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Solar photovoltaic energy production comparison of east, west, south-facing and tracked arrays

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ABSTRACT The energy production of east, west, and south facing solar photovoltaic (PV) modules were measured over two years at the Renewable Energy Learning Center in Vermilion, Alberta. The east and the west PV modules were tilted at an angle of 17.5° versus 68° for the south facing module. The results showed that the south-facing modules produced approximately 35% more energy annually than the east or west-facing modules. However, during the months of May, June and July the east/west facing modules out-produced the south-facing module. Energy production of each orientation was comparable to estimations using popular PV performance prediction software.

At the same site, a 5 kW fixed–mount array was compared to an electrically identical, two-axis tracked array. The tracking array produced approximately 31% more energy than the fixed mount annually. The difference was less when the fixed array was seasonally adjusted. The tracked array always produced more energy than the fixed mounted array but the differences were more profound during the summer season. Both of these studies have implications for the design solar photovoltaic systems used in rural locations or mounted on agricultural buildings.

Keywords: Solar Photovoltaic, Micro-generation, Solar Tracked

INTRODUCTION As part of the research in solar photovoltaic systems conducted at Lakeland College's Renewable Energy Learning Center, the energy generation of solar PV modules installed at different orientations on the roof was measured. The objective of the experiment was to determine the difference in energy production between a south facing module set at an optimal tilt angle (latitude+10°) and east, west facing modules set at angle typical of most residential roofs. In this experiment, the tilt angle for the south facing module was 67.95° which was slightly higher than optimal tilt angle of 63° for the latitude of Vermilion, Alberta. The tilt angle for both the east and west facing modules was 17.5° which represents a 4:12 roof slope.

A second experiment was conducted between a fixed solar PV array and dual-axis tracking array of similar size. The fixed solar array was initially set at tilt angle of 53.3° (latitude) and the dual-axis tracking solar array's orientation and tilt angle varied according to the sun's position. Appendix A contains an overhead photo of the Renewable Energy Learning Center showing all the PV systems.

MATERIALS AND METHODS There were 5 identical modules installed on the roof, two on the east facing side, two on the west facing side and one on the south facing side. The type of modules installed were Conergy PH 230P with a rated power of 230W and module efficiency of 14% under standard test conditions.

Arrays of Conergy PH 225P solar modules were used for the fixed vs. dual-axis tracking systems. The fixed array was comprised of two individual PV strings of 12 solar modules, for a total of 24 solar modules. The dual-axis tracking array consisted of an array of 24 solar modules also made up of two 12-module series strings. Both fixed and dual-axis tracking arrays had a rated power of 5400W each driving a 5000W grid-tie inverter. A.C. power output was truncated to 5000W by the inverter.

RESULTS AND DISCUSSION

ENERGY PRODUCTION OF ROOF PV MODULES The energy generated from the PV modules was calculated for each month and the results are summarized below. The data for the 2 west side panels and the 2 east side panels were averaged together.

Table 1: Energy production for south, west, and east side PV modules for each month in 2014 given per module.

	Energy Production (kWh)			Energy Production Relative to South PV Module (%)	
Month	South PV Module	West PV Module	East PV Module	West PV Module	East PV Module
January	18.9	3.5	4.6	18.7	24.1
February	23.0	2.6	3.6	11.2	15.5
March	39.9	19.2	18.2	48.0	45.6
April	27.0	24.4	24.5	90.6	90.8
May	29.1	32.0	33.7	110.0	115.8
June	24.5	30.6	30.7	125.0	125.7
July	32.2	37.9	37.0	117.6	114.8
August	30.1	29.9	30.3	99.3	100.6
September	26.8	19.3	21.5	72.0	80.4
October	26.7	13.1	13.9	48.9	52.1
November	13.0	2.1	2.3	15.9	17.5
December	9.1	1.5	1.7	16.8	18.9
Annual	300.2	216.0	222.0	72.0	73.9

During the winter and fall months much more energy was generated by the south facing modules than the west side and east side facing modules. This difference was partially due to the fact that snow stays on the east/west PV modules longer. The steeper tilt angle of the south module caused snow to slide off. However, the main reason for the higher production was because the tilt angle of the south facing module was steeper. During the winter/fall when the sun was lower in the sky the sun's rays strike the module at an incidence angle closer to zero. The incidence angle is defined as the angle between the sun's rays and a line perpendicular to the module surface. (Dunlop, 2010).

The best performance from the PV module occurs when the sun's rays strike the module at an incidence angle of 0° and the performance declines the further it deviates from this (Honsberg & Bowden, Motion of the sun, 2015). When the sun's rays are at an incidence angle of 0° to the module, the sun's energy is concentrated upon the smallest possible surface area on the module. However, when the sun's rays strike the module on an angle the sun's energy is spread out over a larger surface area which reduces the solar intensity (Bowden & Honsberg, 2015).

During the summer months the energy production was greater on the east and west facing modules because the solar elevation was higher in the summer favouring the shallower tilt angle of the east and west facing modules. Overall, the west PV module produced 72% of the energy generated by the south facing module which represented a 39% increase in production for the south module over the west facing module. Similar values are found when comparing south facing vs. the east facing module

Actual Energy Production vs. PV Watts Simulation A simulation was conducted using PVWatts Calculator on the National Renewable Energy Laboratory website for the south, east and west facing modules (National Renewable Energy Laboratory, 2015). For the south facing modules and the east/west facing modules the system losses were calculated to be 5.39% and 6.82%, respectively. The solar radiation data used for the simulation was obtained from typical metrological year data set for Edmonton, Alberta. Unfortunately, this data was not available for Vermilion, Alberta but the differences between the two were minor since they were located at similar latitudes. The comparison between actual and predicted energy production for all the roof modules is shown below:

Table 2: Table below shows the actual solar energy produced by the south, east, and west facing module vs. the energy predicted by the PV-Watts Simulation. The actual energy output is also reported as a percent of the predicted output.

	South Facing Module			East Facing Module			West Facing Module		
	Predicted	Actual	% Difference Between Actual and Predicted	Predicted	Actual	% Difference Between Actual and Predicted	Predicted	Actual	% Difference Between Actual and Predicted
Month	kWh		%	kWh		%	kWh		%
Jan.	22	18.9	86.0	7	4.5	65.0	7	3.5	50.5
Feb.	27	23.0	85.3	12	3.6	29.8	12	2.6	21.5
March	37	39.9	107.9	24	18.2	75.9	24	19.2	79.9
April	30	26.9	89.8	27	24.5	90.6	27	24.4	90.4
May	30	29.1	97.0	33	33.7	102.1	33	32.0	97.0
June	29	24.4	84.3	34	30.7	90.4	34	30.6	89.9
July	29	32.2	111.1	33	37.0	112.1	33	37.9	114.9
Aug.	29	30.1	103.9	29	30.3	104.5	29	29.9	103.2
Sept.	25	26.8	107.0	20	21.5	107.6	20	19.3	96.3
Oct.	25	26.7	106.9	13	13.9	107.1	13	13.1	100.4
Nov.	18	12.9	71.9	7	2.3	32.4	7	2.1	29.4
Dec.	13	9.1	69.8	5	1.7	34.3	5	1.5	30.6
Annual	314	300.2	95.6	244	222.0	91.0	244	216.0	88.5

The simulation accurately predicted the amount of energy produced by the south facing module. For the annual energy production the simulation predication was only 4.4% greater than the actual energy production. The simulated energy production was accurate, but to a lesser extent for both the east and west side facing modules with the simulation predicting 9% and 11.5% greater production, respectively. It is hypothesized that the reason for the less accurate prediction of the east and west facing modules was due to snow cover. Even though this factor was taken into account for the system loss calculation, it may have been under-estimated in the simulation.

Daily Power Production The power generation was measured for each of the solar modules over the duration of the day to observe how their output differed seasonally. The graphs below show the difference in power generation of the east, west, and south modules over a day in the winter and in spring (Figures 1 and 2).

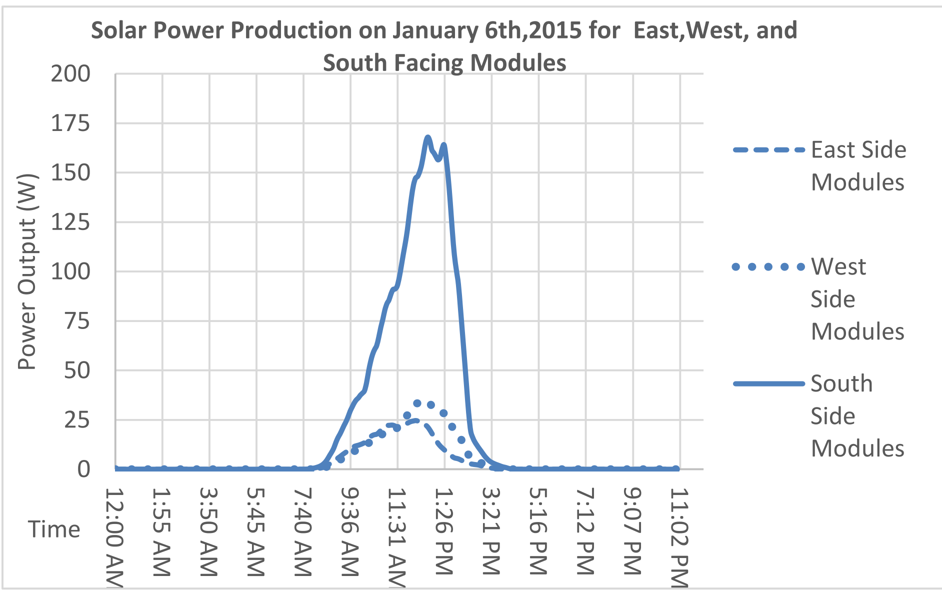

Figure 1: Power production of east, west, and south facing modules on January 6th, 2015

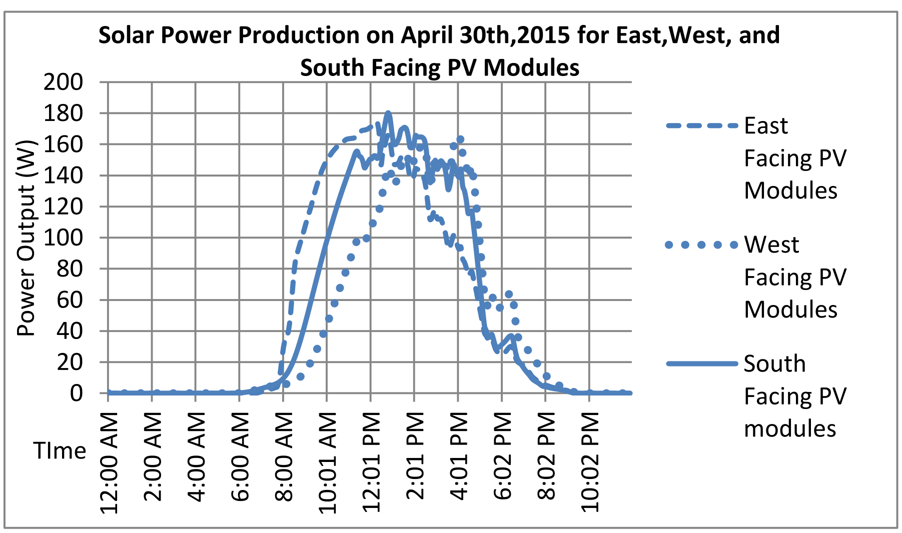

Figure 2: Power production for east, west, and south facing modules on April 30th, 2015

Figure 2 shows the south side modules produced considerably more power than the east or west side facing modules on January 6th, 2015. The reasons for this were already discussed in the previous section. During the winter each module started and stopped producing power about the same time of day due to the small variations in solar azimuth. During the winter months, the solar azimuth, the compass direction in which sunlight is coming from, is different than during the summer months. The sun does not rise exactly due east but actually south of east and sets south of west (Honsberg & Bowden, Azimuth angle,2015). During the spring months the sun will rise further to the east and set further to the west than during the winter months. As a result, the east side modules produced more power than the other modules at the beginning of the day and conversely the west side panels produced more power at the end of the day (Figure 2). A sun path diagram for Vermilion, Alberta that shows the changes in solar elevation and solar azimuth throughout the year is contained in the appendix A.

Energy Production of Fixed and Dual Axis Tracked Arrays The energy production for both the two solar fixed arrays as well as dual-axis tracked array were measured for the year 2013 and summarized on a monthly basis. The results are shown in the table below:

Table 5: Monthly energy generation for fixed solar array and dual-axis tracking array stated in kWh and percent increase. The net tracked generated was the tracker energy generated less the energy consumption of the tracker drive motor

	Energy Generated (kWh)			Energy Consumed (kWh)	Percentage Increase (%)	
Month	Fixed PV Array	Tracked PV Array	Net Tracked PV Array	Tracker Drive	Tracked over Fixed	Net Tracked over Fixed
January	347.7	375.4	371.4	4.0	8.0	6.8
February	443.5	487.4	483.7	3.6	9.9	9.1
March	907.9	1029.5	1025.3	4.1	13.4	12.9
April	872.7	1114.6	1110.4	4.2	27.7	27.2
May	925.1	1415.2	1410.8	4.4	53.0	52.5
June	657.4	1024.0	1019.7	4.3	55.8	55.1
July	884.6	1372.0	1367.6	4.5	55.1	54.6
August	823.8	990.4	986.1	4.3	20.2	19.7
September	828.9	1075.6	1071.5	4.1	29.8	29.3
October	560.8	661.5	657.3	4.3	18.0	17.2
November	256.6	332.6	328.7	3.9	29.6	28.1
December	211.8	270.0	266.1	4.0	27.5	25.6
Annual	7720.7	10148.1	10098.6	49.5	31.4	30.8

In every month the dual-axis tracked array outperformed the fixed array. Over the entire year the tracking array produced 31.44% more energy than the fixed array. The consumption of the motor on tracker had a negligible impact on the differences in energy production, reducing the percentage advantage by less than 1%. The production advantage of the tracker over the fixed array is more pronounced during the months of May, June, and July because the variation in solar elevation and solar azimuth is more than in the winter months. The variation in sun path is described by the chart in appendix A. The tracking array can compensate for changes in azimuth and elevation whereas the fixed array cannot. Correspondingly, during the months of January and February the differences in energy production between the fixed and tracked arrays are smaller because the solar azimuth and elevation do not change drastically over the course of a day.

Energy Production of Seasonally Adjusted, Fixed and Tracked PV Arrays A second experiment was conducted between March 21st, 2014 to March 21st, 2015 in which the fixed PV array tilt angle was adjusted to optimize production for the winter and summer season. Between March 21st to October 7th, 2014 the tilt angle was set to 41.6° and from October 7th,2014 to March 21st,2015 was set to 64.6°. The results of the experiment are shown below:

Table 6: Monthly energy generation for fixed seasonally adjusted solar array and dual-axis tracking array and the percentage increase in energy production of the tracking array over the fixed array. The net tracked generated was the tracker energy generated less the energy consumption of the tracker drive motor

	Energy Generated (kWh)			Energy Consumed (kWh)	Percentage Increase (%)	
Month	Fixed (kWh)	Tracked (kWh)	Net Tracked (kWh)	Tracker Drive (kWh)	Tracked over Fixed	Net Tracked over Fixed
March 21st-March 31st	335.1	423.8	422.2	1.6	126.5	126.0
April	693.0	892.1	887.7	4.4	128.7	128.1
May	815.4	1083.3	1078.7	4.6	132.8	132.3
June	710.3	983.0	978.7	4.4	138.4	137.8
July	906.3	1280.4	1276.1	4.3	141.3	140.8
August	803.4	1043.3	1039.0	4.2	129.9	129.3
September	653.3	845.1	841.0	4.1	129.4	128.7
October	619.8	735.2	730.9	4.2	118.6	117.9
November	275.9	263.2	259.2	4.0	95.4	93.9
December	256.1	249.6	245.5	4.1	97.5	95.8
January	440.4	459.6	455.6	4.0	104.3	103.4
February	496.1	529.4	525.8	3.6	106.7	106.0
March 1st-21st	582.1	674.1	671.4	2.7	115.8	115.4
Annual	7587.2	9462.0	9411.8	50.2	124.7	124.0

Over the entire year, the tracking array produced 24.7% more energy than the seasonally adjusted fixed array which is much lesser than the 31.4% change between the tracking array and fixed array production output observed in 2013. Also, during the months of November and December the fixed PV array energy production was actually greater than the tracking array. This anomaly was likely due to the vertical mechanical stops on the tracking array not allowing the array to reach an angle optimum for winter. The results of this analysis suggest seasonally adjusting the fixed modules reduces the differences in energy production between the tracking and fixed arrays.

PV Watts Simulation As with the solar roof experiment, the energy production for both tracking and fixed arrays was compared to a prediction using PV Watts. The system losses were assumed to be 5.39%.The results are shown in a table below:

Table 7: Monthly/annual simulated and actual energy production for 2013 for both fixed PV array and tracking array and percent of prediction actually achieved

	Tracking Array			Fixed Array		
	Predicted	Actual	Difference between Actual and Predicted	Predicted	Actual	Difference between Actual and Predicted
Month	kWh		%	kWh		%
January	528.5	375.4	71.0	449.7	347.7	77.3
February	691.6	487.4	70.5	581.5	443.5	76.3
March	1033.9	1029.5	99.6	814.4	907.9	111.5
April	973.2	1114.6	114.5	706.7	872.7	123.5
May	1165.8	1415.2	121.4	748.1	925.1	123.7
June	1148.6	1024	89.2	731.7	657.4	89.8
July	1132.4	1372	121.2	720.4	884.6	122.8
August	1020.8	990.4	97.0	709.2	823.8	116.2
September	761.7	1075.6	141.2	584.8	828.9	141.7
October	667.9	661.5	99.0	549.7	560.8	102.0
November	434.7	332.6	76.5	378.4	256.6	67.8
December	310.1	270	87.1	269.6	211.8	78.6
Annual	9869.1	10148.2	102.8	7244.3	7720.8	106.6

As with the solar roof experiment, the PV Watts simulation accurately predicted the energy production for both the fixed and tracking PV arrays. The simulation predicted the tracking production as well as actual production within 2.8% and 6.6%, respectively.

CONCLUSION 5.0 The south facing PV module at a tilt angle 67.9° produced significantly more energy over the course of the year than the west and east side modules. The west and east side modules produced only approximately 70% of the energy of the south facing module over the course of the year. However, the east and west modules produced more power during the summer months when the relatively high sun elevation favored the tilt angle of the east and west facing modules. During the winter months the sun's elevation favored the tilt angle of the south facing module. The PV-watts simulation accurately predicted the energy generation of the south facing modules and to a lesser extent the east/west facing modules. The reasons why east/west facing modules predication were not as accurate as the south facing module is hypothesized to be due to the fact that there was snow covering these modules during the winter season and the system losses due to snow cover were not properly taken into account for the system loss calculation.

Depending on the time of year, there was a phase shift in the time in which each module started and stopped producing power over the course of a day. During the winter months this phase shift is practically indistinguishable because the change in solar azimuth was minimal over the course of a day. However, this phenomenon was more evident during the spring/summer months with the east producing and ceasing power generation earlier than the south and west modules. This occurs because the change in solar azimuth over a day is more marked than during the spring/summer months.

Over the entire year the solar tracking arrays produced 31% more energy than the same-sized fixed array. However, when the fixed PV array's tilt angle was adjusted seasonally, the tracking array produced only 24.7% more energy than the tracking array. This suggests that seasonally adjusting the fixed PV array increases energy production over a regular fixed mount and reduces the difference in performance between the tracking and fixed arrays.

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APPENDIX A

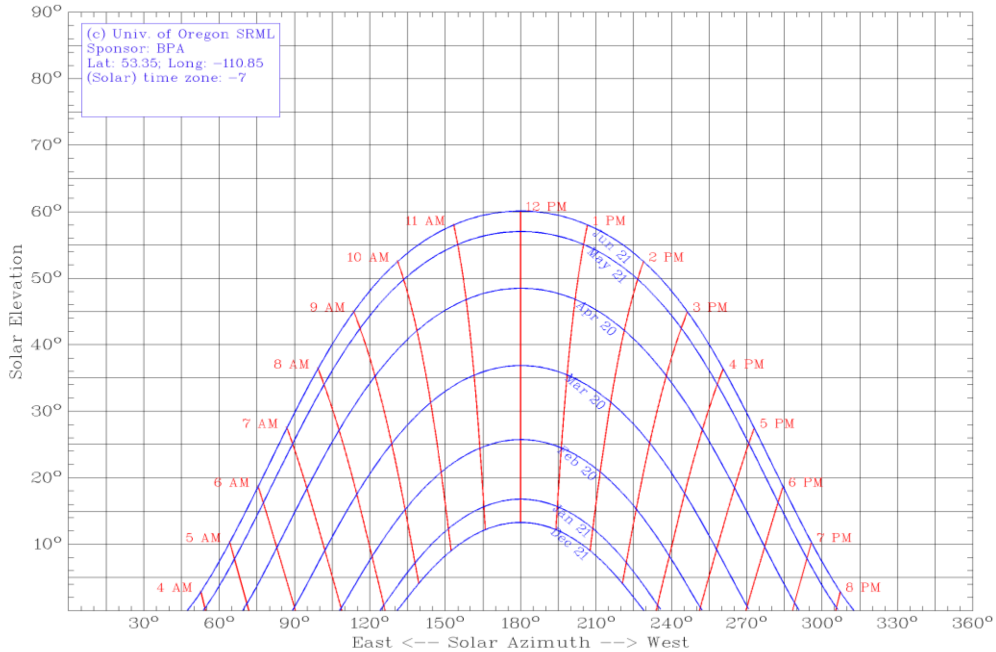

Figure 3: Sun path diagram for Vermilion, Alberta from December 21st to June 21st

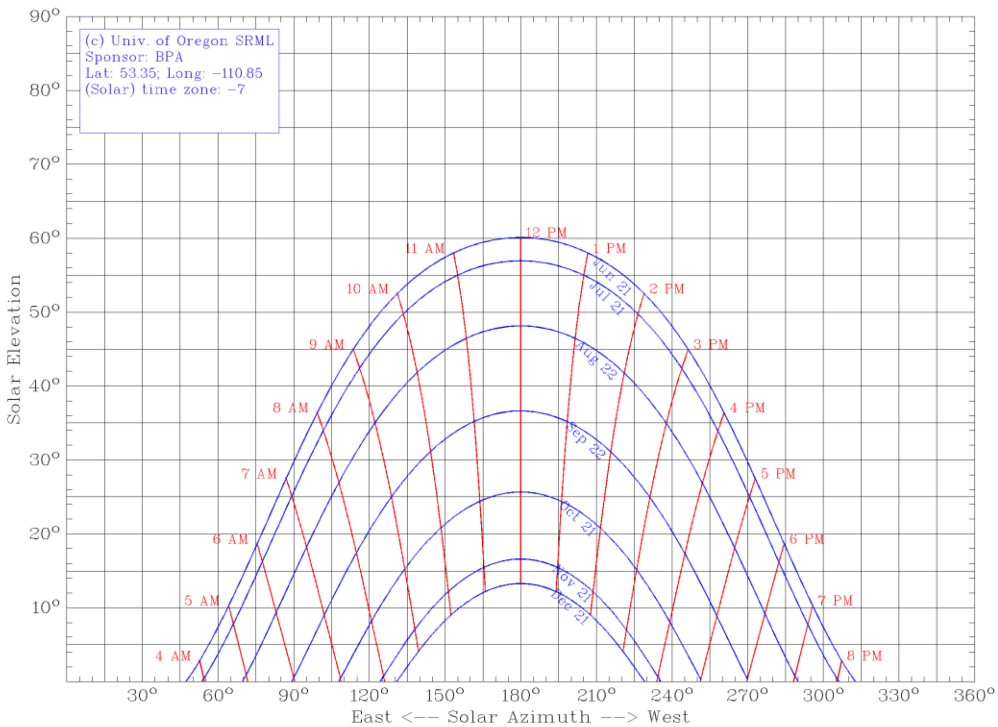

Figure 4: Sun path diagram for Vermilion, Alberta from June 21st to December 21st
(University of Oregon Solar Radiation Monitoring Laboratory, 2015)

Figure 5: Overhead shot of the RELC facility depicting all of the solar PV systems