PERFORMANCE COMPARISON OF FIXED, SINGLE, AND DUAL AXIS TRACKING SYSTEMS FOR SMALL PHOTOVOLTAIC SYSTEMS WITH MEASURED DIRECT BEAM FRACTION

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ABSTRACT

The purpose of this study is to evaluate the side-by-side performance of small photovoltaic systems with fixed, single, and dual-axis tracking capabilities with regard to the presence of direct beam irradiance. Selected geographic regions within the United States will be evaluated for impact to performance utilizing the results of the analysis.

Independent variables of the study include tracking system type (fixed, single, and dual axis), as well as measured direct beam fraction irradiance reported as percent of total irradiance. The dependent variable (performance) is power production from each individual photovoltaic system and reported in units of Watts. The hypothesis is that although power production and irradiance are linearly related, power and direct beam fraction are not.

This study is phase II of an initial study completed at the Appalachian State University Solar Lab during fall 2011 by John W. Robinson and Brian Raichle in which power enhancement from a fixed axis to a single axis tracking system was reported, with a strong direct beam fraction dependency (1).

1. INTRODUCTION

Solar Irradiance may be defined as the amount of solar power that arrives at a specific area of a surface. A typical unit is W/m^2. Because of absorption and scattering by the atmosphere, moisture, and surface features, the angular distribution of solar radiation varies (Figure 1). Also, this angular distribution changes throughout the day and year and is influenced by location, climate, and atmospheric conditions (2). This study addresses tracker performance criteria based upon availability of total irradiance, direct normal irradiance by geographic region, and the associated performance benefit.

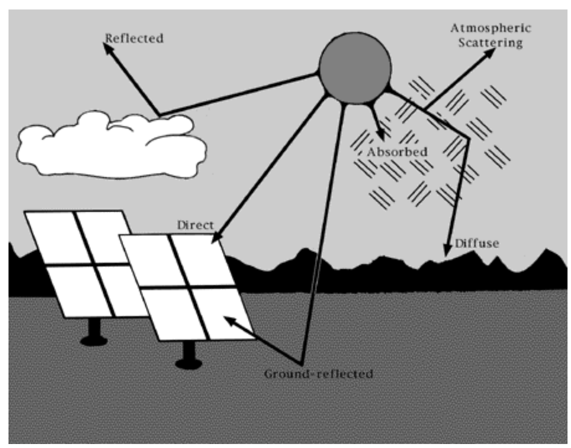

Fig. 1: Environmental impacts on angular distribution.

Several factors affect a PV module's power output. The two main factors considered in this study were the total irradiance level and the direct beam fraction. It is generally accepted that as the total irradiance increases, the power output will increases due to the increase in short circuit current (I_{sc}) (3). Data collected for purposes of this study are represented in Figure 2. The data indicates a positive and relatively direct relationship between power production and total irradiance. The dual axis system produced the most power, followed by the single and fixed axis systems. This is the premise for the analysis of the study in which total irradiance is grouped into performance categories and analyzed by percent direct beam irradiance (direct beam fraction).

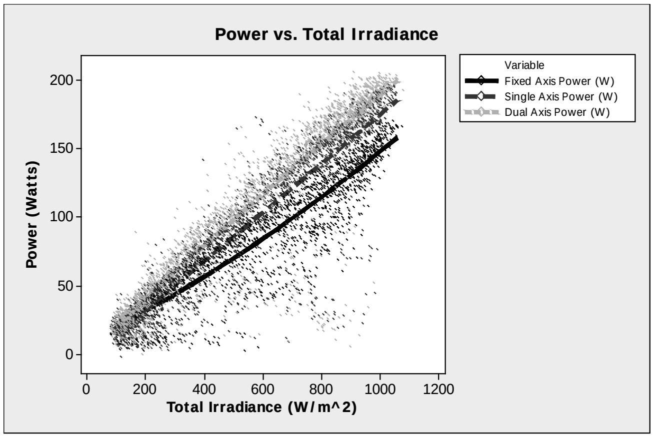

Fig 2: Relationship between power and total irradiance.

Total irradiance can be divided into two components: direct beam and diffuse. Direct beam radiation is the radiation that comes directly from the sun with no scattering in the atmospheric. Diffuse radiation is radiation that has been scattered, either by clouds, rain, or any other potential hazard. As radiation passes through the atmosphere, the incidence angle changes, making it diffuse rather than direct. Direct beam fraction describes the ratio of direct beam to total radiation. Previous research on how various real world direct beam fractions affect PV array power output under varying irradiance conditions is limited.

To have a maximum power output, the PV array needs to capture as much irradiance as possible. To capture the maximum amount of irradiance, the array needs to be pointing toward the sun, thus maximizing effective area and giving the direct beam radiation an incidence angle of 0°. The ability to point toward the sun for a majority of the day can be accomplished to varying degrees by different methods, including fixed mounting systems with optimized tilts and azimuth angles, single-axis tracking systems with optimized tilt, and dual-axis tracking systems. The more complex a system’s tracking capabilities, the greater likelihood that it will capture the most irradiance. This study compared the measured performance advantages associated with tracking technologies.

2. REVIEW OF PREVIOUS STUDIES

Direct beam radiation typically makes up the majority of total solar radiation (4). A PV cell is able to absorb the most radiation when it is perpendicular to the beam. This effect, in addition to increasing effective area, is the reason that the angle to which the panels are tilted makes a big difference in their power output. Therefore, trackers should significantly enhance an array’s energy production. Previous studies have quantified the performance advantages of single and dual-axis tracking systems over fixed mounting. These studies tend to be geographically specific, and not able to generalize results for a wide range of areas based on their analysis methods (5). One study suggests that for “mid latitude regions” the power gains were 36% and 41% more for single-axis and dual-axis, respectively, over fixed mounting (6). Another study found that in Egypt, a dual-axis tracking system could offer a 29.2% power increase over fixed mounting (7). A study done on one July day in Turkey found that for that day in that region, there was a 29.3% and 34.6% efficiency increase from single and dual axis tracking, respectively, over fixed mounting (8). Another study in Algeria found that single-axis tracking offered 30-42% increases in power output relative to fixed mounting, and that dual-axis tracking offered 39-54% increases, both depending on the day and the weather conditions (9). What is lacking in the literature is a methodology that allows generalization of results to all locations based on observable conditions. This study pursues such a generalization by measuring fixed and tracking PV array output as a function of total irradiance and direct beam fraction.

3. METHODOLOGY

To compare the performance of the tracking systems, three nominally identical PV systems were installed: a dual axis tracking system, a passive 1-axis tracking system and a system mounted at a fixed tilt = latitude angle.

3.1 Equipment

The experiment was conducted at the Appalachian State University Solar Research Laboratory in Boone, NC. Direct beam irradiance is measured by a Hukseflux DR-1 Pyrheliometer tracked by a Minitrak II Solar Tracker. Global diffuse radiation is measured by a Hukseflux SR11 Pyranometer.

The three PV systems used a Sharp ND-224UC1 panel and an enPhase M190 microinverter. Before installation of the panels, Isc and Voc were determined to agree within 1% of each other. One panel was mounted at a fixed tilt = latitude, one panel was installed on a single-axis Zomeworks UTR-020 azimuth tracker (tilt set to 40°). This passive tracker uses the weight imbalance due to differential heating of Freon to drive the tracking. The dual axis tracker is a Wattsun AZ 225 active altitude and azimuth tracker. AC electrical power from each PV system was measured using Ohio Semitronics power transducers. A Campbell Scientific data logger recorded measurements every 10 seconds.

3.2 Data analysis

Data was collected every 10 sec from March 31 – October 20, 2012. One minute averages of direct normal irradiance (DNI), global diffuse radiation (GDIFF), and PV outputs were calculated.

"Non-productive" periods of no sunlight were defined as periods when none of the three systems were producing power (primarily night conditions) and eliminated from the study. The purpose of this adjustment was to provide more discrimination within the analysis.

PV power outputs were analyzed as a function of both total irradiance,

$$I_{tot} = DNI + GDIFF$$

and direct beam fraction:

$$DBF = \frac{DNI}{I_{tot}}.$$

To evaluate the data by the presence of total irradiance (I_{tot}), natural groupings were identified and the data grouped with bin range equal to 200 W/m^2. The date is further categorized by percent (of total irradiance) present as *DBF*. Line of best fit is utilized to evaluate the performance by tracker type for each of the I_{tot} categories at direct beam fraction values from 0 to 0.10, expressed as a percentage.

4. PRELIMINARY RESULTS

As stated in the hypothesis, analysis of variance by "tracker type" (Figure 3) shows statistically different performance under "normal operating conditions". The fixed axis system had a mean power of 79 W, the single axis system 94 W (a 16% increase in power over the fixed), and the dual axis system 105 W (a 25% increase in power over the fixed axis).

One-way ANOVA: Fixed Axis Power (W), Single Axis Power (W), Dual Axis Power (W)

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Source    DF        SS       MS       F      P
Factor     2    634710   317355  104.15  0.000
Error   5718  17423934     3047
Total   5720  18058645

S = 55.20   R-Sq = 3.51%   R-Sq(adj) = 3.48%

Level                     N    Mean  StDev
Fixed Axis Power (W)   1907   79.21  44.96
Single Axis Power (W)  1907   93.50  58.13
Dual Axis Power (W)    1907  104.96  61.17

                       Individual 95% CIs For Mean Based on
                       Pooled StDev
Level                  ----+---------+---------+---------+-----
Fixed Axis Power (W)   (--*--)
Single Axis Power (W)                    (--*--)
Dual Axis Power (W)                                    (--*--)
                       ----+---------+---------+---------+-----
                         80.0      88.0      96.0     104.0
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Fig. 3: Tracker performance under normal operating conditions in Boone, NC.

The relationship between power and direct beam fraction (expressed as a percentage) in Figure 4 shows that the relationship under standard irradiance conditions is not linear. Implications are that there will be circumstances where power production will have different degrees of variation.

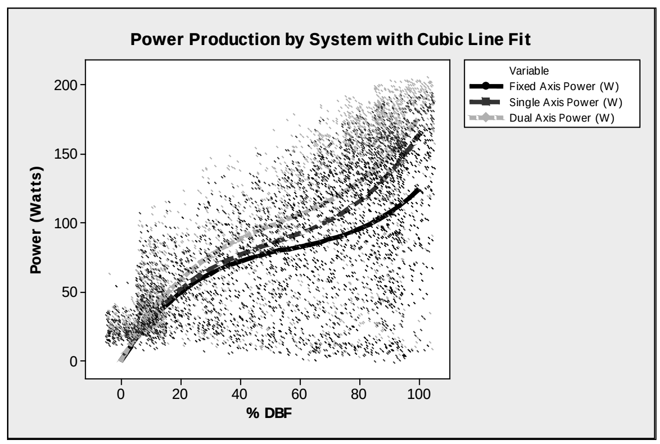

Fig. 4: Relationship between power and direct beam fraction for all measured irradiance levels.

PV power outputs were grouped into 200 W/m^2 I_{tot} bins, and each bin was further indexed according to *DBF*.

Data with total irradiance 900 – 1100 W/m^2 are shown in Figure 5. There is a statistically significant power increase between each tracker type. While the fixed axis remains as a constant power production level, the single and dual continue to increase with increase of DBF.

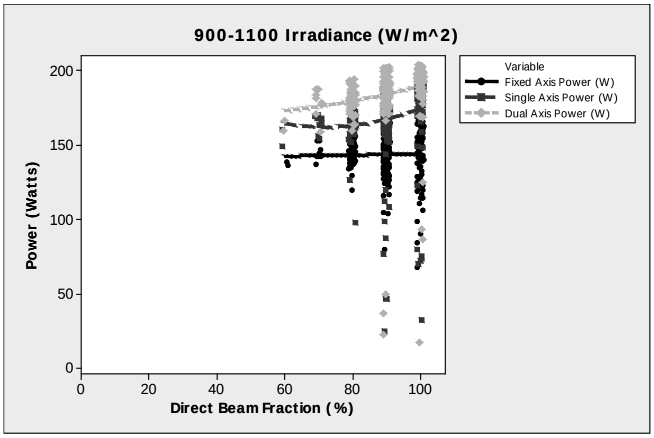

Fig. 5: Power output by irradiance grouping.

Power output with total irradiance of 700-900 W/m^2 showed that each system increased production to approximately 70% DBF, at which point each system showed a decrease in production, the most drastically from the fixed axis tracker, as shown in Figure 6. *DBF* bins as low as 40% were populated. As DBF increases from 70 to 100%, the power production gap between the single and dual axis systems closes from 20 W to 5 W.

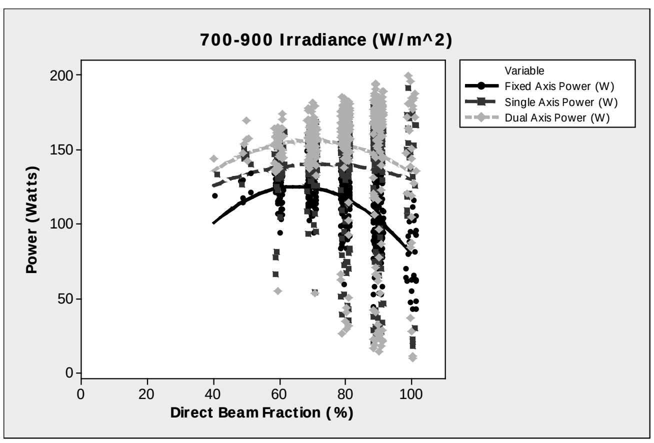

Fig. 6: Power output by irradiance grouping.

Data in the total irradiance bin of 500 – 700 W/m^2 shows the continued decrease in overall performance by each system. The advantage of the dual axis tracker over the single axis is 5 W, while both tracking systems continue to perform 60 W above the fixed. In phase I of this study, it was determined by visual inspection that the Zomeworks single axis passive tracking system was often misaligned in the morning; the tracker might be pointing to the west, where the sun had set the evening before. This means that the PV panel is potentially aligned a full 90° from where it would be normal to the direct irradiance. This is a potential down-side to the Zomeworks passive tracking method.

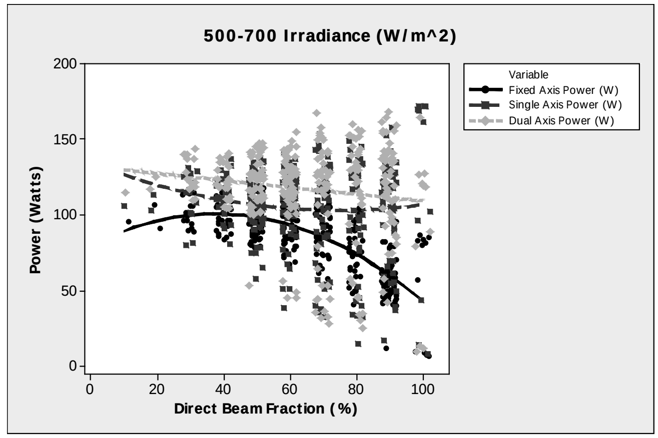

Fig. 7: Power output by irradiance grouping.

In the total irradiance bin of 300-500 W/m^2, shown in Figure 8, the fixed and dual axis trackers performed similarly up to 70% *DBF*. This is likely because the majority of the 90% and 95% *DBF* bins occurred before 9AM when the tracker was likely unable to accurately track.

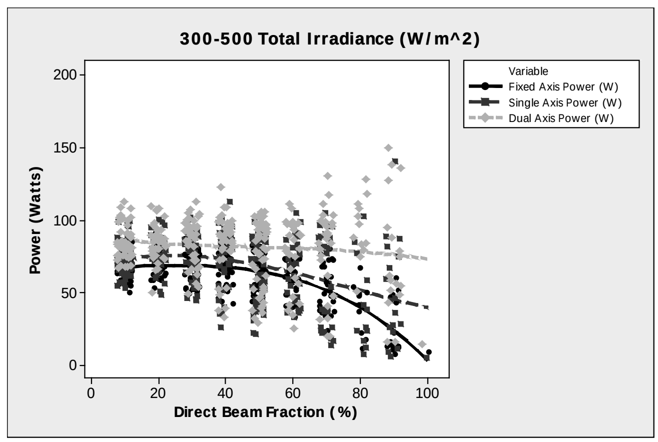

Fig. 8: Power output by irradiance grouping.

The total irradiance bin of 100-300 W/m^2 has lower power output, as shown in Figure 9. At these lowest irradiances, the single axis tracker and fixed tracker have comparable performance throughout the *DBF* range, and the dual axis tracker outperforms both the fixed and single axis trackers throughout the *DBF* range.

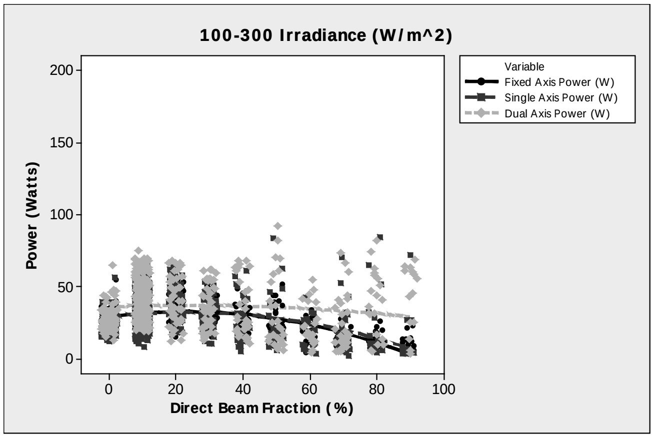

Fig. 9: Power output by irradiance grouping.

5. SUMMARY AND CONCLUSIONS

A positive linear relationship between total irradiance and power production was found in the data collected at the Appalachian State University solar lab between March and October, 2012. A non-linear relationship between power and DBF was present. The data was subsequently indexed into total solar irradiance groups and analyzed by tracker type for power production vs direct beam fraction (as a percentage of total irradiance). The fixed, single axis, and double axis tracker each showed increased power production at total irradiance above 800 W/m^2, at which point power production, although positive, began to decline. Prominent separation between tracker types was present at varying degrees throughout the irradiance, as well as the DBF, ranges in question.

At irradiance levels beyond 900 W/m^2, DBF was present at 60% and above. Fixed tracker power remained constant at 140 Watts, while both single and double axis trackers showed a 10% increase as DBF increased to 100%, averaging 160 and 180 Watts respectively.

At irradiance levels between 700 and 900 W/m^2, the fixed tracking system dropped significantly to 80 Watts, as the single and double axis trackers converged at 140 Watts. This range of radiance proves to be the most significant as it is a common operating range, and houses the most significant difference in performance between the fixed and axis oriented system.

6. ACKNOWLEDGEMENTS

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