Aug. 16	5.0	42.6	15.9	138.2	17.5	12.6	Mostly Sunny
Aug. 17	4.3	42.3	14.4	126.3	16.0	12.7	Partly Cloudy
Aug. 18	3.4	45.1	14.1	115.5	14.0	12.1	Mostly Cloudy
Aug. 19	3.6	40.1	13.3	104.9	13.2	12.6	Mostly Cloudy
Aug. 20	6.9	37.5	8.9	120.1	15.4	12.8	Partly Cloudy
Aug. 21	4.7	28.6	7.6	71.7	10.3	14.3	Mostly Cloudy
Aug. 22	5.8	32.8	9.4	113.0	14.7	13.0	Partly Cloudy
Aug. 23	7.8	33.4	5.8	79.4	11.4	14.4	Mostly Cloudy
Aug. 24	7.4	43.3	12.2	129.6	19.1	14.8	Mostly Sunny
Aug. 25	4.1	46.9	17.8	152.5	18.9	12.4	Mostly Sunny
Aug. 26	3.1	50.1	21.0	157.0	18.9	12.0	Mostly Sunny
Aug. 27	2.8	52.9	21.8	165.2	19.5	11.8	Clear
Aug. 28	3.6	51.1	20.7	163.4	19.5	12.0	Clear
Aug. 29	3.0	50.5	20.8	161.6	19.3	11.9	Clear
Aug. 30	3.3	49.2	18.3	144.9	17.4	12.0	Partly Cloudy
Aug. 31	2.8	54.4	22.1	167.9	19.6	11.7	Clear
Average	4.7	46.2	15.1	141.1	17.1	12.2	

* - On Aug. 1, 2, and 3, there were periods in afternoon when PV array disconnected from utility.

3.2 Effect of Wind Speed on a Fixed PV Array.

Figures 6 and 7 illustrate that an increase in wind speed can also improve the performance of a fixed grid-tied PV array. The AC power curve for the fixed PV array seen in Figures 6 and 7 is distinctly different than the AC power curve in Figures 4 and 5 for the 2-dimensional motorized tracking PV array. The solar radiation for both the higher wind and the moderate to low wind speed days look the same. The AC power does appear to be lower at mid-day for the lower wind speed day compared to the higher wind speed day. The PV module temperature is significantly higher for the lower wind speed day (about a difference of 15^{o}C at 15:00).

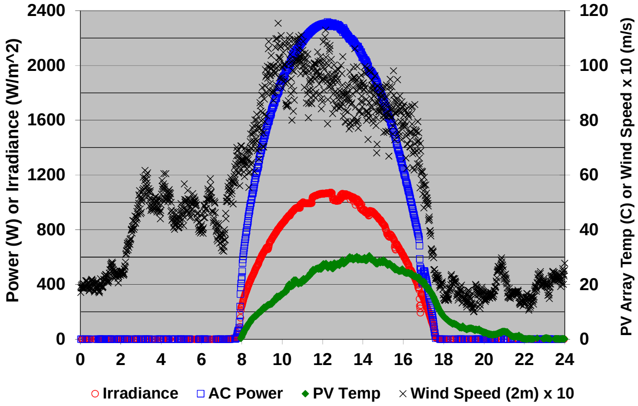

Fig. 6. Effect of high wind speed on PV module temperature and AC power of fixed PV array (Bushland, TX, 11/24/2012).

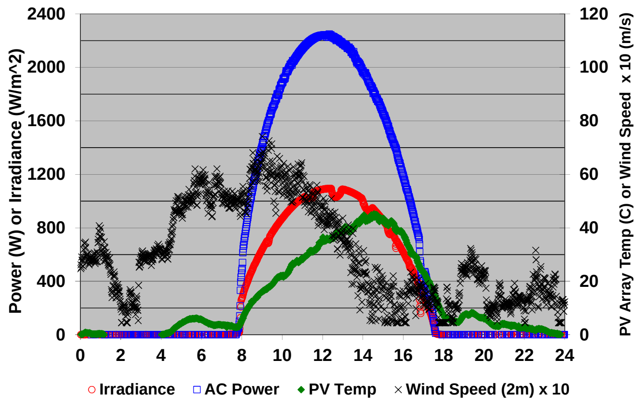

Fig. 7. Effect of moderate to low wind speed on PV module temperature and AC power of fixed PV array (Bushland, TX, 11/25/2012).

Table 2 presented the quantitative performance improvement for the two-dimensional tracking PV array due to increased wind speed. Table 4 presents the quantitative improvement in performance of the fixed PV array due to increased wind speed. There were no clouds on either the high wind or moderate to low wind speed days of Nov. 24, 2012 and Nov. 25, 2012, respectively. The difference in average wind speed between the two days was 4.7 m/s (8:00 to 17:00) which was very close to the difference in wind speed for the two-dimensional tracking PV array. The percentage increase in system efficiency was 4.7% while the percentage improvement in AC power was 2.5% which was similar to that measured on the two-dimensional tracking PV array. Again the solar radiation was down 2.5% which is why the AC power did not increase a similar amount as the system efficiency.

Table 4. Comparison of High Wind Speed Day (HWD) on Nov. 24, 2012 to a Moderate/Low Wind Speed Day (MLWD) on Nov. 25, 2012 for a 2.4 kW Fixed (45°) PV Array Facing South (Bushland, TX).

	HWD	MLWD	HWD	MLWD	HWD	MLWD
	11/24/2012	11/25/2012	11/24/2012	11/25/2012	11/24/2012	11/25/2012
	Hourly Avg.	Hourly Avg.	Hourly Avg.	Hourly Avg.	Hourly Avg.	Hourly Avg.
	Air Temp	Air Temp	PV Temp	PV Temp	Irradiance	Irradiance
Time	deg C	deg C	deg C	deg C	W/m^2	W/m^2
800	1.3	5.9	1.5	6.1	200.2	210.2
900	5.2	8.3	10.5	15.7	600.0	625.8
1000	9.0	10.2	16.6	22.0	838.3	865.3
1100	12.2	11.9	21.7	28.6	977.6	1007.7
1200	14.1	13.8	26.3	34.2	1059.3	1081.3
1300	16.5	16.3	28.1	38.6	1036.2	1062.1
1400	18.5	18.4	29.4	42.6	963.3	991.4
1500	19.5	20.9	27.9	43.0	834.9	848.6
1600	19.6	21.5	24.7	36.4	605.4	611.7
1700	18.0	18.8	20.2	23.4	284.1	282.2
Daily Avg.	13.4	14.6	20.7	29.1	739.9	758.6

	HWD	MLWD	HWD	MLWD	HWD	MLWD
	11/24/2012	11/25/2012	11/24/2012	11/25/2012	11/24/2012	11/25/2012
	Hr. Avg. 2m	Hr. Avg. 2m	Hourly Avg.	Hourly Avg.	Hourly Avg.	Hourly Avg.
	Wind Speed	Wind Speed	AC Power	AC Power	System Eff	System Eff
Time	m/s	m/s	W	W	%	%
800	6.4	5.1	438	449	13.7	13.4
900	8.4	6.3	1382	1396	14.4	14.0
1000	9.9	5.7	1877	1874	14.0	13.6
1100	9.9	5.5	2168	2133	13.9	13.3
1200	9.7	4.6	2292	2234	13.6	13.0
1300	8.9	3.6	2253	2177	13.6	12.9
1400	8.9	2.0	2062	1975	13.4	12.5
1500	8.5	1.4	1748	1654	13.1	12.2
1600	8.0	1.2	1242	1189	12.9	12.2
1700	5.6	1.5	517	498	11.4	11.1
Daily Avg.	8.4	3.7	1598	1558	13.4	12.8

	HWD-MLWD	HWD-MLWD	HWD-MLWD	HWD-MLWD	HWD-MLWD	HWD-MLWD
	Hourly Diff.	Hourly Diff.	Hourly Diff.	Hr. Diff. 2m	Hourly Diff.	Hourly Diff.
	Air Temp	PV Temp	Irradiance	Wind Speed	AC Power	System Eff
Time	deg C	deg C	W/m^2	m/s	W	%
800	-4.6	-4.6	-10.0	1.3	-11.0	0.3
900	-3.1	-5.2	-25.7	2.1	-14.6	0.4
1000	-1.1	-5.4	-27.0	4.2	3.3	0.5
1100	0.3	-6.8	-30.1	4.4	35.7	0.6
1200	0.3	-7.9	-22.0	5.1	58.7	0.6
1300	0.2	-10.4	-25.9	5.3	75.3	0.8
1400	0.0	-13.2	-28.1	6.9	86.4	0.9
1500	-1.5	-15.1	-13.7	7.0	93.7	0.9
1600	-2.0	-11.6	-6.3	6.8	52.9	0.7
1700	-0.8	-3.2	2.0	4.1	19.5	0.4
Daily Avg.	-1.2	-8.4	-18.7	4.7	40.0	0.6

Table 5 shows the daily changes in performance and temperatures for a fixed PV array. The average system efficiency for Nov. 2012 is higher than that of Aug. 2012 (13% versus 12.2%) which at first glance is surprising since the two-dimensional tracking system was tested in Aug 2012. However, Nov 2012 was the hottest November since recordings began about 130 years ago. In addition there were more clear days in November than in August. The solar energy incident on the two-dimensional tracking PV array in Aug. 2012 was about 40% higher than the solar energy incident on the fixed PV array in Nov. 2012.

Table 5. Avg. 2m Height Wind Speed, Avg. PV Module Temperature (Tpv), Avg. Air Temperature (Tair), Avg. Tpv-Tair, Daily Solar Energy, Daily PV array AC energy, Avg. System Eff., and Type of Day for Fixed PV Array during Nov. 2012 (Bushland, TX).

Day of Month	800 to 1800 Average 2m Wind Speed m/s	800 to 1800 Average PVTemp (Tpv) deg C	800 to 1800 Average Tpv-Tair deg C	Daily Total Solar Energy kWh	Daily Total AC Energy kWh	800 to 1800 Average System Eff. %	Type of Day
Nov. 01	5.1	34.4	10.2	121.4	15.2	12.5	Clear
Nov. 02	4.5	35.8	11.7	121.4	15.0	12.4	Clear
Nov. 03	3.9	24.9	11.2	94.3	12.5	13.2	Partly Cloudy
Nov. 04	4.1	29.1	10.7	109.6	14.3	13.0	Mostly Sunny
Nov. 05	4.1	28.2	11.6	111.8	14.6	13.1	Mostly Sunny
Nov. 06	3.4	35.9	15.0	119.7	15.0	12.5	Clear
Nov. 07	6.9	31.3	9.4	117.6	15.1	12.8	Clear
Nov. 08	5.3	31.6	7.8	95.1	12.1	12.7	Partly Cloudy
Nov. 09	8.6	28.5	6.2	112.7	14.7	13.0	Clear
Nov. 10	10.4	25.4	5.0	79.5	10.8	13.6	Mostly Cloudy
Nov. 11	4.2	20.1	13.6	112.5	15.4	13.7	Mostly Sunny
Nov. 12	2.0	27.7	18.9	122.1	16.0	13.1	Clear
Nov. 13	7.7	18.3	8.2	105.3	14.5	13.8	Partly Cloudy
Nov. 14	4.3	30.2	15.6	119.9	15.4	12.8	Clear
Nov. 15	7.6	18.2	6.0	90.2	12.1	13.5	Mostly Cloudy
Nov. 16	4.7	25.2	12.3	110.6	14.7	13.3	Mostly Sunny
Nov. 17	7.0	19.8	6.2	75.5	10.3	13.7	Mostly Cloudy
Nov. 18	7.3	19.3	3.0	48.1	6.6	13.7	Mostly Cloudy
Nov. 19	3.5	30.0	12.5	110.8	14.0	12.7	Mostly Sunny
Nov. 20	3.0	35.5	16.5	118.3	14.6	12.3	Clear
Nov. 21	7.7	22.6	5.2	68.5	9.1	13.3	Mostly Cloudy
Nov. 22	6.2	28.8	10.1	115.1	14.6	12.7	Partly Cloudy
Nov. 23	2.4	26.3	17.1	114.7	14.9	13.0	Clear
Nov. 24	8.2	21.3	7.4	118.0	16.0	13.2	Clear
Nov. 25	3.5	29.4	14.4	121.0	15.6	12.5	Clear
Nov. 26	7.3	14.7	9.4	109.5	15.0	13.7	Clear
Nov. 27	6.1	18.7	10.1	114.0	15.2	13.3	Clear
Nov. 28	3.5	25.1	11.0	110.8	14.2	12.8	Mostly Sunny
Nov. 29	2.6	33.7	15.1	115.5	14.0	12.1	Clear
Nov. 30	2.9	28.5	11.1	84.9	10.4	12.2	Partly Cloudy
Average	5.3	26.6	10.8	105.6	13.7	13.0	

4. CONCLUSIONS

This paper demonstrated that for either a two-dimensional tracking PV array or a fixed PV array, an increase in average wind speed (during daylight hours) of 4.5 m/s on a clear day will increase the AC power about 2.5%. The system efficiency was improved 4 to 5%, but there was not a similar percentage improvement in AC power due to a reduction in solar radiation on days with higher wind speed. The lower solar irradiance on the higher wind speed days may be due to wind speed causing the amount of dust in the atmosphere to increase.

The daily average difference between PV module temperature and air temperature was always less for the same type of day (clear, partly cloudy, mostly cloudy, etc) on days when the wind speed was higher during daylight hours.

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