Investigating the Wavelength of Light and Its Effects on the Performance of a Solar Photovoltaic Module

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Abstract— **In this study, an attempt was made to investigate the wavelengths of light and its effects on the performance of solar photovoltaic module. A case study was conducted to experimentally verify the effect of various colour filters (polythene) on the performance of solar photovoltaic module. Based on the temperature of the cell, solar irradiance and photonic theory, the efficiency and power output of the PV system have been evaluated. An analytical model based on physical parameters was also developed to evaluate the efficiency of solar panel. The results show that the Present day PV technology is influenced by the red color of light. In other words, visible portion of the solar spectrum influences the performance of the solar panel then the infra-red light.**

Keywords: **investigation, wavelength, effects, performance, solar photovoltaic module.**

I. INTRODUCTION

A. Solar Radiation

Huge amounts of energy are generated from the Sun in every second. The energy released from the Sun travels through space as radiation. Due to the long distance between the Earth and the Sun (149.6 x106 km) only a small proportion arrives at the Earth's atmosphere. The intensity of the small proportion radiation arriving on the Earth atmosphere is referred to as the solar constant which is equal to 1367 W/m2. When solar radiation enters Earth's atmosphere, a portion of it is absorbed or scattered by the moisture and the particles in the atmosphere (some are diffuse) while the rest are transmitted (direct beam radiation) to the surface,(Hasem Qasem 2013). The total measured radiation arriving to a horizontal surface, also known as the global horizontal radiation is a combination of direct beam radiation corrected to the angle of incidence and the diffuse radiation. The solar radiation arriving at the Earth is distributed across different wavelengths. The radiation power of each wavelength received by unit area is known as the Spectral Irradiance. The influence of the atmosphere on the spectral irradiance depends on the path length and optical transmittance properties, where the attenuation of the spectral irradiance areexponential function of the distance that the radiation travels. The Air Mass (AM) defines the ratio of the actual distance travelled to that of the path of shortest distance (G.N Green 2000).

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B. Solar Photovoltaic Module

Photovoltaic phenomenon has been recognized since 1839, when French physicist Edmond Becquerel was able to generate electricity by illuminating a metal electrode in a weak electrolyte solution. The photovoltaic effect in solids was first studied in 1876 by Adam and Day, who made a solar cell from selenium that had an efficiency of 1–2%. The photovoltaic effect was explained by Albert Einstein in 1904 via his photon theory. A significant breakthrough related to modern electronics was the discovery of a process to produce pure crystalline silicon by Polish scientist Jan Czochralski in 1916. The efficiency of first generation silicon cells was about 6%, which is considerable lower than that of contemporary solar cells (about 14–20%,) (kumar and Rosen 2011). Early efforts to make photovoltaic cells a viable method of electricity generation for terrestrial applications were unsuccessful due to the high device costs. The ''energy crises'' of 1970s spurred a new found of initiatives in many countries to make photovoltaic systems affordable, especially for off-grid applications. The significant reductions in the prices of photovoltaic cells in more recent years has rejuvenated interest in the technology, e.g., the annual growth since 2000 in the production of PV system has exceeded 40% and present total installed capacity worldwide has reached about 22 GW(Kumar and Rosen, 2011).

Photovoltaic System refers to the technology that converts solar energy directly into electricity, through the use of Solar cells or similar device. Solar photovoltaic system has gained significant attention rapidly since the last decade, due to the depletion and adverse environmental impacts of conventional fossil fuels. Solar cells are an alternative method for generating electricity directly from sunlight. This technology is growing rapidly, and is expected to reach full maturity in the 21st century. Solar photovoltaic conversion efficiency has improved as the general technology has advanced, growing from the first passive collection methods to the current applicable methods. Studies have been done towards the next advancement for increased output and efficiency (M.A Green 2005). Four main types of PV installations exist: grid-tied centralized (large power plants); grid- tied distributed (roof/ground mounted small installations); off-grid commercial (power plants and industrial installations in remote areas); and off-grid (mainly stand-alone roof/ground based systems for houses and isolated applications). The balance-of-system requirements of each installation differ significantly. For example, off-grid stand-alone applications often require a battery bank or alternative electrical storage capacity (Kumar and Rosen, 2011). Photovoltaic systems can be further distinguished based on the solar cell technology. Silicon (Si) based technologies can be categorized as a crystalline silicon and amorphous silicon or thin film, and are considered the most mature. Crystalline silicon cells can have different crystalline structures: mono-crystalline (mono- crystalline) silicon, multi-crystalline silicon and ribbon cast multi-crystalline silicon (Kumar and Rosen, 2011). A key feature of photovoltaic systems is their ability to provide direct and instantaneous conversion of solar energy into electricity without complicated mechanical parts or integration (Phuangpornpitak and Kumar, 2011).

C. Wavelength of light

The color of light is determined by its wavelength and dictated in the color spectrum. The sun emits energy in the form of electromagnetic waves. White light from the Sun includes all colors of the visible spectrum and ranges in wavelength from about 400 nanometers (nm) to about 780 nm. Sunlight is a different color – it contains more of the high-energy violet end of the spectrum. Red photons have the least energy, and blue photons have the most energy,(Kribus .A 2002). Green is in between the two. The energy of the photons is determined by their frequency.

$E=hf$ (1)

It is becoming increasingly apparent that wavelength of light have a significant influence on the performance of photovoltaic modules. Currently available solar cells respond well to some, but not all, wavelengths .Different solar cells are designed to operate efficiently at different wavelengths depending on the materials used to manufacture them. Research in the area of solar cells continues with an increasing interest to develop cells that will respond well at the widest range of wavelengths. The range of the wavelengths or frequencies of electromagnetic radiation is called the electromagnetic spectrum. Visible radiation is just a small part of the entire electromagnetic spectrum. It is, however, the only region that can be seen by the human eye. Visible radiation has wavelengths from approximately 400 to 750 nanometers (nm, 1 nm = 10-9 m) and ranges in color from violet to red. White light, or sunlight, is composed of all of these colors. The table below shows the various colors of visible light and their corresponding wavelengths. TheWavelength of Visible Light ranges from 400 to 700 nm. The visible spectrum of the electromagnetic spectrum is known as visible light. The visible spectrum has various different colours with different wavelengths. The violet colour has shortest wavelength while the red colour has the longest wavelength. The wavelength of various colours of the visible spectrum is given in the table below, but we will discuss wavelength of each colour, in detail, one by one.

Table 1: Different colours or light and there corresponding wavelengths

Colour	Wavelength (nm)
Red	622 – 780
Orange	597 – 622
Yellow	577 – 597
Green	492 – 577
Indigo	420 – 450
Blue	455 – 492
Violet	390 – 455

D. White Light

The white light extends from the 400 nm to 750 nm. The white colour when passed through the prism it gets diffracted into all the other colours.

E. Ultraviolet Light

Ultraviolet light belongs to electromagnetic spectrum and it extends from end of visible region and x-rays. Ultraviolet light is in the range of 10 nm to 400 nm with energies from 3eV to 124 eV. Ultraviolet light gets its name because it is the light closest to the violet portion of visible light.

F. Red Light: The red light of the visible spectrum has a wavelength of about 650 nm. The best place to see natural red colour is at sunrise and sunset when red or orange colours are present. This is because at the sunrise and sunset the wavelengths associated with red and orange colours are not properly scattered by the atmosphere than the wavelength of other colours (like blue and purple).

G. Yellow Light

The yellow light has a wavelength of about 570 nm. Low-pressure sodium lamps, like those used in parking lots, emit a yellow (wavelength 589 nm) light.

H. Green Light

The green light has a wavelength of about 510 nm. Grass appears green because all of the colours in the visible part of the spectrum are absorbed by the grass except green. The grass reflects green wavelength, therefore the grass appears green.

I. Blue Light

The blue light which we see has a wavelength of about 475 nm. The atmosphere scatter shorter wavelength efficiently and hence the wavelength associated with blue colour is scattered more efficiently by the atmosphere. This is the reason why we see sky to be blue. **Violet Light:** The violet light has a wavelength of about 400 nm. As already discussed the violet and blue which belongs to short wavelength region are more efficiently scattered as other wavelengths. Our eyes are more sensitive to the blue colour and hence we see sky blue and not violet.

J. Indigo Light

The indigo lies between the blue colour and the violet colour and hence the wavelength of indigo lies between 420 nm to 450 nm.

K. Infrared Light

Infrared (IR) radiation belongs to electromagnetic radiation spectrum. Infrared has a longer wavelength than visible light. Infrared is close to red colour in visible spectrum and hence it is sort of "redder-than-red" light or "beyond red" light, that is why the name infrared. Infrared radiation cannot be seen but can only be feelas a heat. The best example of feeling the infrared by yourself is feeling the heat after the burner is turned off,(Wikipedia 2015).

II. MATERIALS AND METHOD

A. Solar Photovoltaic Module, Coloured Filters (polythene), and Multimeter

Solar Photovoltaic Module: A photovoltaic module however is a packaged connected assembly of solar cells, and the have been configured to produce enough electrical energy to power all the electrical appliances in a system when adequately placed under sunlight. Traditional photovoltaic cells turn a relatively small part of the sun's light spectrum into electricity, limiting their efficiency and power output. The cell's silicon material responds to a limited range of wavelength, ignoring those that are longer and shorter. As the wavelength varies from short to long, the cell's output rises and falls in a jagged curve. Newer photovoltaic cells designs achieve higher efficiency by converting more wavelengths into useful energy. Photovoltaic module performance is characterized by its open circuit voltage (V_{oc}), short circuit voltage (I_{sc}), maximum power voltage (V_{mp}), and maximum power current(I_{mp}) which have been configured to react to all wavelengths of light incident on it . There are basic types of solar modules namely; Mono-crystalline (single-crystalline)solar module, Polycrystalline(multi-crystalline or semi-crystalline) solar module, and Thin film solar module. However the solar photovoltaic module to be used is a module of a mono crystalline solar module of 700mW power capacity mounted on a stand that can be adjusted for optimum tilt(15 degrees north) and exposure to sunlight. The module Properties and other experimental parameters are given in the table below.

Plate 1: A 10w solar module

Table 2.The specification and experimental parameters of the solar module employed for the experimental study

SPECIFICATION	PARAMETERS
Maximum system voltage	8V
Open Circuit Voltage (Voc)	6.5 V
Short Circuit Current (Isc)	238Ma
Dimensions(mm)	180 x 120
Weight(kg)	3kg
Temperature Co-efficient	25 °C

B. Colour Filters

A colour filter is a material that allows the passage of light through it, a coloured filter of a specific colour allows its own colour to pass through and absorbers the remaining colours. For example if you pass white light through a red colour filter, then red light comes out the other side. This is however so because the red filter only allows red light through,the other colours (wavelengths) of the spectrum are absorbed .Colour filters were used to absorb all wavelengths of light except that of their own colour, thus tinting the light that colour. So, when a panel is covered with a colour-filter.

Plate 2:: Different colour filters

Plate 3: Different Polythene leathers which could also used as a colour filter

III. EXPERIMENTAL VERIFICATION USING SOLAR PHOTOVOLTAIC MODULE, COLOUR FILTERS AND MULTI-METER

The photovoltaic module was mounted on a stand that can be adjusted for optimum tilt (15 degrees south) and exposure to sunlight. The colour filters were used to absorb all wavelengths of light except that of their own colour, thus tinting the light of that colour. So, when a panel is covered with a colour-filter(coloured polythene), it means it is exposed to a light of specified wavelength: however shorter for blue, medium for green and longer for red. The photovoltaic solar module after been covered with different colour filters and the changes in panel voltage and current output is measured and recorded. Six colour filters of different transmittance were used(red, yellow-orange, white, green, blue, and light).Using the digital multimeter to measure the open circuit voltage(V_{oc}) and short circuit current(I_{sc}) of the solar panel is measured as a series of filters(polythene) are placed over the solar panel. The experiment is repeated for module without filters on a bright sunlight. The ratio of the solar panel power output shaded by the filter to the output of the panel without a filter can be used to investigate the dependence of the solar cell output on wavelength. This information can also be used to evaluate the wavelength of light emitted by the source.

A. Measuring the Efficiency of The Photovoltaic Module

Efficiency in photovoltaic solar panels is measured by the ability of a panel to convert sunlight into usable energy for human consumption. Knowing the efficiency of a panel is important in order to choose the correct panels for your photovoltaic system. For smaller roofs, more efficient panels are necessary, due to space constraints. How do manufacturers determine the maximum efficiency of a solar photovoltaic panel though ,the panel efficiency determines the power output of a panel per unit of area. The maximum efficiency of a solar photovoltaic cell is given by the equation.

$$\text{Maximum efficiency} = \frac{Maximun\ Power\ Output}{Incident\ Radiation \times Area\ of\ Collector}$$

The incident radiation flux could better be described as the amount of sunlight that hits the earth's surface in W/m2. The assumed incident radiation flux under standard test conditions (STC) that manufacturers use is 1000 W/m2. Keep in mind though, that STC includes several assumptions and depends on your geographic location.

IV. RESULTS

The experimental results of output power and efficiency of the solar PV panel was compared, with and without filter as given in Table 4 and 5.

Table 4: Without Filter

COLOUR	WAVELENGHT (nm)	CURRENT (A)	VOLTAGE (V)	POWER (W)	EFFICENCY (%)
White (full sun)	390 – 780	0.38	6.90	2.62	12.12

Table 5: With Filter

COLOUR	WAVELENGHT (nm)	CURRENT (A)	VOLTAGE (V)	POWER (W)	EFFICENCY (%)
Blue	455 – 495	0.20	6.00	1.22	5.64
Green	495 – 575	0.23	6.25	1.43	6.62
Yellow	575 – 595	0.22	6.15	1.35	6.25
Orange	595 – 625	0.21	6.09	1.28	5.92
Red	625 – 780	0.25	6.35	1.58	7.34

A. Power Output Variation

For a crystalline solar cell, the electrical output voltage is a function of the temperature, Intensity and colour of the wavelengths of light incident on it.

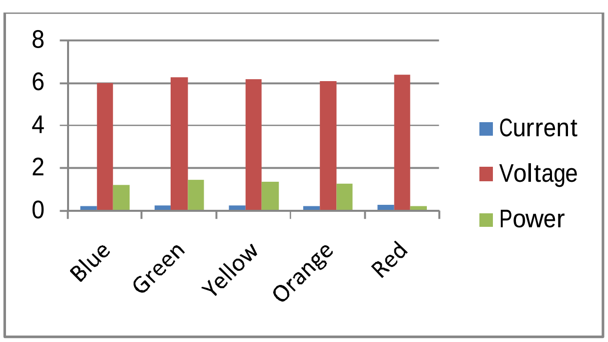

Figure 2: The voltages, current andpower variation of the module with different colours of the wavelength of light

The voltages, current andpower variation of the module withdifferent filters are presented in Figure 1. Due to filters, the module power wassignificantly reduced in comparison with the module without filters. A greateramount of current was generated when light of a longer wavelength fell upon the photovoltaic cell. However, the wavelengths of orange light didnot follow the trend. This signifies that a relationship between wavelength andcurrent may not be completely linear. Outside factors may have also influencedthe result. We assumed that blue light shining on a solar panel would give off the higher volt reading because it has the shortest wavelength and the highestenergy, but it was actually the lowest.

B. Efficiency Variation

The photovoltaic conversion efficiency of the modules with different filters is estimated and shown in Figure 1. The best efficiency obtained was when no filter was used. This is due to the reason that module without filter was receiving all the photons of solar radiation compared to the module with filters

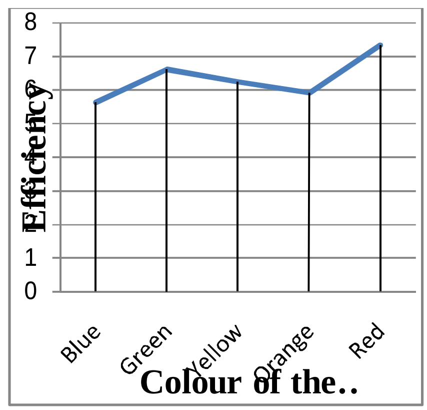

Figure 2: Variation of the efficiency with different colours of the wavelength of light

C. Spectral Response

The ability of solar cell to capture energy is not just determined by the strength of the energy, but by the ability to 'detect' light. This is most often related to the energy's frequency/wavelength. The types of energy (colour, frequency, wavelength) a device can detect is called its 'spectral Response'. This is often given as a numerical range of wavelengths (frequencies, or colours), But the wavelength/colour that corresponds to the highest peak of the spectral response graph, will be the type of light that particular panel can best convert to electricity After analyzing the data, it was determined that the output of the panel under sun light was significantly higher than any of the other coloured light .This is almost certainly due to the loss of light intensity inherent to the tint of the colour Filters. The blue filter yielded an output lower than the other entire colour filter. This proves that the spectral response of the solar panel for the blue light is the lowest. The spectral response of panel for green light is slightly higher than that of yellow and orange. Red and blue all had outputs significantly higher than green, which is concurrent with the intensity readings blue s intensity fell short of the next lowest, by this study, it is once again proved that visible portion of the solar spectrum influences the performance of the Solar panel than the Infra-Red light.

V. CONCLUSION

The purpose of this study is to investigate the wavelength of light and its effects on the performance of a solar photovoltaic module. After analyzing the results, it was concluded that the wavelengths of light do affect the performance of solar cell. Red color light generates more electricity than other colours. Contrary to popular belief, longer wavelengths of visible light, the ones with less photon energy, are more efficient with photovoltaic cells than shorter, more
energetic wavelengths. The efficiency of solar panels in general could be improved by exposure to red light. If a way could be found to eliminate or even only reduce the light intensity lost due to tinting, the efficiency of solar panels in general could be improved by exposure to red light.

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