Experimental Analysis of an Optimal Angle of Inclination for Solar Photovoltaic Systems in Blantyre District, Malawi

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Abstract

The tilt angle of a Solar Photovoltaic (SPV) panel plays an important role in determining the performance of SPV System. In this paper, an optimal angle of inclination for SPV system was analysed through an experimental investigation in five sites within Blantyre district from the year 2022 to 2023 during the months of October to December. In the experiment, the SPV module was set at a 0°, 5°,10°,15°,20°,25°,30°,35°,40°,45°,50° and 55° angles, facing due north. At each angle, short circuit current and open circuit voltage was measured simultaneously, using two digital multimeters, one for measuring short circuit current and the other for measuring open circuit voltage. It was observed that during the months of October, November and December, higher power output values were recorded between 0° to 15° and during this period, the optimum angle was found at 15° due north which also provide some room for self-cleaning of the module. Analysis of Variance (ANOVA) was used to test the mean difference in power output between solar modules exposed at the same angle of orientation in all experimental sites. Alpha value for power output was 0.019 and it was observed that there was no significant variation in power output of solar modules exposed at the same angle of orientation in all sites within Blantyre district. It was concluded that there is no significant difference in power output between solar PV modules installed in different sites within Blantyre district, if they are installed at the same angle of orientation. It is therefore, recommended to install SPV modules at an angle of 15° due north in Blantyre district, during the months of October, November and December.

Keywords: Solar photovoltaic, Tilt angle, Optimum angle, Open circuit voltage, Short circuit current

1.0 Introduction

Energy performance is one of the key pillars in ensuring inclusive and sustainable economic growth across the globe (Ahmad & Zhang, 2020). There are five major renewable energy sources namely; Solar energy which is harnessed from the sun, geothermal energy from heat inside the earth, wind energy, biomass from plants and hydropower from waterflow (Ang et al., 2022). Amongst these sources, biomass is an important fuel, mostly in developing countries like Malawi, for cooking and heating, especially in rural areas where 95% the people are not connected to the grid (Jagger et al., 2022). However, the increase in population has accelerated to the damage of the environment through unsustainable use of natural resources such as wanton cutting down of trees for firewood (Ngwira & Watanabe, 2019).

Solar Photovoltaic systems are becoming more popular. However, PV Systems that are not properly maintained and optimised do not generate sufficient energy and therefore, do not meet customers' expectations (Bhavna, 2022). This gives the impression that solar energy is not reliable and sustainable. Another problem is that most of unqualified PV system installers have limited technical capacity, especially on technical know-how of solar PV Systems (Wyllie et al., 2018).

An efficient Solar Photovoltaic system plays a major role, especially in very remote areas and to the low-income communities that are not connected to the electricity grid. Using solar PV System, people can always be connected and in control, thus making life much easier as they could perform many domestic chores even at night. By using solar powered lights, students can be able to study till late at night and therefore, improve their performance at school. Furthermore, solar PV systems can help to empower people economically through the running of small businesses such as, charging cell phones, barber shops, video shows and internet cafes, amongst others. Solar powered lights protect people from harmful sources of lighting such as candles and paraffin. These produces toxic smoke which may cause lung related diseases. The main objective of this study was therefore, to analyse an optimal angle of inclination for solar PV Systems in Blantyre district, Malawi.

The tilt angle of the PV module is the measure of the

angle between a module and a horizontal surface; representing the x direction, or the measure of the angle between the module and a vertical surface representing the y direction (Mamun et al., 2021). Hassan et al (2021), evaluated the optimum tilt angle by searching for maximum values on clear sky conditions in Iraq using a numerical optimization process. The results showed that the optimum tilt angle decreased to 0^0 in July and the maximum was 64^0 in December. They concluded that the optimum tilt angle increased during winter and decreased during summer.

A very similar study was conducted by (Muslim, 2019) in Iraq where Matrix Laboratory (MATLAB) R2014 software was used to estimate the optimum tilt angle and the hourly solar radiation on tilted surface. Najaf City, California and New Delhi were used as case studies and their results showed that the annual optimum tilt angle is approximately equal to the location latitude in which the solar system is set up. They concluded that the optimum tilt angles for summer months' ranges between 0° and 30°, with 30° to 60° in winter months. Though Hassan et al (2021) illustrated that the optimum tilt angle varied between 0^0 and 64^0 and that some areas in the southern part of Iraq have lower tilt angle than the northern part, they went further to compare their results with Muslim (2019), who concluded that the annual optimum tilt angle is approximately equal to the location latitude in which the solar system is set up. They reported that using the determined latitude generated some loss values for the incident solar radiation, and this value varied from one region to another. The highest loss was recorded in the western part with 0.38% to 0.42%, whereas the eastern part showed loss values from 0.12% to 0.16%.

Another study was conducted by Chinchilla et al (2021) who used several models for computing the annual optimum tilt angle for fixed solar photovoltaic arrays or solar collectors, in many locations of the world. Irradiance data from two public databases (Energy Plus and BSRN) comprising of 2603 sites from around the world was used. It was shown that, while the results are relatively consistent when considering each dataset independently, it is more convenient to combine them in order to get accurate results.

Ullah et al (2019) investigated optimal tilt angles and effects of Soiling on PV energy production in Pakistan through both simulation and outdoor experimental investigation. In outdoor experiment, five PV panels adjusted at different tilt angles were used to find the optimum tilt angle for a given day. The short circuit current and open circuit voltage of PV panels were simultaneously measured after every 15 minutes. The experimental results were found to be in close agreement with the simulated results with the recommendation that fixed solar panels need to be adjusted frequently. The more frequently the PV panel is adjusted, the more it harvests the energy.

Solar PV modules work best when their surface is perpendicular to the sun rays (Abdallah et al., 2020). However, that task is compromised by the rotation and the revolution of the earth (Ihaddadene et al., 2017). To attain maximum power output, there is need to find the best angle for mounting of solar panels. Handoyo et al (2013), explained that the tracking system is the best way to use when we want to achieve the optimum tilt angle. However, this system requires energy input for its operation and is also very expensive to low-income households. This is the reason why fixed PV Systems are commonly used during installations. Kamanga et al (2014), conducted a similar study using Global Solar Radiation (GSR) data to find the daily and monthly optimum tilt angles for PV modules. They found out that the optimum tilt angle was 0^0 between October and February while from March to September, the optimum angle was 25^0. They concluded that fixed solar panels with no seasonal adjustments in Zomba, Malawi, should be installed at 25^0, facing north.

Though many studies have been done on optimum angle for PV systems, Malawi is one of the countries that has received much little attention in this field of study except for a few such as Kamanga et al (2014), and Mafuta et al (2017). Jacobson & Jadhav (2018) provided estimates of photovoltaic (PV) panel optimal tilt angles for all countries worldwide under National Renewable Energy Laboratory's PV Watts program. Solar resource and wind speed data from a nearby meteorological stations were combined from a specific location with 30 years of historic temperature to find annual optimum tilt angle. Some of Malawi's neighbouring countries which were included are Zambia, Zimbabwe, Tanzania and South Africa. However, Malawi was left out in the program. It was therefore important to conduct this study in order to find optimum tilt angle for Blantyre district, Malawi.

2.0 Materials and Methods

2.1 Description of the Study Area

The study was carried out within Blantyre district in the following areas: Mpemba, Bangwe, Mapanga, Chileka and Chilomoni from the year 2022 to 2023 during the months of October to December. In Mpemba, experimental investigation was carried out at Mafunde Primary School ground which is located 400m off the main road from Ziboda stage, opposite Escom Training Centre. It is on the south of latitude 15°53'27" and to the east of longitude 34°58'35".

In Bangwe, experiments were done at Bangwe Primary School Campus, located on the south of latitude 15°49'30"and to the east of longitude 35°05'18" (GPS Receiver). In Mapanga, experiments were done at Mapanga Prison ground, located on the south of latitude 15°45'29" and to the east of longitude 35°05'48" (GPS Receiver). In Chileka, experiments were conducted at Chileka Police ground behind Chileka Police Station, located on the south of latitude 15°41'06" and to the east of longitude 34°57'59". (GPS Receiver). In Chilomoni Township, experiments were conducted at Mary Queen of Peace Primary School ground within Beehive Campus. Beehive is located on the south of latitude 15°77'59"and to the east of longitude 34°97'56". Figure 1 shows sites of experimental investigation within Blantyre district.

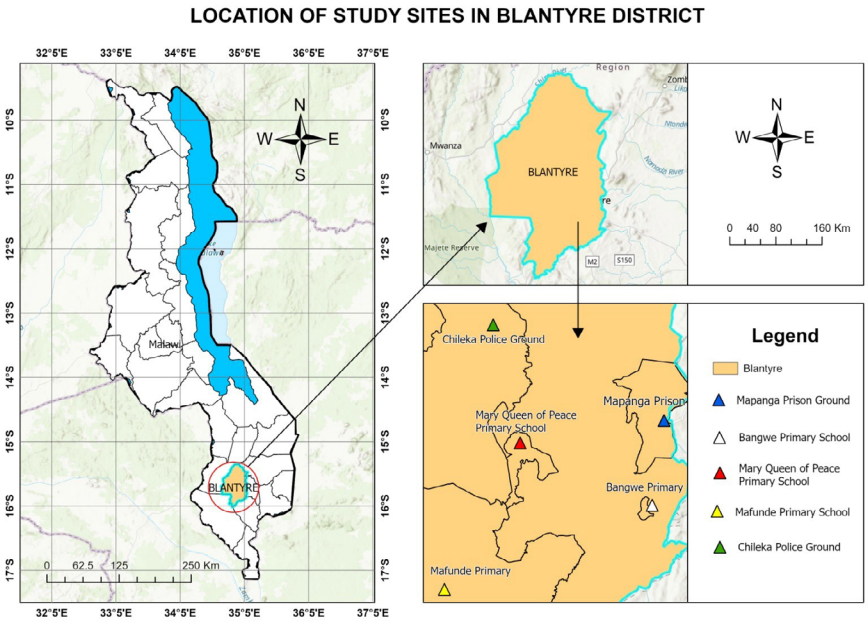

Figure 1: Experimental sites within Blantyre district

Each experimental site had two working stations named station A and station B. Both stations used solar modules of the same specifications, to avoid variations in the power output. They were set at a distance of 2 meters apart for referencing during experiment. In this case, both modules were exposed to same weather conditions and thus expected equal output. Figure 3 shows station A and B before setting up the experiment.

In the year 2022, experiments were done from 3rd October to 30th December while in 2023, experiments were done from 2nd October to 29th December. These experiments were not conducted on Saturday and Sundays and all public holidays. All experiments, started from 9am to 3pm. In all sites, V_{OC} and I_{SC} were measured at the same time from both stations and average readings were recorded.

During the experiment, V_{OC} and I_{SC} was measured simultaneously with other sites and on the same days. This was done in order to find out whether values at a site, would provide an optimum angle that is different from other experimental sites within the same months. Another reason was to find out if the mean difference between solar modules exposed at the same angle of orientation in all sites would be significant.

Table 1: Equipment Description

Parameter	Value
Maximum Power (P_{max})	100W
Open circuit Voltage (V_{oc})	22.1
Rated Voltage (V_{mpp})	18.2
Short circuit current (I_{sc})	6 A
Dimension (mm)	1005 x 665 x 30
Number of Cells	36
Weight (Kgs)	7.6

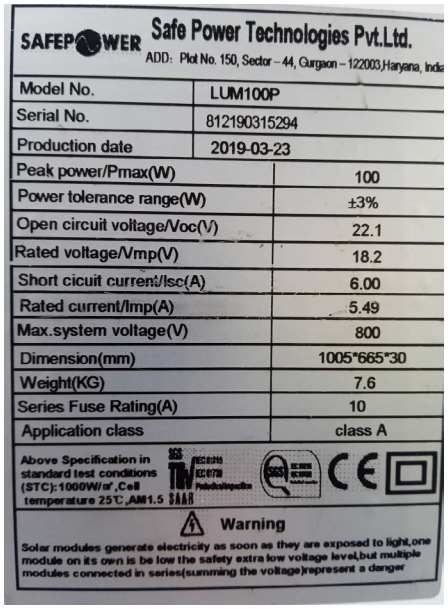

Figure 2: Specifications of PV Module



Figure 3: Experimental Setup

The PV module stand was fabricated using angle Iron to provide a strong supporting structure and later calibrated from 0 to 55 degrees with a 5-degree angle difference as shown in figure 3. During the time of experiment, the module was set at 0° at each working station where short circuit current and open circuit voltage was measured at the same time, using two digital multimeters: one for measuring short circuit current and the other for measuring open circuit voltage. The average readings were recorded. This trend continued up to 55 degrees. Figure 4, shows measuring instruments which were used in the experiment.

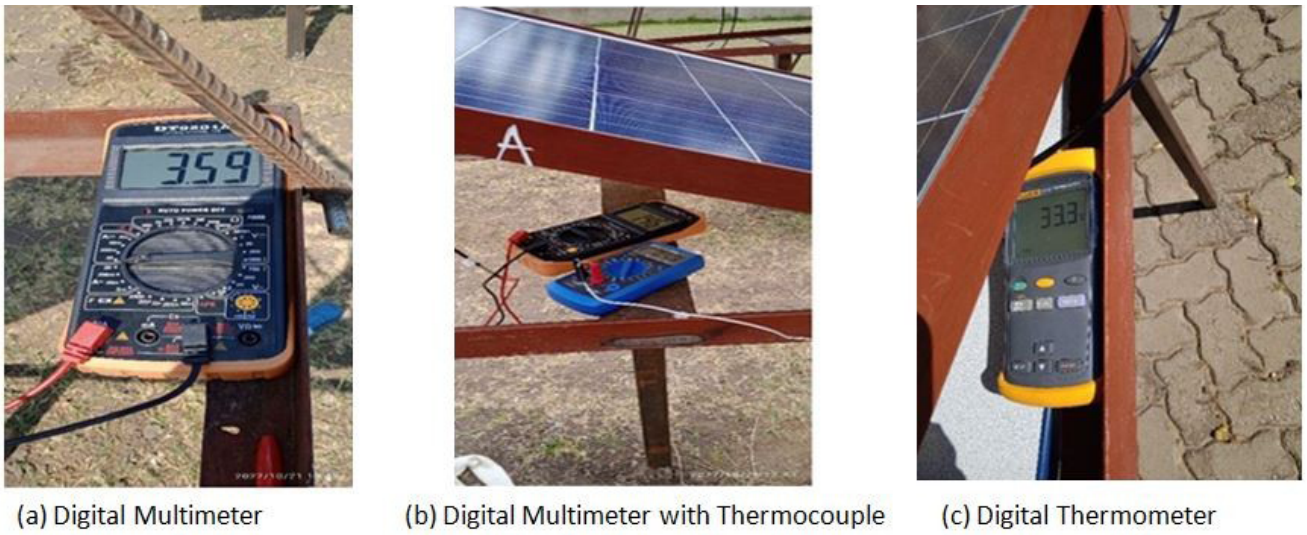

Figure 4: Measuring Instruments

Two digital multimeters were used at each station in order to get readings of both V_{OC} and I_{SC} of both stations at the same time. In an outdoor experiment, variables such as wind speed, temperature and insolation can change anytime which can also affect V_{OC} and I_{SC} output. This can affect experimental outcome if they are being recorded separately. After taking the readings, the average V_{OC} and I_{SC} for both stations was then recorded. The module was then set at 10°. This time then, to see whether there would be a difference in open circuit voltage and short circuit current of the module when the angle has been changed. This trend continued with the measuring of average open circuit voltage and short circuit current at each 5° interval until up to 55°. Short circuit current and Open Circuit voltage was measured at each position and IV characteristics at each angle was observed for better understanding of the results.

3.0 Findings and Discussions

3.1 Optimal angle of inclination for solar PV System in Blantyre district, Malawi

Figure 4 shows average power output in response to changes in tilt angles.

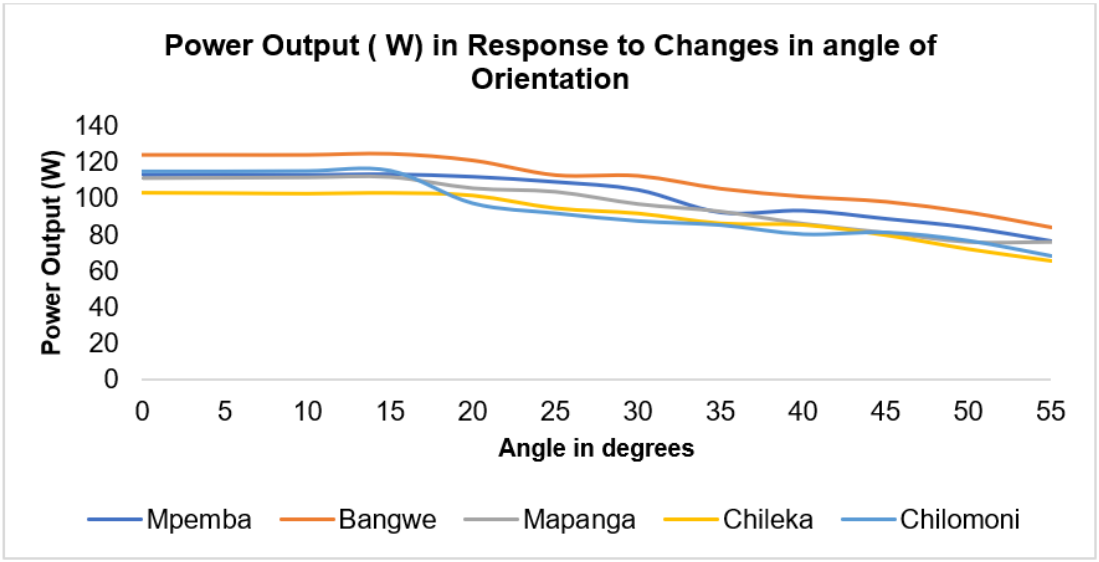

Figure 4: Output power (W) in response to tilt Angle

Figure 4: Output power (W) in response to tilt Angle

Figure 4 shows, the power output of the module which is the product of average V_{OC} and I_{SC} in response to tilt angle. From 0°, 15°, the trend in power output has been almost the same in all sites. Power output has been almost constant with slight increase at 15°. Above 15°, power output has been greatly decreasing in response to an increase in tilt angle. As the tilt angle increases above 15°, the power output also decreases.

It can be observed that higher power output values are recorded between 0° to 15° from October to December and we can generally say that the optimum tilt angle should be between 0 to 15°. It should be noticed however, that between 0° to 10°, the power output is slightly lower compared to power output at 15°. As the angle of inclination is increasing above 15°, the power output is also decreasing gradually up to 55°. In this case, it can be observed that the optimum tilt angle is at 15° due north, and is therefore ideal for harvesting maximum power from the module in Blantyre district, in October, November and December. It is also ideal to tilt our angle at 15° because dust and other debris can easily accumulate at an angle between 0° and 10° compared to 15° which provide some room for self-cleaning of the module. In the long run, efficiency of the module installed between 0° and 10° would start to decrease compared to the module installed at 15° if they are all left uncleaned for a long time. Based on these findings, the tilt angle for Blantyre district in Malawi, should be installed at 15° facing due north between October and December. However, it has also been observed that the tilt angle of 15° is approximately equal to the location latitudes where experimental setup was done. From this study, optimum angle was determined by measuring values at the maximum power output from the PV module. The highest amount of short circuit current and power produced by PV panel was observed at 15° which is also considered to be our optimum angle.

These results from Mpemba (S; 15°53'27", E; 34°58'35"), Bangwe (S; 15°49'30" E; 35°05'18"), Mapanga (S; 15°45'29" E;35°05'48"), Chileka (S; 15°41'06" E; 34°57'59") and Chilomoni (S; 15°77'59" E; 34°97'56" slightly differ from results of Kamanga et al., (2014) who conducted their study in Zomba (S; 15°38'71" E; 35°33'83"). They found out that the optimum tilt angle is 0° between October and February. They also concluded that solar panels should be installed at 25° facing true north in cases where the PV solar panels are fixed with no seasonal adjustments.

However, results from this experimental investigation are in line with experiments conducted by Muslim (2019) and Hassan et al (2021). They reported that the annual optimum tilt angle is approximately equal to the location latitude where solar PV system has been installed.

3.2 Significance of the results

Using Analysis of Variance (ANOVA) test in Statistical Package for the Social Sciences (SPSS), the mean difference between solar modules exposed at the same angle of orientation in all sites is significant at the 0.05 level. From the experimental study, alpha value for power output is 0.019 and is less than 0.05. Therefore, there is no significant variation in power output of solar modules exposed at the same angle of orientation because the sites are very close to show any significant differences. Furthermore, the difference in altitude, microclimate and urban effects around experimental sites are also minimal (Blantyre topographic map, elevation, terrain)

3.3 Limitations of the Study

This experiment did not use a data logger which is more accurate than manual recording of results. Irradiance was also not measured during the time of experiment. This can lead to some errors during experiment. To minimize the impact of these errors, two working stations were used instead of one for referencing, before recording of the final results. Therefore, both stations were exposed to the same weather conditions. However, data logger should be considered in the next similar experiment.

Another limitation was that experiments were done three months only instead of the whole year. The next researcher should therefore consider conducting experiments for the whole year. This will help to find an optimum angle for the whole year under fixed conditions.

4.0 Conclusion and Recommendations

An optimal angle of inclination for SPV system was analysed through an experimental investigation in five sites within Blantyre district from the year 2022 to 2023 during the months of October to December. Two working stations were set at each site named station A and station B. Modules of the same specifications were used throughout the experiment to avoid variations in the power output. At each angle in a station, short circuit current and open circuit voltage was measured simultaneously with another station, using two digital multimeters at each station, one for measuring short circuit current and the other for measuring open circuit voltage. ANOVA was used to test the mean difference in power output between solar modules exposed at the same angle of orientation in all experimental sites.

It was observed that there was no significant variation in power output of solar modules exposed at the same angle of orientation in all sites within Blantyre district. The optimum angle was found at 15° due north. It was also observed that the tilt angle of 15° is approximately equal to the location latitudes of all sites where experimental setup was done. It is therefore, recommended to install SPV modules at an angle of 15° due north in Blantyre district, during the months of October, November and December.

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Appendices

A1: Homogeneous Subsets

ANOVA TEST					
Power_Optimum_Angle					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2680.537	4	670.134	3.234	.019
Within Groups	11395.618	55	207.193		
Total	14076.154	59			

A2: Power Optimum Angle

Location	N	Subset for alpha = 0.05	
		1	2
Power Output for Chileka	12	90.7398	
Power Output for Chilomoni	12	94.1331	94.1331
Power output for Mapanga	12	97.0078	97.0078
Power output for Mpemba	12	101.1165	101.1165
Power Output for Bangwe	12		110.1229
Sig.		.404	.064
Means for groups in homogeneous subsets are displayed.			

A3: Multiple Comparisons

Location	(J) Location	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Power output for Mpemba	Power Output for Bangwe	-9.00642	5.87641	.546	-25.5798	7.5670
	Power output for Mapanga	4.10867	5.87641	.956	-12.4647	20.6821
	Power Output for Chileka	10.37667	5.87641	.404	-6.1967	26.9501
	Power Output for Chilomoni	6.98342	5.87641	.758	-9.5900	23.5568
Power Output for Bangwe	Power output for Mpemba	9.00642	5.87641	.546	-7.5670	25.5798
	Power output for Mapanga	13.11508	5.87641	.184	-3.4583	29.6885
	Power Output for Chileka	19.38308*	5.87641	.014	2.8097	35.9565
	Power Output for Chilomoni	15.98983	5.87641	.064	-.5836	32.5632

Power output for Mapanga	Power output for Mpemba	-4.10867	5.87641	.956	-20.6821	12.4647
	Power Output for Bangwe	-13.11508	5.87641	.184	-29.6885	3.4583
	Power Output for Chileka	6.26800	5.87641	.823	-10.3054	22.8414
	Power Output for Chilomoni	2.87475	5.87641	.988	-13.6986	19.4481
Power Output for Chileka	Power output for Mpemba	-10.37667	5.87641	.404	-26.9501	6.1967
	Power Output for Bangwe	-19.38308*	5.87641	.014	-35.9565	-2.8097
	Power output for Mapanga	-6.26800	5.87641	.823	-22.8414	10.3054
	Power Output for Chilomoni	-3.39325	5.87641	.978	-19.9666	13.1801
Power Output for Chilomoni	Power output for Mpemba	-6.98342	5.87641	.758	-23.5568	9.5900
	Power Output for Bangwe	-15.98983	5.87641	.064	-32.5632	.5836
	Power output for Mapanga	-2.87475	5.87641	.988	-19.4481	13.6986
		3.39325	5.87641	.978	-13.1801	19.9666

Supplementary Material

OPTIMUM ANGLE ON THE PERFORMANCE OF PV SYSTEM				
Mpemba	Angle in degrees	V_{OC}	I_{SC}	VI
	0	20.5	5.51	112.955
	5	20.5	5.52	113.16
	10	20.5	5.51	112.955
	15	20.5	5.53	113.365
	20	20.4	5.49	111.996
	25	20.4	5.35	109.14
	30	20.3	5.16	104.748
	35	20.2	4.57	92.314
	40	20.2	4.62	93.324
	45	20.1	4.42	88.842
	50	20.1	4.18	84.018
	55	20.1	3.81	76.581
Bangwe	Angle in degrees	V_{OC}	I_{SC}	VI
	0	20.4	6.07	123.828
	5	20.4	6.07	123.828

	10	20.4	6.07	123.828
	15	20.5	6.07	124.435
	20	20.4	5.92	120.768
	25	20.3	5.55	112.665
	30	20.3	5.53	112.259
	35	20.3	5.18	105.154
	40	20.2	4.99	100.798
	45	20.2	4.85	97.97
	50	20.2	4.56	92.112
	55	20.2	4.15	83.83
Chileka	Angle in degrees	V_{OC}	I_{SC}	VI
	0	20.5	5.03	103.115
	5	20.5	5.02	102.91
	10	20.4	5.03	102.612
	15	20.4	5.05	103.02
	20	20.4	4.98	101.592
	25	20.3	4.66	94.598
	30	20.3	4.52	91.756
	35	20.3	4.25	86.275
	40	20.2	4.23	85.446
	45	20.2	3.95	79.79
	50	20.2	3.57	72.114
	55	20.2	3.25	65.65
Chilomoni	Angle in degrees	V_{OC}	I_{SC}	VI
	0	20.3	5.66	114.898
	5	20.3	5.66	114.898
	10	20.3	5.67	115.101
	15	20.3	5.68	115.304
	20	20.2	4.82	97.364
	25	20.2	4.55	91.91
	30	20.1	4.36	87.636
	35	20.1	4.25	85.425
	40	20	4.02	80.4
	45	19.9	4.09	81.391
	50	19.9	3.86	76.814
	55	19.9	3.44	68.456