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SOLAR SPECTRUM EFFECTS ON THE PERFORMANCE OF PHOTOVOLTAIC (PV) CELLS

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ABSTRACT

In this work, an experiment was conducted to examine the effects of solar spectrum radiation on solar modules with color filtering. Two mono-crystalline solar modules were used, one for color filtering or specific light wavelength and the other for the reference or natural spectrum, which were placed side by side. Two data loggers were used for taking voltage readings periodically from the solar modules with the color filter and the reference. The two solar modules were installed strategically for accurate experimental data and the environmental temperature was not less than 25^{0}C. Each reading was recorded at 50-second intervals in volts, which is the primary parameter. Microsoft Excel was used to evaluate the data, which was analyzed and represented with diagrams. Seven filters were analyzed but the yellow filter produced the highest average amount of output voltage when compared to the other colors. It shows that the yellow filter has the best energy conversion. Contrary to popular opinion, photovoltaic cells respond better to longer, less energetic visible light wavelengths than to shorter, more intense ones. Hence, exposure to yellow light has the potential to increase the overall efficiency of solar panels.

1. Introduction

The sun emits vast amounts of solar energy, but only a small fraction reaches the Earth due to its considerable distance. The solar constant, at 1,367 watts per square meter, quantifies the intensity of the solar energy reaching the earth. As this energy enters Earth's atmosphere, it undergoes scattering, absorption, and diffusion by moisture and particles. The remaining radiation directly reaches the Earth's surface, contributing to global horizontal radiation. This radiation is characterized by different wavelengths, forming spectral irradiance with UV radiation (wavelength < 400 nm) accounting for 5%–10%, visible light (400–700 nm) for 40%, and infrared light (> 700 nm) for the remaining 50% of the total energy.

Tesla considered radiant energy systems which were a good source of energy [1]. Edmond Becquerel discovered photovoltaic phenomena in 1839, generating an electrical current by exposing a metal electrode to light in a conductive fluid. Adam and Day explored solid materials in 1876, creating a solar cell from selenium with 1-2% efficiency. Albert Einstein's 1905 photon theory explained the photovoltaic effect. In 1916, Jan Czochralski's discovery of pure crystalline silicon marked a breakthrough for modern electronics,

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leading to first-generation silicon cells with 6% efficiency, significantly lower than today's 14–20% [2]. Solar cells for renewable energy are now deploying inverted perovskite materials that can give an efficiency of over 25% [3].

Improvement in the efficiency of solar cell's performance for energy production can be done by using different wavelengths of the visible light spectrum. The use of solar cells is more economical and can be used in powering satellites and telescopes, whereas the use of other sources of fuel will be expensive and complex. In [4], the authors investigated the wavelength of light and its effects on the performance of a solar photovoltaic module using six filters and data was manually collected with a multimeter giving error prone readings. The red colored filter was the most efficient. We intend to improve on their work by using seven colored filters and a data logger which took readings every 50 seconds for seven days. Hence, the use of more data will help reduce errors in the results. In [5], the authors evaluated the performance of photovoltaic system using artificial light on five colored filters and concluded that yellow colored filter was the most efficient. Authors in [6] conducted an experiment in an outdoor environment like ours; however, they used five filters with magenta being the most efficient. A variety of factors such as location of the experiment, duration, panel size, and data collection method tend to affect the results.

2. Materials and Method

The experiment was performed in the Department of Electrical/Electronic Engineering situated at Ugbowo Campus, University of Benin, Benin City, Edo State, Nigeria (6^0 24` N, $5^0$ 36` E).

I. Solar Panel

The solar panel is used colloquially for photovoltaic (PV) modules. A PV module is an assembly of photo-voltaic cells mounted in a framework for installation. Photovoltaic cells use sunlight as a source of energy and generate direct current electricity. A photovoltaic (PV) cell, also known as a solar cell, can either reflect, absorb, or let through, light that strikes it. The semiconductor material that makes up the PV cell can conduct electricity more effectively than an insulator but not as effectively as a good conductor like a metal. In PV cells, a variety of semiconductor materials are employed. A solar panel is created by assembling the cells created from the wafer. The most space-efficient type of silicon solar cell is monocrystalline as presented in Figure 1. Of all the silicon-based solar cells, they also have the benefit of having the longest lifespan. Many manufacturers will provide warranties on this kind of system for up to 25 years, which is half of its anticipated lifespan [7].

Figure 1: A monocrystalline PV module

II. Color Filters

The majority of light sources produce light across the whole visible light spectrum at various wavelengths. However, it is frequently preferable to generate light with a constrained wavelength spectrum. Specialized filters that transmit some wavelengths while selectively absorbing or reflecting undesirable wavelengths can be used to achieve this easily.

To selectively transmit the desired wavelengths while blocking others, color filters are typically made of transparent pieces of colored glass, plastic, or lacquered gelatin (e.g. Wratten filters). The two most popularfilters used today are interference filters, which eliminate chosen wavelengths through internal

destructive interference, and absorption filters, which absorb undesirable wavelengths. No matter how the filter is made, a tiny quantity of the incident light is reflected off the surface and a small amount is absorbed. In majority of the time, these artifacts are really small and have no impact on the filter's main purpose.
The color filters used in this experiment are seven in number, which are Yellow, Red, Green, Blue, Orange, Purple, andPink Filter.

III. Data Logger

Data loggers as presented in Figure 2 employ a sensor to gather information about physical quantities, which is then converted to a digital format, processed by a CPU, and then stored with a time stamp in internal memory. They frequently include tiny, battery-operated devices. Data loggers can be connected wirelessly to a device or utilized as stand-alone units with a local interface. They can also utilize software to monitor and analyze the collected data by interacting with a computer. Since most standalone devices run on batteries, they can record continuously and for long periods.

Figure2: A data logger

IV. Panel Specification

The specifications of the two monocrystalline solar modules are given as (the modules have the same specifications):
Material: Monocrystalline Silicon
Color: Black
Peak power: 4W
Working voltage: 5.5V (Charge 3V-5V)
Working current: 0-720mA
Operating temperature: 0 to +60^{o} C
Size: 18*15.5cm / 7.08*6.1inch
Weight: 482g / 1.06Ib

V. Experimental Details

The setup consists of two monocrystalline solar modules (one for color filtering or specific light wavelength and the other for the reference or natural spectrum) placed side by side.Two data loggers were used in taking the voltage readings periodically and automatically from the solar modules (color filter and reference). The two solar modules were installed at strategic location for accurate experimental data. Experiment was taken in an environment having temperature not less than 25^{0}C. Readings were recorded by the data logger every 50 seconds. The experiment was carried out for seven days, with each pair i.e. filtered module and reference, setup per day from 7am to 7pm.

3. Results and discussion

Microsoft Excel was used to analyze the data collected and tables and charts were generated. Each setup was performed each day for a specific filter and its reference. Each setup had a total recorded quantity of data over 800 since they were recorded every 50 seconds by the logger, hence the need to take the average of each hour spanning from 7am to 7pm, summing up to just twelve sets of values which were recorded in a table in twelve rows. Taking averages of each hour made it possible to easily study the characteristics and relationship between each filtered module and its reference without compromising experimental values.

I. Diagrammatic Representation

Abbreviations are used in tables and charts. Note, that all data/values in the table and charts are recorded in voltage (volt).

YF/YFA - Yellow Filter/ Yellow Filter Average
YFR/YFRA - Yellow Filter Reference/ Yellow Filter Reference Average
RF/RFA - Red Filter/ Red Filter Average
RFR/RFRA - Red Filter Reference/ Red Filter Reference Average
GF/GFA - Green Filter/ Green Filter Average
GFR/GFRA - Green Filter Reference/ Green Filter Reference Average
BF/BFA – Blue Filter / Blue Filter Average
BFR/BFRA - Blue Filter Reference/ Blue Filter Reference Average
OF/OFA - Orange Filter/ Orange Filter Average
OFR/OFRA - Orange Filter Reference/ Orange Filter Reference Average
PrF/PrFA - Purple Filter/ Purple Filter Average
PrFR/PrFRA - Purple Filter Reference/ Purple Filter Reference Average
PiF/PiFA - Pink Filter/ Pink Filter Average
PiFR/PiFRA - Pink Filter Reference/ Pink Filter Reference Average

II. Yellow Filter and its Reference

The data for yellow filter and its reference is as presented in this session.

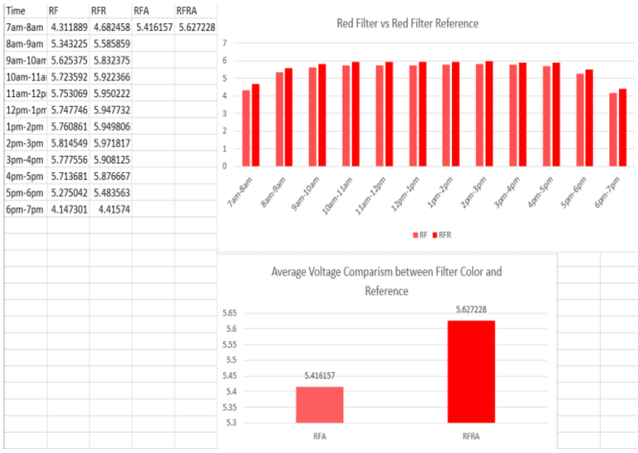
Time	YF	YFR	YFA	YFRA
7am-8am	4.895956	5.098265	5.560882	5.694957
8am-9am	5.574154	5.644662		
9am-10am	5.648194	5.777944		
10am-11a	5.722127	5.847014		
11am-12p	5.830417	5.944556		
12pm-1pm	5.803694	5.920817		
1pm-2pm	5.82693	5.944778		
2pm-3pm	5.944333	6.039361		
3pm-4pm	6.018028	6.160704		
4pm-5pm	5.718917	5.856338		
5pm-6pm	5.452352	5.589417		
6pm-7pm	4.295479	4.51563		

Figure3: Yellow filter and reference diagrammatic relationship

The bar charts in Figure 3 represent the filter and non-filter values of voltage against time. The total average value of both the yellow filter and its reference represented in the bar chart shows the diagrammatic and statistical evaluation of the total average values, same with the per-hour chart. This enablesoneto make a clear comparison in other to analyze the data to realize our objectives.A similar analysis is done for every other filter and its reference, as presented in Figures 4 to 9.

III. Red Filter and its Reference

The data for yellow filter and its reference is as presented in this session.



Time	RF	RFR	RFA	RFRA
7am-8am	4.311889	4.682458	5.416157	5.627228
8am-9am	5.343225	5.585859		
9am-10am	5.625375	5.832375		
10am-11a	5.723592	5.922366		
11am-12p	5.753069	5.950222		
12pm-1pm	5.747746	5.947732		
1pm-2pm	5.760861	5.949806		
2pm-3pm	5.814549	5.971817		
3pm-4pm	5.777556	5.908125		
4pm-5pm	5.713681	5.876667		
5pm-6pm	5.275042	5.483563		
6pm-7pm	4.147301	4.41574		

Figure 4: Red filter and reference diagrammatic relationship

IV. Green Filter and its Reference

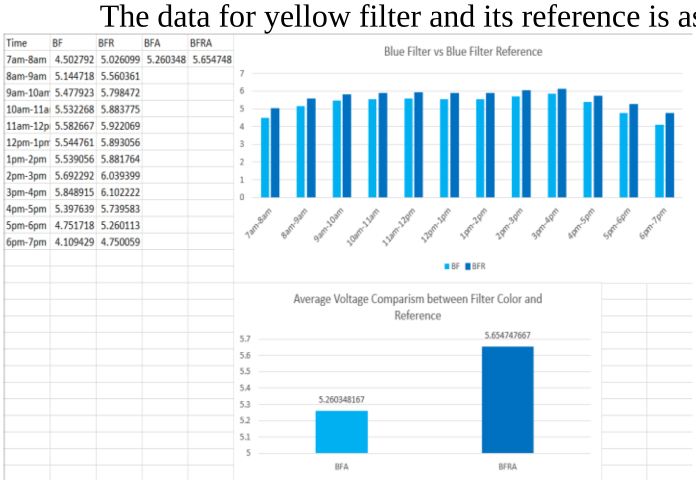
The data for yellow filter and its reference is as presented in this session.

Time	GF	GFR	GFA	GFRA
7am-8am	4.632722	4.97207	5.09893	5.340345
8am-9am	5.338493	5.242		
9am-10am	5.611861	5.760514		
10am-11a	5.700986	5.66		
11am-12p	5.678917	5.872264		
12pm-1pm	5.632521	5.877268		
1pm-2pm	5.695917	5.926		
2pm-3pm	5.797667	5.993268		
3pm-4pm	5.766	5.988389		
4pm-5pm	5.015097	5.319958		
5pm-6pm	3.335479	3.878408		
6pm-7pm	2.9815	3.594		

Figure 5: Green filter and reference diagrammatic relationship

V. Blue Filter and its Reference

The data for yellow filter and its reference is as presented in this session.

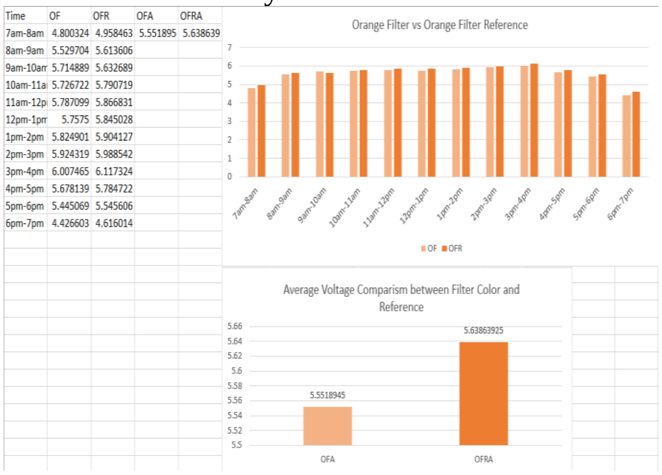


Time	BF	BFR	BFA	BFRA
7am-8am	4.502792	5.026099	5.260348	5.654748
8am-9am	5.144718	5.560361		
9am-10am	5.477923	5.798472		
10am-11a	5.532268	5.883775		
11am-12p	5.582667	5.922069		
12pm-1pm	5.544761	5.893056		
1pm-2pm	5.539056	5.881764		
2pm-3pm	5.692292	6.039399		
3pm-4pm	5.848915	6.102222		
4pm-5pm	5.397639	5.739583		
5pm-6pm	4.751718	5.260113		
6pm-7pm	4.109429	4.750059		

Figure 6: Blue filter and reference diagrammatic relationship

VI. Orange Filter and its Reference

The data for yellow filter and its reference is as presented in this session.

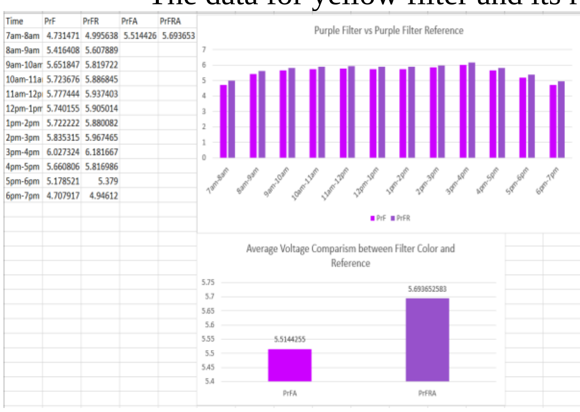


Time	OF	OFR	OFA	OFRA
7am-8am	4.800324	4.958463	5.551895	5.638639
8am-9am	5.529704	5.613606		
9am-10am	5.714889	5.632689		
10am-11am	5.726722	5.790719		
11am-12pm	5.787099	5.866831		
12pm-1pm	5.7575	5.845028		
1pm-2pm	5.824901	5.904127		
2pm-3pm	5.924319	5.988542		
3pm-4pm	6.007465	6.117324		
4pm-5pm	5.678139	5.784722		
5pm-6pm	5.445069	5.545606		
6pm-7pm	4.426603	4.616014		

Figure 7: Orange filter and reference diagrammatic relationship

VII. Purple Filter and its Reference

The data for yellow filter and its reference is as presented in this session.

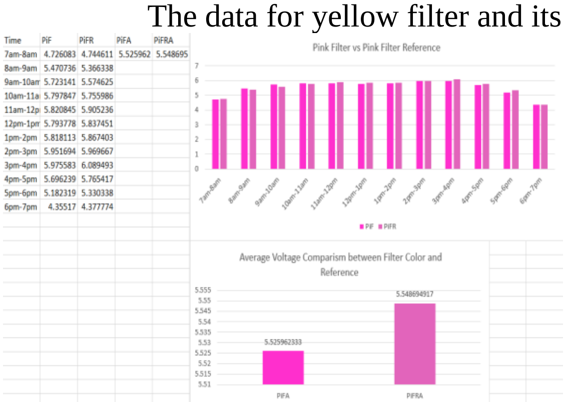


Time	PrF	PrFR	PrFA	PrFRA
7am-8am	4.731471	4.995638	5.514426	5.693653
8am-9am	5.416408	5.607889		
9am-10am	5.651847	5.819722		
10am-11am	5.723676	5.886845		
11am-12pm	5.777444	5.937403		
12pm-1pm	5.740155	5.905014		
1pm-2pm	5.722222	5.880082		
2pm-3pm	5.835315	5.967465		
3pm-4pm	6.027324	6.181667		
4pm-5pm	5.660806	5.816986		
5pm-6pm	5.178521	5.379		
6pm-7pm	4.707917	4.94612		

Figure 8: Purple filter and reference diagrammatic relationship

VIII. Pink Filter and its Reference

The data for yellow filter and its reference is as presented in this session.



Time	PiF	PiFR	PiFA	PiFRA
7am-8am	4.726083	4.744611	5.525962	5.548695
8am-9am	5.470736	5.366338		
9am-10am	5.723141	5.574625		
10am-11am	5.797847	5.755986		
11am-12pm	5.820845	5.905236		
12pm-1pm	5.793778	5.837451		
1pm-2pm	5.818113	5.867403		
2pm-3pm	5.951694	5.969667		
3pm-4pm	5.975583	6.089493		
4pm-5pm	5.696239	5.765417		
5pm-6pm	5.182319	5.330338		
6pm-7pm	4.35517	4.377774		

Figure 9: Pink filter and reference diagrammatic relationship

IX. General Table and Color Comparison

Figure 10 shows the general representation of all the data obtained from the setups i.e. from the seven colors used in the experiment. The bar chart consists of only the color filters without their references against their voltages. The references were omitted because this analysis was made under the assumption that the experiment for each filter was carried out in one day (since all references should be the same for the same day and the references is also directly proportional to each color filter). This is necessary so that a direct comparison of the filters can be observed, in order to see which filter best produce the highest voltage.

Time	YF	YFR	RF	RFR	GF	GFR	BF	BFR	OF	OFR	PrF	PrFR	PiF	PiFR
7am-8am	4.895956	5.098265	4.311889	4.682458	4.632722	4.97207	4.502792	5.026099	4.800324	4.958463	4.731471	4.995638	4.726083	4.744611
8am-9am	5.574154	5.644662	5.343225	5.585859	5.338493	5.242	5.144718	5.560361	5.529704	5.613606	5.416408	5.607889	5.470736	5.366338
9am-10am	5.648194	5.777944	5.625375	5.832375	5.611861	5.760514	5.477923	5.798472	5.714889	5.632689	5.651847	5.819722	5.723141	5.574625
10am-11am	5.722127	5.847014	5.723592	5.922366	5.700986	5.66	5.532268	5.883775	5.726722	5.790719	5.723676	5.886845	5.797847	5.755986
11am-12pm	5.830417	5.944556	5.753069	5.950222	5.678917	5.872264	5.582667	5.922069	5.787099	5.866831	5.777444	5.937403	5.820845	5.905236
12pm-1pm	5.803694	5.920817	5.747746	5.947732	5.632521	5.877268	5.544761	5.893056	5.7575	5.845028	5.740155	5.905014	5.793778	5.837451
1pm-2pm	5.82693	5.944778	5.760861	5.949806	5.695917	5.926	5.539056	5.881764	5.824901	5.904127	5.722222	5.880082	5.818113	5.867403
2pm-3pm	5.944333	6.039361	5.814549	5.971817	5.797667	5.993268	5.692292	6.039399	5.924319	5.988542	5.835315	5.967465	5.951694	5.969667
3pm-4pm	6.018028	6.160704	5.777556	5.908125	5.766	5.988389	5.848915	6.102222	6.007465	6.117324	6.027324	6.181667	5.975583	6.089493
4pm-5pm	5.718917	5.856338	5.713681	5.876667	5.015097	5.319958	5.397639	5.739583	5.678139	5.784722	5.660806	5.816986	5.696239	5.765417
5pm-6pm	5.452352	5.589417	5.275042	5.483563	3.335479	3.878408	4.751718	5.260113	5.445069	5.545606	5.178521	5.379	5.182319	5.330338
6pm-7pm	4.295479	4.51563	4.147301	4.41574	2.9815	3.594	4.109429	4.750059	4.426603	4.616014	4.707917	4.94612	4.35517	4.377774
Average	5.560882	5.694957	5.416157	5.627228	5.09893	5.340345	5.260348	5.654748	5.551895	5.638639	5.514426	5.693653	5.525962	5.548695

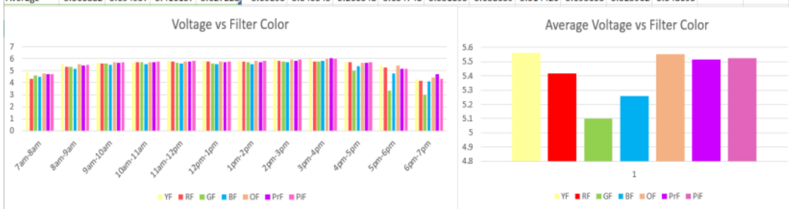


Figure 10: General comparison diagram

Figures 11, 13, 15, 17. 19, 21 and 23 show the plot of the filter against its reference, while the difference in the figures show the variance of the hourly average between the reference and filtered modules. When the difference is positive, it means that the reference is higher than the filtered module, otherwise, it will be negative. It is observed that the period of lowest readings is at 7-8 am and 6-7 pm, while the highest readings occur at 2-4 pm. However, the reference module produces a higher total average voltage when compared to the filtered module as can be seen in Figures 12, 14, 16, 18, 20, 22, and 24. It shows that the reference module produces a higher overall voltage from 7am to 7pm.

X. Overall Data Evaluation for Yellow Filter and Reference

The overall data evaluation for yellow filter and reference is as presented.

Time	YF	YFR	Diff
7am-8am	4.895956	5.098265	0.202309
8am-9am	5.574154	5.644662	0.070508
9am-10am	5.648194	5.777944	0.12975
10am-11am	5.722127	5.847014	0.124887
11am-12pm	5.830417	5.944556	0.114139
12pm-1pm	5.803694	5.920817	0.117123
1pm-2pm	5.82693	5.944778	0.117848
2pm-3pm	5.944333	6.039361	0.095028
3pm-4pm	6.018028	6.160704	0.142676
4pm-5pm	5.718917	5.856338	0.137421
5pm-6pm	5.452352	5.589417	0.137065
6pm-7pm	4.295479	4.51563	0.220151

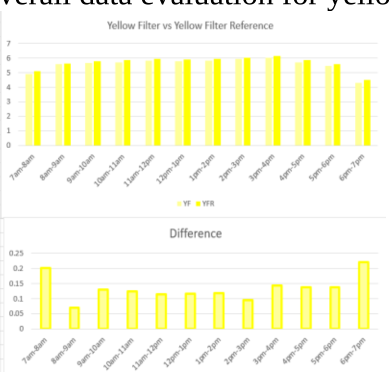


Figure 11: YF and YFR Difference

YFA	YFRA	DIA
5.560882	5.694957	0.134075

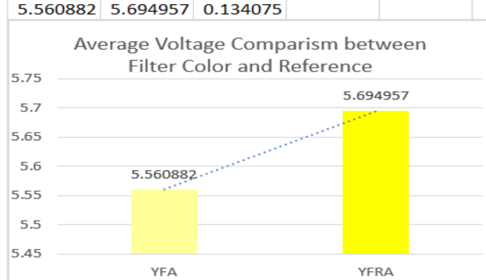


Figure 12: Average diagrammatic representation

XI. Overall Data Evaluation for Red Filter and Reference

The overall data evaluation for red filter and reference is as presented.

Time	RF	RFR	Diff
7am-8am	4.311889	4.682458	0.370569
8am-9am	5.343225	5.585859	0.242634
9am-10am	5.625375	5.832375	0.207
10am-11a	5.723592	5.922366	0.198774
11am-12p	5.753069	5.950222	0.197153
12pm-1pm	5.747746	5.947732	0.199986
1pm-2pm	5.760861	5.949806	0.188945
2pm-3pm	5.814549	5.971817	0.157268
3pm-4pm	5.777556	5.908125	0.130569
4pm-5pm	5.713681	5.876667	0.162986
5pm-6pm	5.275042	5.483563	0.208521
6pm-7pm	4.147301	4.41574	0.268439

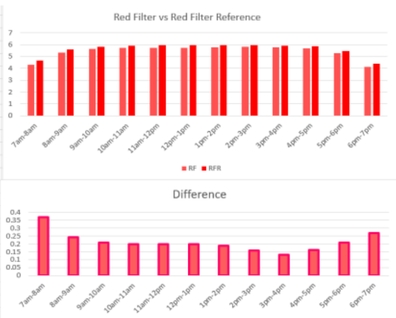


Figure 13: RF and RFR Difference

RFA	RFRA	DIA
5.416157	5.627228	0.211071

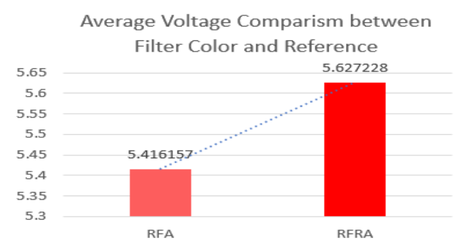


Figure 14: Average diagrammatic representation

XII. Overall Data Evaluation for Green Filter and Reference

The overall data evaluation for green filter and reference is as presented.

Time	GF	GFR	Diff
7am-8am	4.632722	4.97207	0.339348
8am-9am	5.338493	5.242	-0.09649
9am-10am	5.611861	5.760514	0.148653
10am-11a	5.700986	5.66	-0.04099
11am-12p	5.678917	5.872264	0.193347
12pm-1pm	5.632521	5.877268	0.244747
1pm-2pm	5.695917	5.926	0.230083
2pm-3pm	5.797667	5.993268	0.195601
3pm-4pm	5.766	5.988389	0.222389
4pm-5pm	5.015097	5.319958	0.304861
5pm-6pm	3.335479	3.878408	0.542929
6pm-7pm	2.9815	3.594	0.6125

Figure 15: GF and GFR Difference

GFA	GFRA	DIA
5.09893	5.340345	0.241415

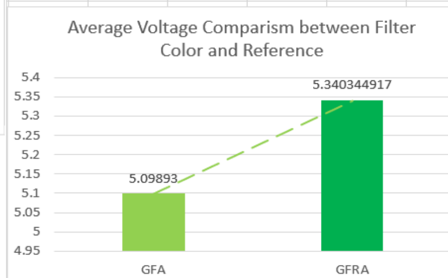


Figure 16: Average diagrammatic representation

XIII. verall Data Evaluation for Blue Filter and Reference

The overall data evaluation for blue filter and reference is as presented.

Time	BF	BFR	Diff
7am-8am	4.502792	5.026099	0.523307
8am-9am	5.144718	5.560361	0.415643
9am-10am	5.477923	5.798472	0.320549
10am-11a	5.532268	5.883775	0.351507
11am-12p	5.582667	5.922069	0.339402
12pm-1pm	5.544761	5.893056	0.348295
1pm-2pm	5.539056	5.881764	0.342708
2pm-3pm	5.692292	6.039399	0.347107
3pm-4pm	5.848915	6.102222	0.253307
4pm-5pm	5.397639	5.739583	0.341944
5pm-6pm	4.751718	5.260113	0.508395
6pm-7pm	4.109429	4.750059	0.64063

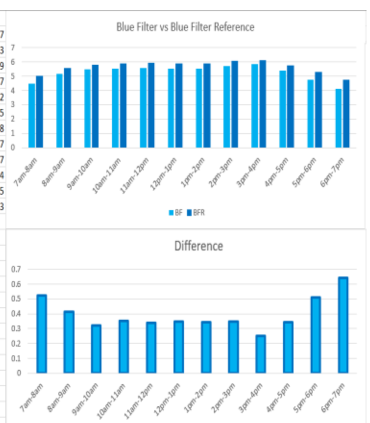


Figure 17: BF andBFR Difference

BFA	BFRA	DIA
5.260348	5.654748	0.394399

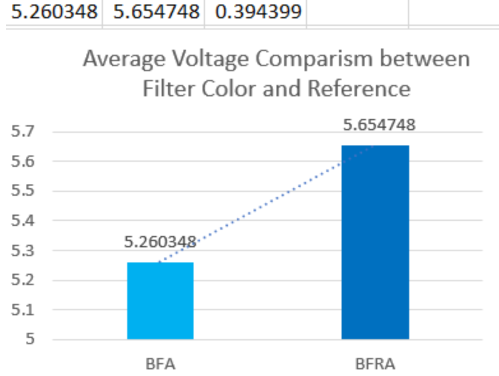


Figure 18: Average diagrammatic representation

XIV. Overall Data Evaluation for Orange Filter and Reference

The overall data evaluation for orange filter and reference is as presented.

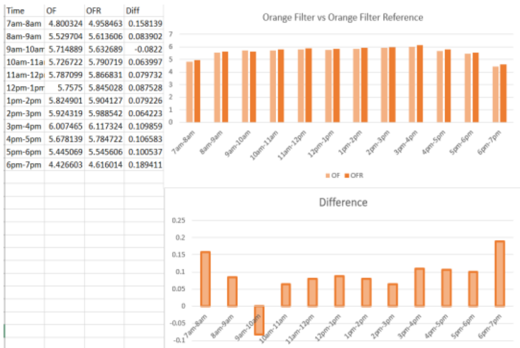


Figure 19: OF and OFR Difference

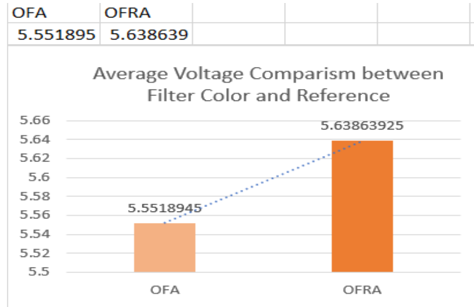


Figure 20: Average diagrammatic representation

XV. Overall Data Evaluation for Purple Filter and Reference

The overall data evaluation for purple filter and reference is as presented.

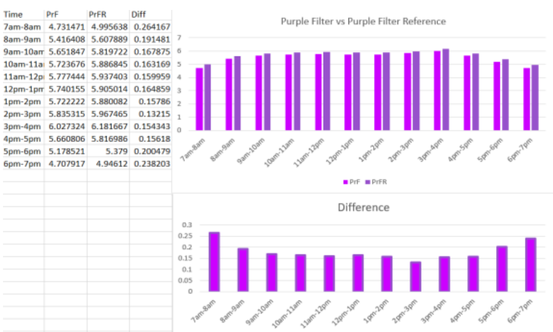


Figure 21: PF and PFR Difference

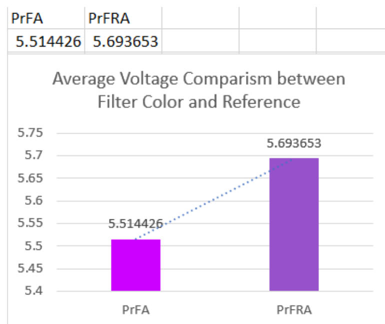


Figure 22: Average diagrammatic representation

XVI. Overall Data Evaluation for Pink Filter and Reference

The overall data evaluation for blue filter and reference is as presented.

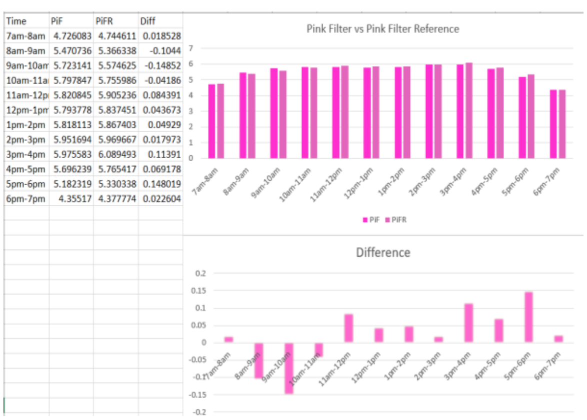


Figure 23: PiF and PiFR Difference

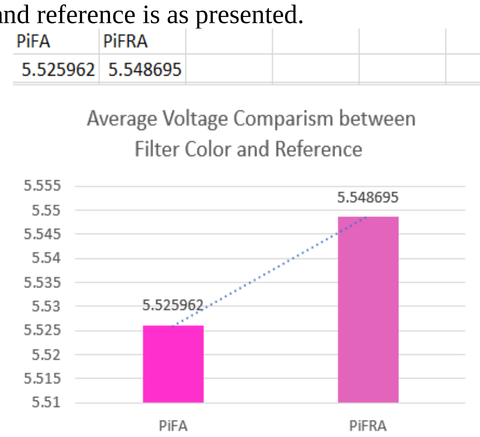


Figure 24: Average diagrammatic representation

4. CONCLUSION

This investigation assessed the solar spectrum's impact on modules, confirming that sun irradiance affects outputs in line with initial goals. Output voltage increases proportionally with solar intensity, notably peaking from 2 pm to 4 pm, contrary to common belief. Different wavelengths had varied effects, with the natural spectrum consistently producing higher voltages. Time of day significantly influences output, with the lowest outputs in the morning/evening and the highest between 2 pm and 4 pm, indicating a clear link between sunlight duration and module performance. The yellow filter exhibited the highest average output voltage compared to the other colors, indicating superior electrical conversion, which corroborates the work in [5] which used artificial light source. Surprisingly, photovoltaic cells respond better to longer, less intense visible light wavelengths, like yellow light, potentially enhancing solar panel efficiency.

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