STUDENT SUMMER INTERNSHIP TECHNICAL REPORT

Analysis of Solar Generated Power in the Southeastern United States

DOE-FIU SCIENCE & TECHNOLOGY
WORKFORCE DEVELOPMENT PROGRAM

Date submitted:

September 30, 2015

Principal Investigators:

Natalia Duque (DOE Fellow Student)
Florida International University

Ralph L. Nichols, Mentor
Savannah River National Laboratory

Florida International University Program Director:

Leonel Lagos, Ph.D., PMP®

Submitted to:

U.S. Department of Energy
Office of Environmental Management
Under Cooperative Agreement # DE-EM0000598

FIU | Applied Research Center
FLORIDA INTERNATIONAL UNIVERSITY

ABSTRACT

Photovoltaic (PV) systems are becoming important sources of energy. Its use has been rising in the past decade, especially in the developing countries. PV systems efficiency depends greatly on which part of the world it is located, and also on its configuration. It is widely accepted that the ideal configuration for PV systems is either single-axis tracking or double-axis tracking systems that follow the sun as its position changes throughout the day. This research work attempts to better understand the solar energy generation patterns and its seasonal variation according to its configuration. Data from Colleton Solar Farm, located in Walterboro, South Carolina, was available for analysis. A total of 10,010 PV modules were distributed in two different configurations: 60% of the panels (6,006) on a fixed axis with a latitude tilt of 25°, and 40% of the panels (4,004) on a single-tracking axis. The tracking panels received a total of 14% more irradiance than the fixed panels, but two distinct patterns were observed: during the colder months the fixed axis modules generate an average of 10% more power; during the hotter months, the single-axis tracking modules generate an average of 22% more solar power than the fixed configuration. The Mann-Whitney test was conducted to compare the difference in energy generation between the fixed panels and the single-axis panels, concluding that for the months of April through August the populations are distinct with significantly more electricity being produced by the tracking system. The Spearman's Rank Order coefficient, ρ, was calculated to measure the correlation between total average PV power generation and demand on the grid. A strong direct correlation can be observed in the summer months, from April to October, and almost no correlation is observed for the rest of the months.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

PV	photovoltaic
AC	alternate current
DC	direct current
OECD	Organization for Economic Co-operation and Development
IEA	International Energy Agency
POA	plane-of-array
SCPSA	South Carolina Public Service Authority

1. INTRODUCTION

Photovoltaic (PV) systems are becoming important sources of energy. According to the International Energy Agency (IEA), PV electricity generation has grown between 34% to 82% for OECD (Organization for Economic Cooperation and Development) countries over the past decade, and installed capacity in these countries reached 63.6 GW at the end of 2011 (International Energy Agency, 2013). Solar energy generation has been widely studied in the western United States, but not many studies have been conducted for the southeastern region. The objective of this paper is to try to better understand the seasonal variations of PV power generation and its availabulity when it is most needed in the power grid.

The amount of power produced by a photovoltaic system depends upon the amount of irradiation to which it is exposed (Eke & Senturk, 2012). It is widely accepted that the ideal configuration for PV systems is either single-axis tracking or double-axis tracking systems that follow the sun as its position changes throughout the day (single-axis), and also throughout the year (double-axis). This paper also attempts to compare the electricity yield between single-axis tracking systems and optimally tilted fixed axis panels.

2. EXECUTIVE SUMMARY

This research work has been supported by the DOE-FIU Science & Technology Workforce Initiative, an innovative program developed by the US Department of Energy's Office of Environmental Management (DOE-EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2015, a DOE Fellow intern, Natalia Duque, spent 10 weeks doing a summer internship at Savannah River National Laboratory in Aiken, South Carolina under the supervision and guidance of Mr. Ralph L. Nichols, Fellow Engineer at the Environmental Sciences & Biotechnology Directorate. The intern's project was initiated on June 1st, 2015 and continued through August 7th, 2015, with the objective of better understanding photovoltaic energy generation in the southeastern region of the United States.

3. RESEARCH DESCRIPTION

Colleton Solar Farm

Colleton Solar Farm is located in Walterboro, South Carolina (latitude: 32.91, longitude: -80.68). It is the state's largest solar energy farm with a total of 10,010 photovoltaic (PV) panels and a peak generating capacity of 3 megawatts (MW) on clear days. It started operation in December 2013 and has produced an estimated 8,000 MWh in approximately one year and a half.

The total electrical energy produced by the PV panels, in the form of direct current (DC), is sent to a total of five (5) inverters. These inverters convert the electricity generated by the solar modules into alternating current (AC) that can then be sent into the utility grid.

The PV panels are distributed in two different configurations: fixed and single-axis tracking. A total of 6,006 PV panels (60%) are fixed in the ground with a 25° inclination towards the south (true south). The other 4,004 (40%) of the PV panels track the sun's path, east to west, throughout the day. These tracking panels are not inclined; they are horizontal, parallel to the ground. An aerial view of the panels can be seen in Figure 1.

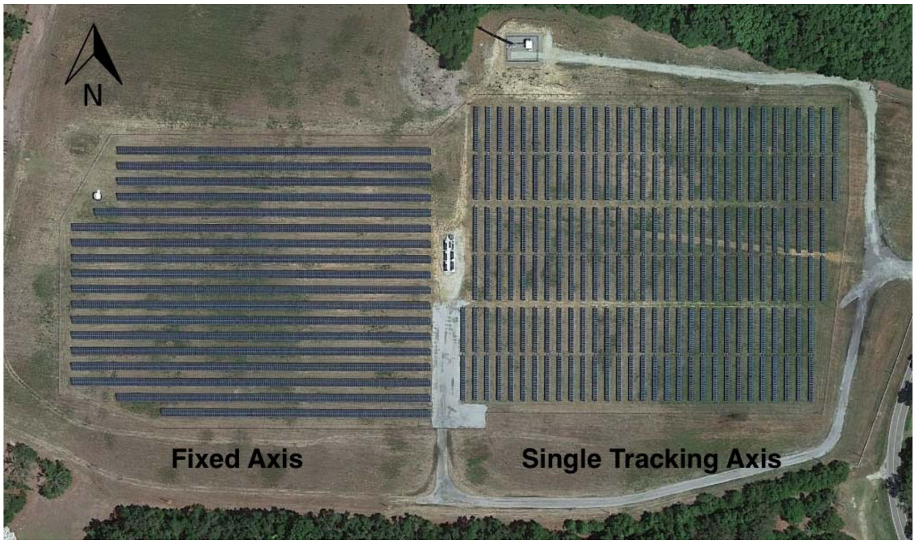

Figure 1. Colleton Solar Farm aerial view.

The technical specification for the PV modules and the inverters are presented in Tables Table 1 andTable 2, respectively.

Table 1. PV Modules Technical Specifications

300W Canadian Solar CS6X PV module specification	
CS6X 300P	
Nominal Max. Power (Pmax)	300 W
Opt. Operating Voltage (Vmp)	36.1 V
Opt. Operating Current (Imp)	8.30 A
Open Circuit Voltage (Voc)	44.6 V
Short Circuit Current (Isc)	8.87 A
Module Efficiency	15.63%
Operating Temperature	-40°C ~ +85°C

Table 2. Inverters Technical Specifications

SMA 500U inverters specifications	
Sunny Central 500U	
AC Power Output (Nominal)	250 kW
AC Voltage (Nominal)	480 V_{AC} WYE
AC Frequency (Nominal)	60 Hz
Current THD	< 5%
Power Factor (Nominal)	> 0.99
AC Output Current Limit	300 A_{AC} @ 480 V_{AC}
DC Input Voltage Range	300 – 600 V_{DC}
MPP Tracking	300 – 600 V_{DC}
PV Start Voltage	400 V_{DC}
Maximum DC Current	800 A_{DC}
Peak Efficiency	97.50%
CEC Weighted Efficiency	97%
Power Consumption	69 W Standby, <1000 W with fans
Ambient Operating Temperature	−13 to 113 °F at full power output up to 122 °F at reduced power

Dataset Assembly

Data compiled for this study was for the time period of February 2014 to January 2015. It consisted of measurements made in 15-minute intervals for DC power, average plane-of-array (POA) irradiance (for fixed panels), and average tracker irradiance (for tracking panels). The original data was reported as DC power going into each of the 5 inverters. Inverters 1, 2, and 3 were connected to the fixed axis panels and inverters 4 and 5 were connected to the single-tracking axis panels.

In order to compare the power generation between fixed and tracking axis panels, a data normalization procedure had to be conducted since the two populations differed in size. The total number of PV panels was 10,010, with 6,006 configured as fixed axis and 4,004 as single-axis tracking. For the energy generation comparison between fixed and tracking axis, the data was divided by the number of panels. This way, the analysis was conducted using a common scale.

Methodology

After the database was assembled, a comparison of power generated between inverters was conducted. The purpose of this analysis was to check if major electricity generation differences occurred within similar configurations. The next step was to compare the energy generation between fixed and single-tracking arrays with daily and monthly variations to verify if the tracking assembly maximizes solar radiation collection.

A peak coincidence analysis was then conducted in order to examine whether or not there is any correlation between peak energy demand and peak PV energy generation.

Irradiance

The total irradiance exposure for the panels was measured and compared for the two different arrays. Overall, the most irradiance captured by the PV panels was between the months of May and August, as seen in Figure 2, with the tracking panels (tracker irradiance) receiving more than the fixed panels (plane of array – POA). The total annual average irradiance from tracking panels was 14% more than for fixed panels. Nonetheless, annual average irradiance for colder months (November, December, January and February) was 10% higher for fixed panels than tracking modules, as shown in Table 3.

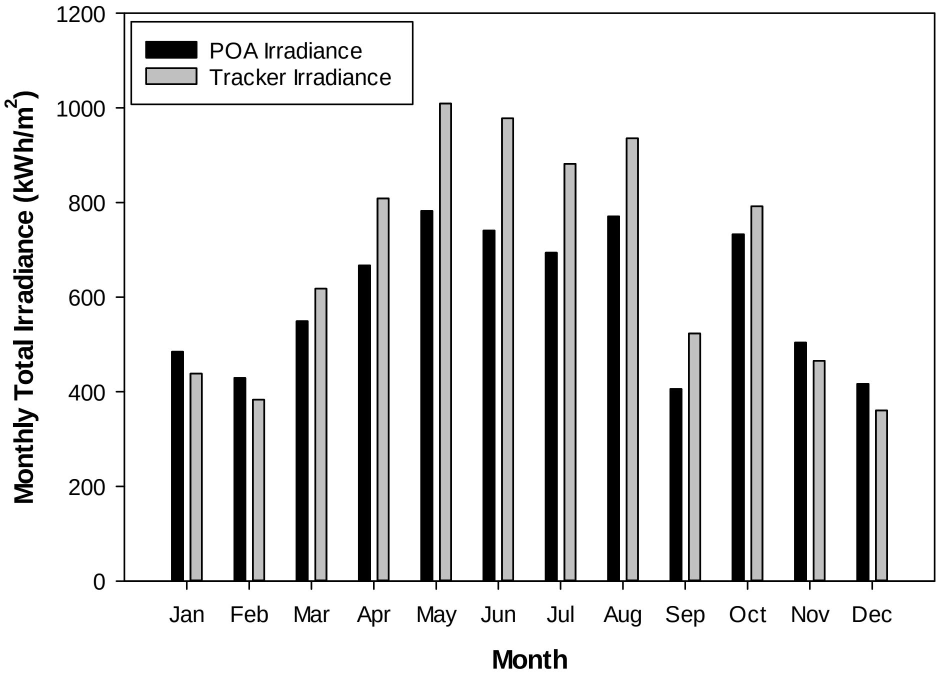

Figure 2. Monthly irradiance.

Table 3. Percentage Difference in Irradiance Between Fixed and Tracking Panels

Month	Total Irradiance for fixed panels (kWh/m^2)	Total irradiance for tracking panels (kWh/m2)	Percentage difference
January	484.95	438.43	10.61
February	429.22	383.20	12.01
March	549.54	618.20	11.11
April	666.79	808.42	17.52
May	782.38	1008.97	22.46
June	740.86	978.35	24.28
July	694.00	881.45	21.27
August	770.75	935.62	17.62
September	406.03	523.21	22.40
October	733.15	792.22	7.46
November	504.18	465.24	8.37
December	416.63	360.62	15.53

4. RESULTS AND ANALYSIS

Inverters Comparison

As noted before, the arrangement of the PV panels whose generated power went to inverters 1, 2 and 3 is fixed axis, and that for inverters 4 and 5 is single-tracking axis. After plotting the average power generated each month by the hour of the day, no significant difference was noted between similar arrays, except for the month of September, in which the power going into inverter 2 was slightly less than for inverters 1 and 3. This difference might be explained by a failure in Inverter 2 from 9/15/14 to 9/19/15. The graph is shown in Figure 3.

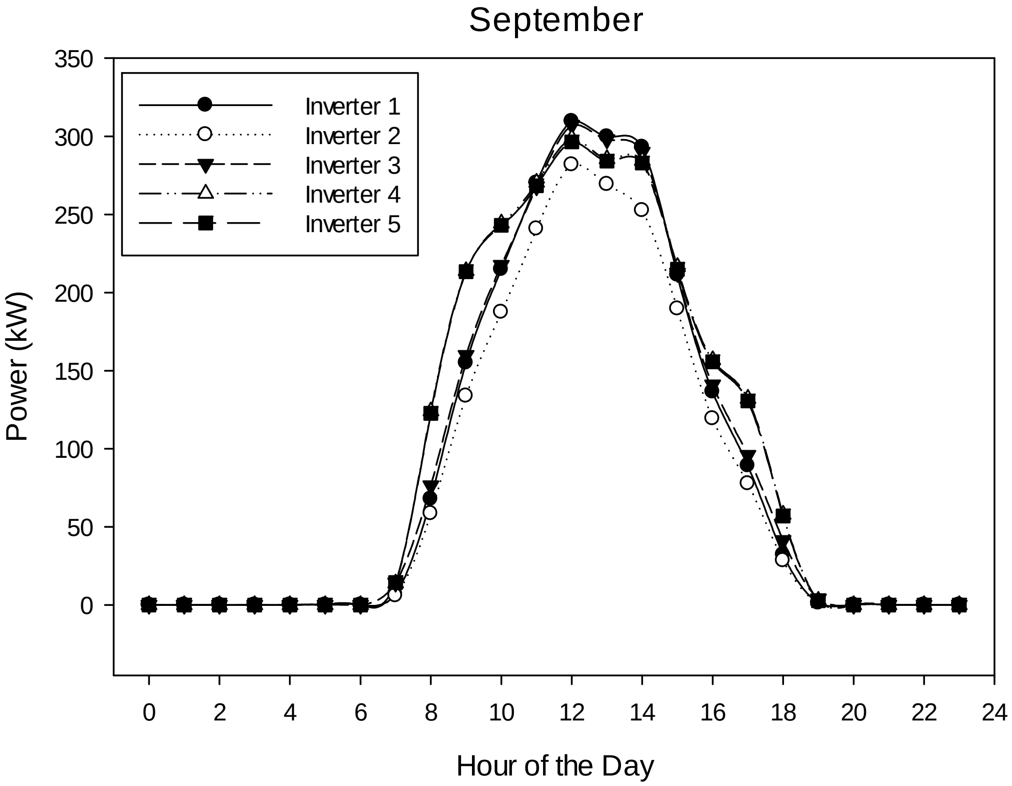

Figure 3. Inverter comparison for September.

The profile for the colder months is similar to the January generation graph, shown in Figure 4. For hotter months the profile is similar to the August generation shown in Figure 5.

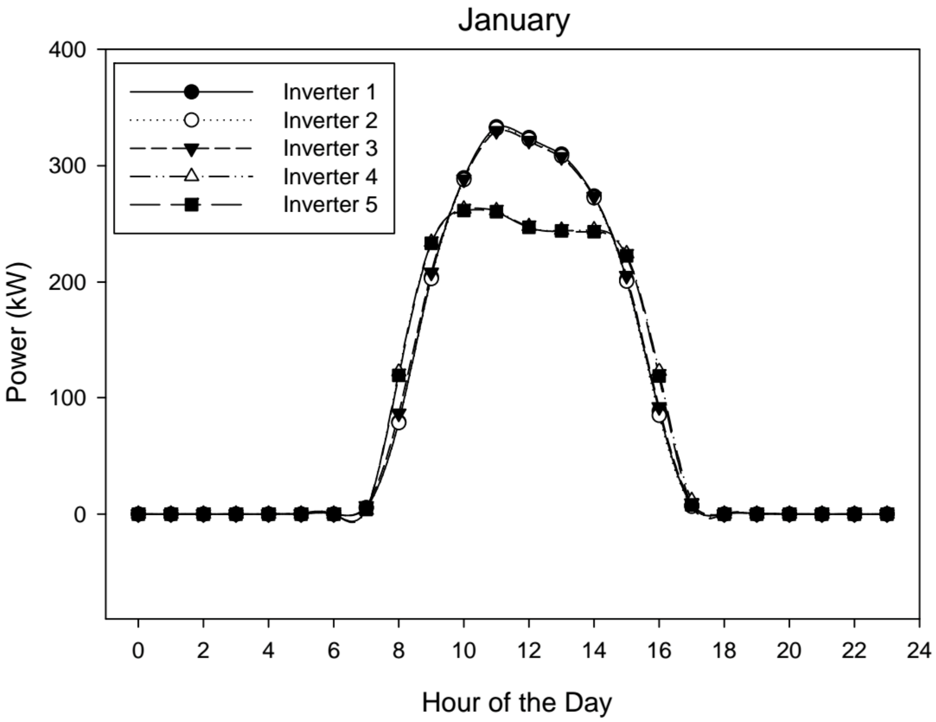

Figure 4. Inverter comparison for January.

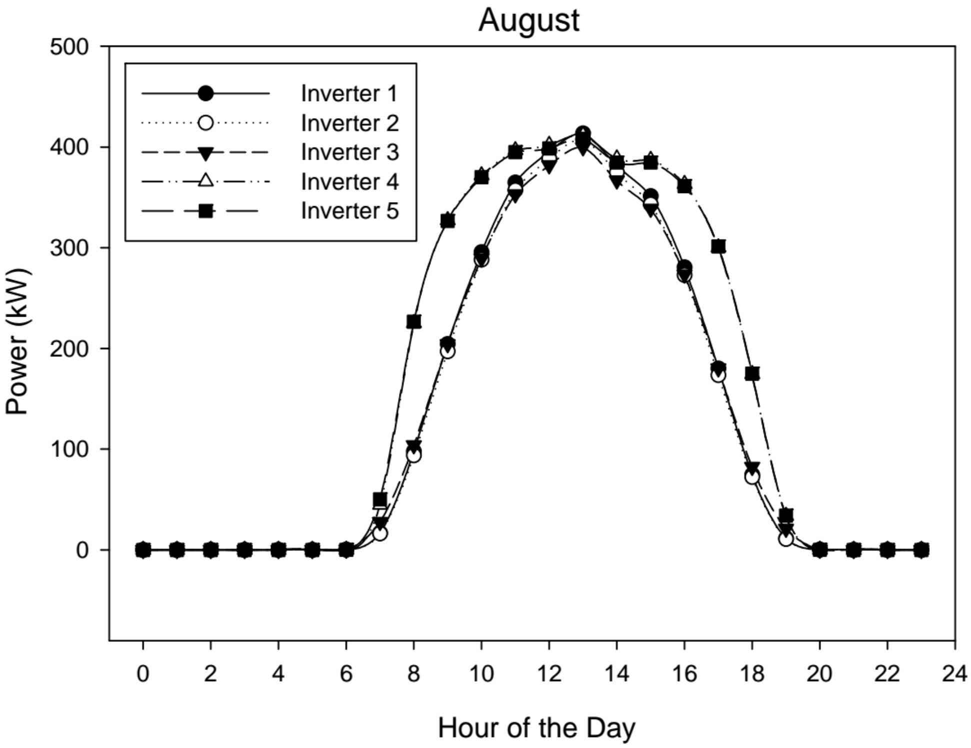

Figure 5. Inverter comparison for August.

We believe these two patterns are related to the sun's position in the sky and the panel's inclination –or lack of-. Figure 6 shows a graph of the sun's position between the summer and winter solstices for Walterboro, SC. On December 21st (winter solstice) at 12PM, the solar elevation is approximately 33°**;** and on June 21st (summer solstices) at 12PM, the solar elevation is approximately 80°**.**

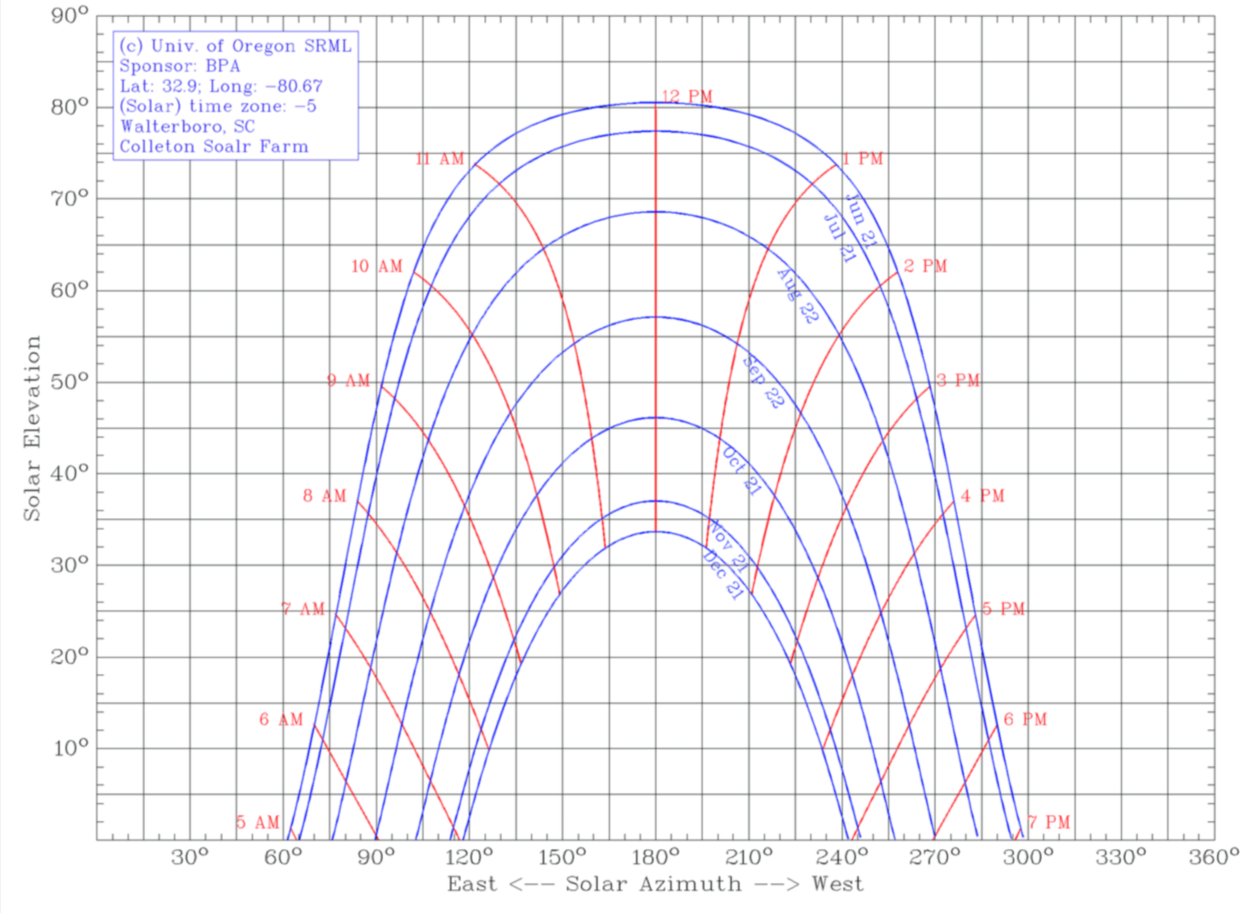

Figure 6. Sun position between summer and winter solstices

The power incident on a PV module depends not only on the power contained in the sunlight, but also on the angle between the module and the sun. When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight (in other words, the power density will always be at its maximum when the PV module is perpendicular to the sun) (Honsberg & Bowden).

As mentioned before, the tracking modules are lying flat on the ground and the fixed modules are tilted 25°**.** During winter months, the fixed panels are facing the sun more directly than the tracking panels; therefore the solar radiation incident is higher. During the summer months, both arrays face the sun in a semi-direct manner; therefore the solar radiation incident is similar. Figure 7 shows a graphical representation.

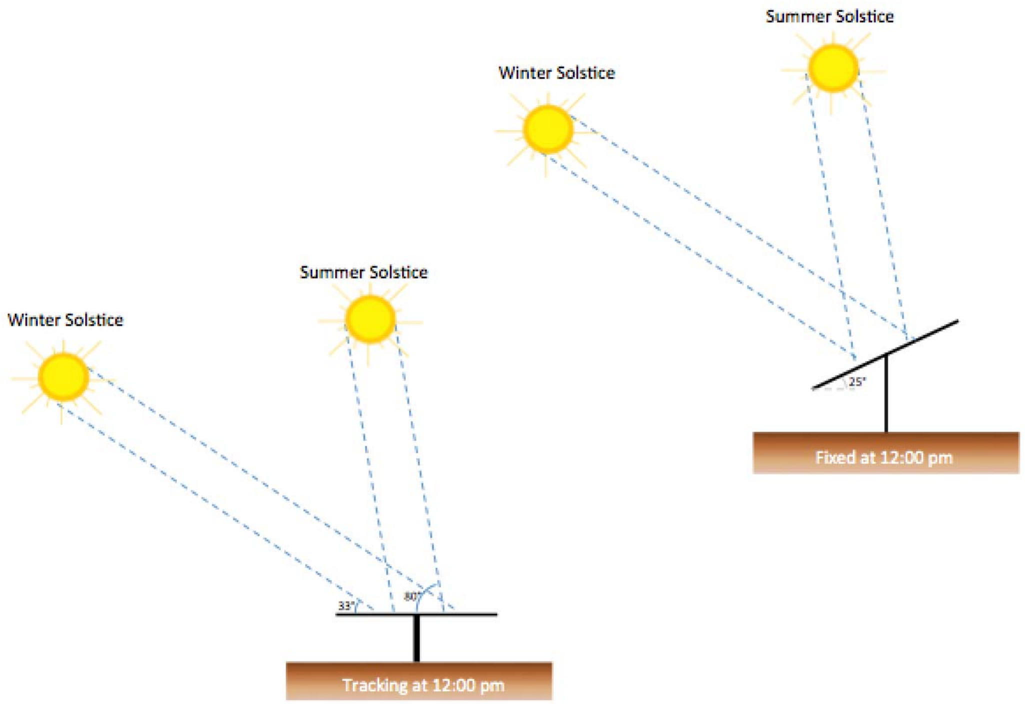

Figure 7. Solar radiation incident during summer and winter solstices.

Performance Results of Fixed and Tracking PV Systems

The Mann-Whitney test was conducted to compare the difference in energy generation between the fixed panels and the single-axis panels. The Mann-Whitney test is nonparametric and is used to test whether two independent samples of observations are drawn from the same or identical distributions. If the means of the ranks in the two groups are very different, the P value will be small.

For the months of April through August we can conclude that the populations are distinct. For the rest of the months there is no compelling evidence that the populations differ. Results are shown in

Table 4.

The results from the Mann-Whitney test can be corroborated after plotting the daily energy yield per panel each day of the month. We can see that during the colder months, the generation is fairly similar between fixed and tracking configurations, with the fixed panels generating slightly more (Figure 8). For the hotter months, the tracking panels generate significantly more electricity than the fixed panels (Figure 9).

Table 4. Mann-Whitney Test Results

Reported Energy							
Month	**Fixed, Wh/panel/day**			**Tracking, Wh/panel/day**			**Mann-Whitney, p**
	Median	**Mean**	**Std Dev**	**Median**	**Mean**	**Std Dev**	
January	1106.32	1057.06	573.54	1124.40	984.53	536.67	0.499
February	1196.15	1078.14	708.71	1141.85	963.57	674.57	0.507
March	1170.85	1295.52	714.67	1241.60	1461.59	863.03	0.181
April	1768.62	1502.70	571.92	2229.67	1840.68	803.62	0.015
May	1725.55	1617.90	430.67	2321.31	2128.87	684.70	<0.001
June	1627.16	1556.61	272.27	2236.15	2096.51	435.29	<0.001
July	1478.28	1411.95	304.58	1898.35	1815.11	516.55	<0.001
August	1628.88	1513.11	318.65	2161.55	1908.92	480.82	<0.001
September	1006.45	1008.90	456.78	1064.88	1145.76	578.94	0.404
October	1649.19	1616.18	284.09	1793.78	1717.07	330.16	0.086
November	1301.67	1113.47	586.43	1289.13	1066.10	564.09	0.446
December	828.99	886.76	552.00	735.58	796.31	499.58	0.272

In Table 5 we can better appreciate the difference in generation between fixed and tracking PV panels. The table depicts the percentage of total energy generation. The highest values have been shaded for easier understanding.

Table 5. Percentage Generation Comparison

Month	**Total energy generation for fixed panels (Wh)**	**Total energy generation for tracking panels (Wh)**	**% Total generation contributed by fixed**	**% Total generation contributed by Tracking**
January	32768.84	30520.30	51.78	48.22
February	30187.98	26979.96	52.81	47.19
March	40161.17	45309.24	46.99	53.01
April	45080.87	55220.27	44.95	55.05
May	50154.85	65994.83	43.18	56.82
June	46698.40	62895.37	42.61	57.39
July	43770.58	56268.40	43.75	56.25
August	46906.41	59176.65	44.22	55.78
September	30267.03	34372.88	46.82	53.18
October	50101.53	53229.25	48.49	51.51
November	33404.19	31983.01	51.09	48.91
December	27489.46	24685.73	52.69	47.31

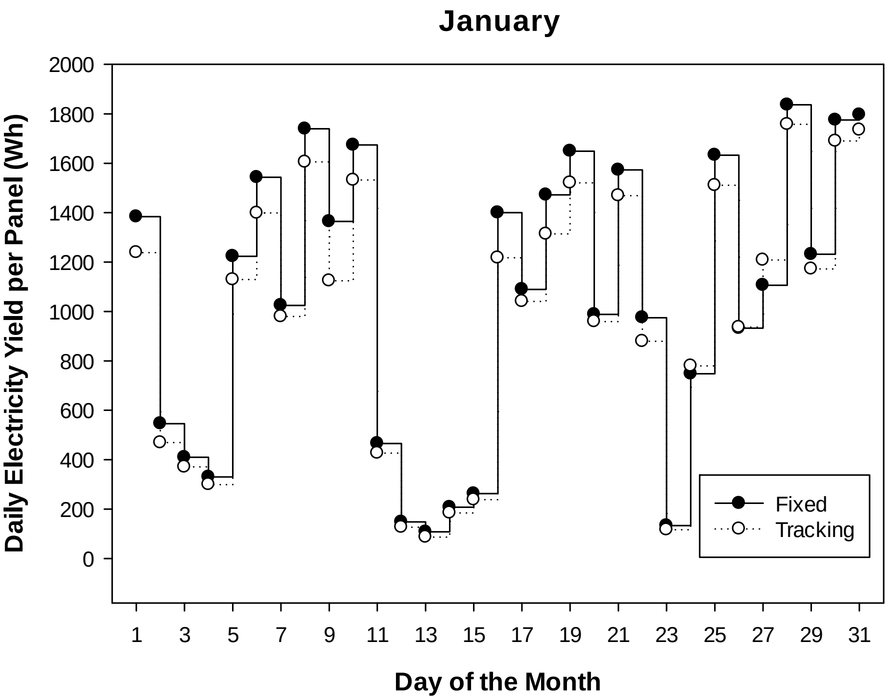

Figure 8. Daily electricity yield for January.

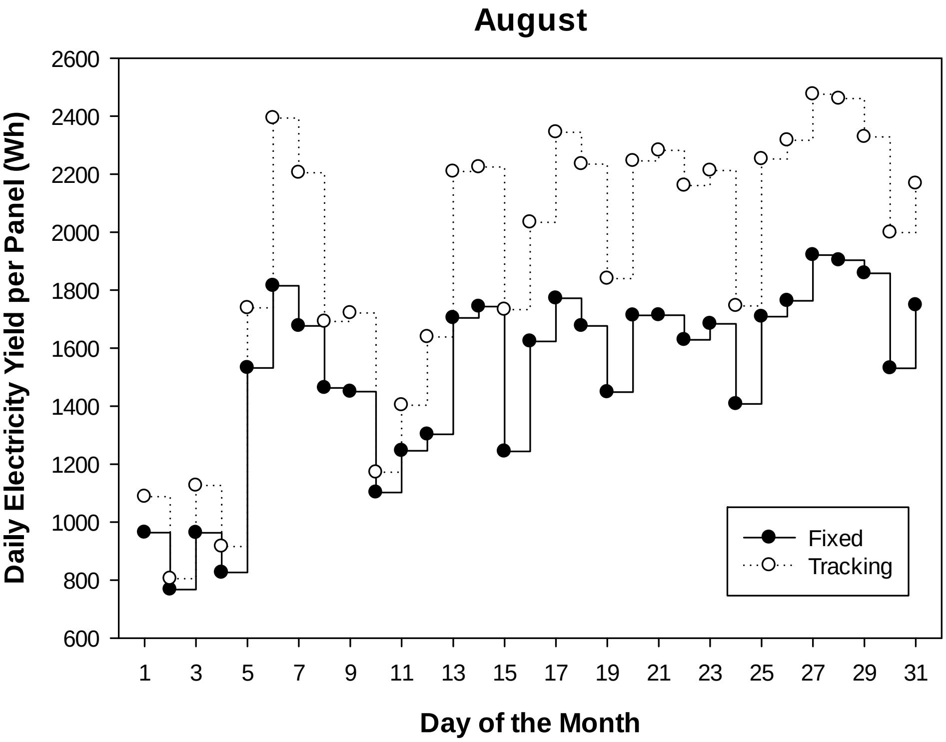

Figure 9. Daily electricity yield for August.

Peak Generation vs. Peak Demand

Analysis of peak coincidence between generation and demand is important to understand whether or not PV energy is going to be available when it is most needed. Hourly demand data reported by the South Carolina Public Service Authority (SCPSA) was used in the analysis. Data for the years 2006 to 2012 was averaged by month to determine average hourly demand.

The coincidence of peak power generation and the peak power demand on the grid varied seasonally and two distinct patterns were obvious. The colder months resembled the January profile, shown in Figure 10. One possible explanation for this trend is the use of domestic heating systems early in the morning, around 7 AM and at night, around 8PM. The hotter months resembled the August profile, shown in Figure 11. This trend reflects the constant use of air conditioning systems throughout the day during summer months.

The Spearman's Rank Order coefficient, ρ, was calculated to measure the correlation between total average PV power generation and demand on the grid. Spearman's rank correlation coefficient is a nonparametric measure of the statistical dependence between two variables that are not normally distributed. Spearman's coefficient, ρ, ranges between -1 and 1, with 1 indicating a strong negative correlation, 1 indicating a strong direct correlation, and 0 indicating no correlation. A strong direct correlation between power generated and electricity demand ($\rho>0.70$) suggests that peak PV power generation coincides with peak demand.

Table 6 summarizes the results for the test. A strong direct correlation can be observed in the summer months, from April to October, and almost no correlation is observed in the other months. This indicated that during the summer, PV energy is going to be delivered to the power grid when it is most needed and most expensive.

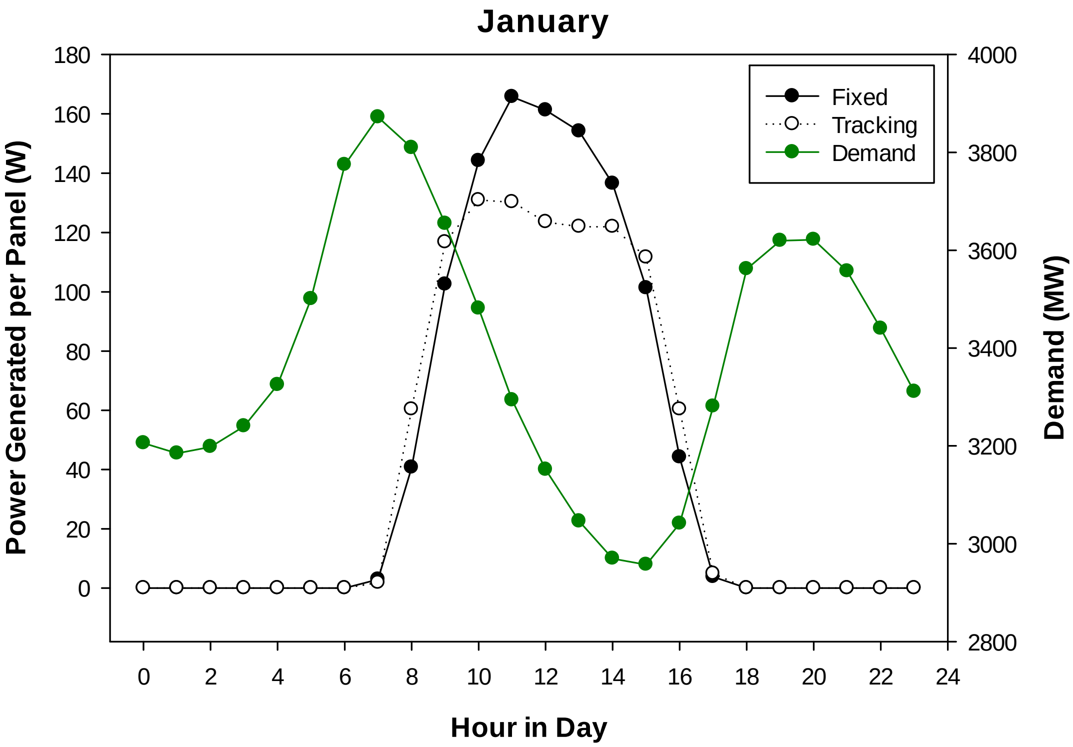

Figure 10. Power generated vs. Demand for January.

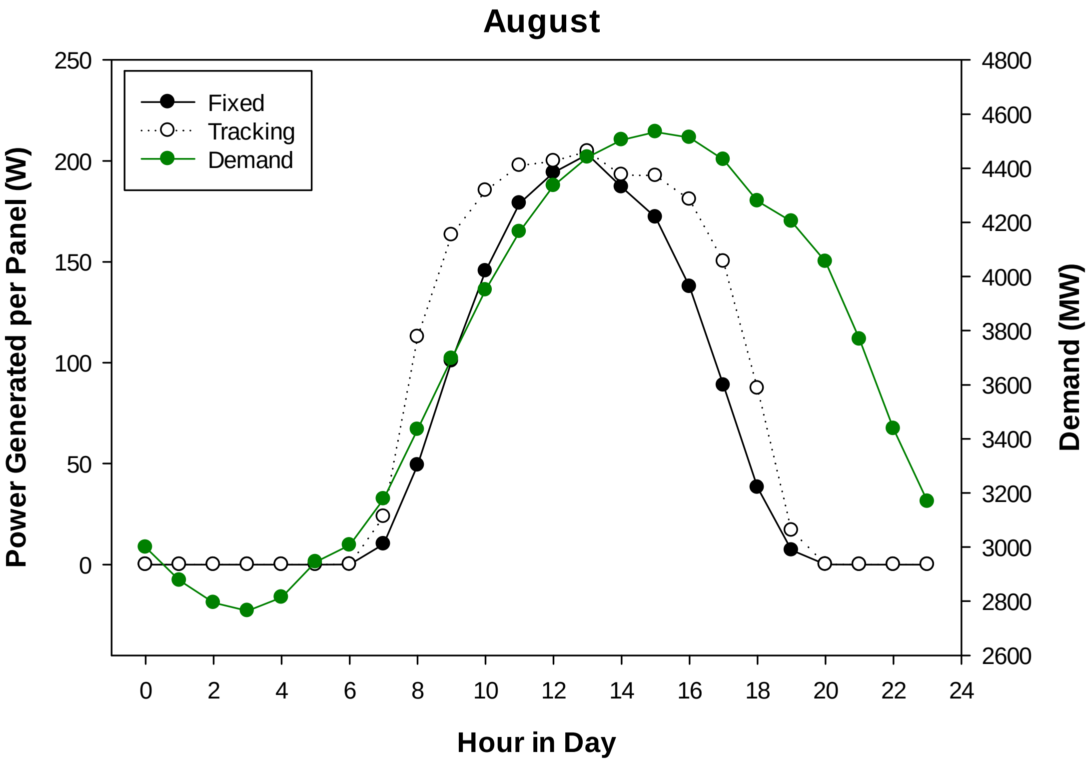

Figure 11. Power generated vs. Demand for August.

Table 6. Results of Spearman's Rank Order Correlation Analysis

Month	Spearman's rank order coefficient, ρ
January	-0.09
February	-0.18
March	0.30
April	0.70
May	0.82
June	0.85
July	0.87
August	0.87
September	0.83
October	0.75
November	0.27
December	-0.03

5. CONCLUSION

Overall, the single-tracking PV panels generated more electricity than the fixed axis panels. Two distinct patterns were observed, one for summer months and one for colder months. During the colder months (November to February) the fixed axis panels generated an average of 4% more electricity than the tracking panels. The single-axis tracking panels generated an average of 10% more electricity during the hotter months (March to October) than the fixed axis modules. One suggestion to improve the generation output of the tracking panels in wintertime is to tilt the panel at an optimal angle towards the south, this way the solar radiation incident would increase. During the summer months, peak electricity generation coincides with peak electricity demand on the grid. This makes this renewable source of energy more valuable since it aids the grid when the electricity cost per kWh is more expensive to generate.

6. REFERENCES

Eke, R., & Senturk, A. (2012). Performance comparison of a double-axis sun tracking versus fixed PV system. *Solar Energy* (86), 2665-2672.

International Energy Agency. (2013). *Photovoltaic and Solar Forecasting: State of the Art.* IEA-PVPS.

Honsberg, C., & Bowden, S. (n.d.). *Solar Radiation on a Tilted Surface*. Retrieved September 29, 2015, from PV Education: http://www.pveducation.org/pvcdrom/properties-of-sunlight/solar-radiation-on-tilted-surface

Nichols, R. L., Kohn, J. L., & Boessneck, E. (n.d.). Variability of the wind shear profile on the coast of South Carolina, USA. *Renewable Energy an International Journal* .