

## *Extended Essay*

**Topic:** Solar panels and the photovoltaic effect

**Research question:** How does varying the angle of a solar panel affect the power output across it keeping wavelength of light constant?

**Subject:** Physics

**Personal code:** krl018

**Word count:** 3898 words

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## 1.0 Introduction

The world is losing its non-renewable energy sources rapidly like fossil fuels (they are set to run out by 2060), and thus, it needs to start utilizing the more renewable sources like solar energy. We need to maximize the electricity output per unit area of land since solar panels are relatively large and costly to set up but in the long term, they turn out to be economical.

Solar panels have a blue or black coating (this is done because dark blue or black colors are generally the best at absorbing heat and light), which acts as an anti-reflective coating aiding its sunlight absorption efficiency and capacity. Usually, solar panels are installed on the roofs of buildings or houses to absorb the most sunlight. However, recently the world has seen an increase in demand for colored solar panels which could be installed on the sides of buildings, to not only generate power but also to maintain the aesthetics of the building. An example of aesthetic designs are red coated solar panels used to blend into the side of a red colored building.

Electrical output of solar panels is affected due to various factors like temperature or resistance of the panel, but two main factors are its angle with respect to the incident light, and the wavelength of incident light. For example, a solar panel installed on the side of a building, at an angle, would not generate the same amount of power as a panel exposed to the bare sun.

## 1.1 Research Question

This gets us to the research question, ‘**How does varying the angle of a solar panel affect its power output, keeping wavelength of light constant?**’

## 2.0 Background information

### 2.1 Semiconductors, the photoelectric and photovoltaic effects, and Band Theory

#### **Semiconductors**

A semiconductor is a material that has an electrical conductivity between that of a conductor and an insulator. *“Holes and electrons are the main charge carriers for the flow of current in semiconductors. Holes (absence of electrons) are the positive electric charge carrier, whereas electrons are the negative charge carriers<sup>2</sup>.”*

*“An intrinsic type of semiconductor is made to be very pure chemically”<sup>1</sup>*. It is made up of only a single type of element, such as silicon<sup>2</sup>. The types of semiconductors used in solar panels, however, are extrinsic semiconductors. Extrinsic semiconductors make the use of suitable replacement atoms called impurities to improve their electricity generation. The process of adding impurity atoms to the pure semiconductor is called “doping”.

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<sup>1</sup> “The Use of Semiconductors in Solar Energy Technology.” *AZoM.com*, 8 February 2023, <https://www.azom.com/article.aspx?ArticleID=22419> . Accessed 6 October 2023

<sup>2</sup> “How does solar power work? | Solar energy explained.” *National Grid*, 16 May 2023, <https://www.nationalgrid.com/stories/energy-explained/how-does-solar-power-work> . Accessed 14 December 2023.

The element silicon<sup>3</sup> is mainly used for the construction of solar panels, however other materials like germanium can be used. As can be seen in figure below, silicon is tetravalent, meaning it has four electrons in the outer shell.

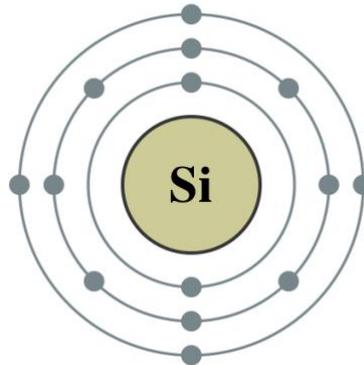


Figure 1 shows the atomic structure of silicon<sup>4</sup>.

This means that silicon atoms have a lattice structure in which each of the four valence electrons covalently bonds with one other electron from the neighboring silicon atom, completing the octet. However, in solar panels, these extrinsic semiconductor structures are “doped” with other elements and atoms to create “holes” and extra non-bonded electrons.

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<sup>3</sup> “How do solar panels generate electricity?” *Good Energy*, <https://www.goodenergy.co.uk/how-do-solar-panels-work/> . Accessed 14 September 2023.

<sup>4</sup> Boyle, Rebecca. “Meet Silicene, Single-Atom-Thick Sheets of Silicon That Could Supersede Graphene.” *Popular Science*, 2 May 2012, <https://www.popsci.com/technology/article/2012-05/meet-silicene-single-atom-thick-sheets-silicon-could-supersede-graphene/> . Accessed 1 November 2023.

**P-type** semiconductors are made by doping tetravalent materials with trivalent ones (3 electrons in the outermost shell), like Boron. These boron atoms bond with the silicon atoms thus creating “holes” or gaps where electrons are deficient.

If, however, a silicon sheet is doped with a pentavalent dopant, like phosphorous, it will create an electron rich material, hence making it negatively charged, or “**n**”-type.<sup>5</sup>

### **The photoelectric effect**

The photoelectric effect occurs when electrons are ejected when light is incident on a surface of a material. This effect provided necessary evidence that light can be quantized or carried in discrete packets.

When light hits the surface of a solar panel, electrons gain energy from the photons to become “excited”, leaving their energy level. These electrons need a minimum frequency of light, known as the threshold frequency, to be able to leave the material. The photoelectric effect does not occur below this frequency. If the frequency of light is below the threshold frequency, no electrons are released, even if the intensity of the light is increased just because there isn’t enough energy to cause the electrons to be ejected.

The energy of a photon is:

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<sup>5</sup> “From sunlight to electricity - Curious.” *Australian Academy of Science*, 17 August 2015,

<https://www.science.org.au/curious/technology-future/solar-pv> . Accessed 14

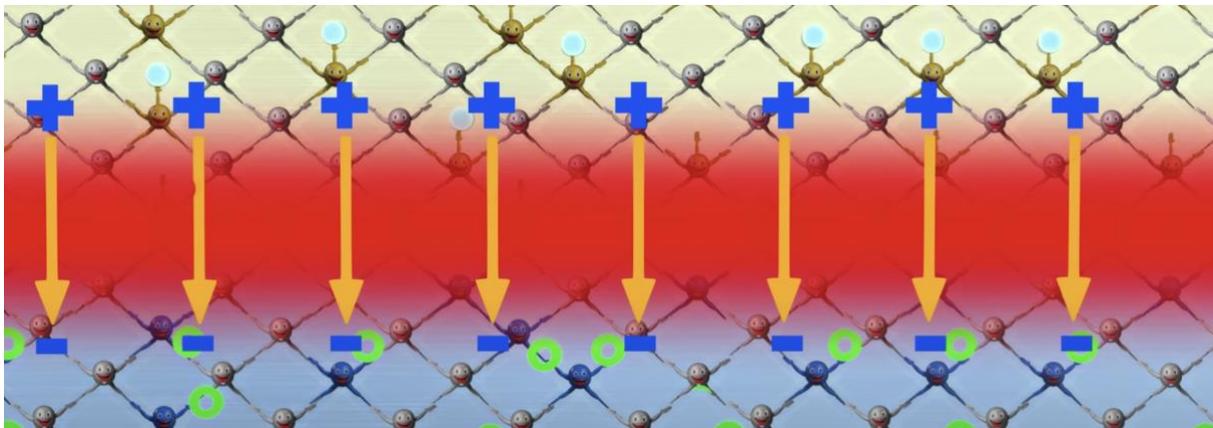
December 2023.

$$E=hf$$

As seen above, the energy of a photon is directly proportional to its frequency, and since  $h$  is a constant, frequency must be increased to increase the energy of a photon.

When p and n types of materials are fused together, a p-n junction is formed and some of the electrons from the n-type material, which has excess electrons, travel to the p-type material. However, not all the electrons travel to the p-type material, nor the holes to the n-type material, causing the formation of a “depletion region” at the junction of the materials.

Since electrons have moved from the n-type material to the p-type, the n-type and p-type materials will gain a slight positive and negative charge respectively. An electric field will thus be formed, acting as the driving force needed to move the electrons in a circuit.



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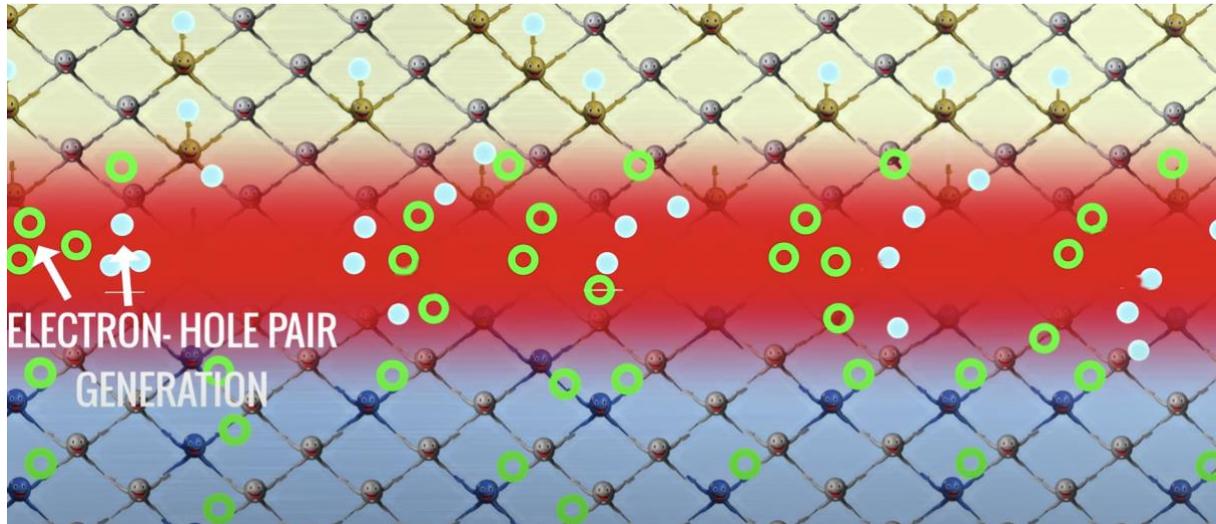
Figure 3 shows the electric field formed due to the migration of electrons.

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<sup>6</sup> “How do Solar cells work?” *YouTube*, 28 November 2018,

[https://www.youtube.com/watch?v=L\\_q6LRgKpTw](https://www.youtube.com/watch?v=L_q6LRgKpTw) . Accessed 7 November 2023.

When light hits the surface, it reaches till the depletion region thus exciting the electrons in the depletion region. Due to the energy from the light, electron-hole pairs will be ejected out.



7

Figure 4 shows generation of electron-hole pairs due to the light's penetration.

The electrons accumulate on the top and the holes on the bottom due to the electric field formed, creating a potential difference between the materials and a current to flow in an external wire. When the sides get connected, excess electrons from the n-type material flow to the p-type semiconductor and start filling the holes. This constant creation of electron-hole pairs in the depletion region due to incident sunlight keeps the electrons flowing from the n-

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<sup>7</sup> “How do Solar cells work?” *YouTube*, 28 November 2018,

[https://www.youtube.com/watch?v=L\\_q6LRgKpTw](https://www.youtube.com/watch?v=L_q6LRgKpTw) . Accessed 7 November 2023.

type to the p-type. The minimum potential difference along the semiconductor's P-N junction to cause the diffusion of electrons and holes is called *barrier potential*<sup>8</sup>.

## **Band Theory**<sup>9</sup>

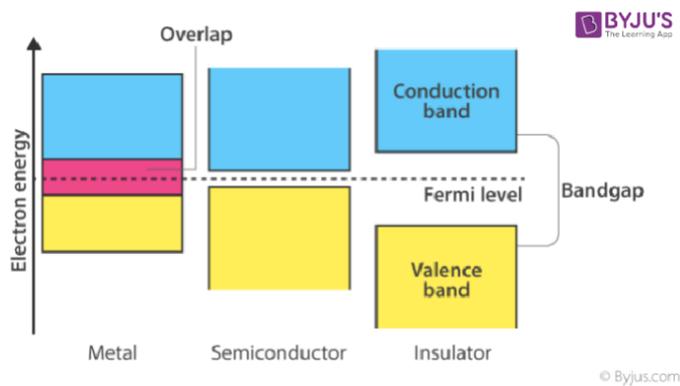
To see the difference between metals and semiconductors, it is helpful to see the diagram<sup>10</sup> below. In semiconductors, there is a small gap between the conduction and valence band, that thermal excitations of electrons can bridge the gap. Electrons from the valence band can easily jump to the conduction band with the energy from incident photons. These bands

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<sup>8</sup> “What is potential barrier ?” Semiconductor for You, 1 November 2017, <https://www.semiconductorforu.com/what-is-potential-barrier/> . Accessed 19 December 2023.

<sup>9</sup> “Conduction Band - Definition, Valence Band vs Conduction Band.” BYJU'S, <https://byjus.com/jee/conduction-band/> . Accessed 19 December 2023.

<sup>10</sup> “Photovoltaic effect.” Energy Education, [https://energyeducation.ca/encyclopedia/Photovoltaic\\_effect](https://energyeducation.ca/encyclopedia/Photovoltaic_effect). Accessed 19 December 2023.



overlap in metals which makes it easy for electrons to get excited and move from valence band to conduction band.

Figure 2 shows the conduction and valence bands in various materials.

## The photovoltaic effect

“The PV effect is a process that, when sun lights strike on the boundary layer of semiconductor materials, electric current can be generated<sup>11</sup>.” When sunlight reaches the depletion region where there is no charge, the photons are absorbed by the electrons – only if they are of a suitable wavelength – making them jump to a higher energy state which is the “conduction band”. When they jump, a hole is left behind in the valence band, and they move into the conduction band when they get excited. The electrons in the conduction band are free to move around, and because of their mobility, an electric current can be generated.

In solar panels, in the p-n junction the n-type material is heavily doped and is thinner, while the p-type material is lightly doped and is thicker. This way of doping creates a bigger

<sup>11</sup> “,” , - YouTube, 13 November 2023,

<https://www.sciencedirect.com/topics/engineering/photovoltaic-effect> . Accessed 12 January 2024.

depletion region, causing more electrons and holes to be released. More free electrons create a larger electric current through an external wire.

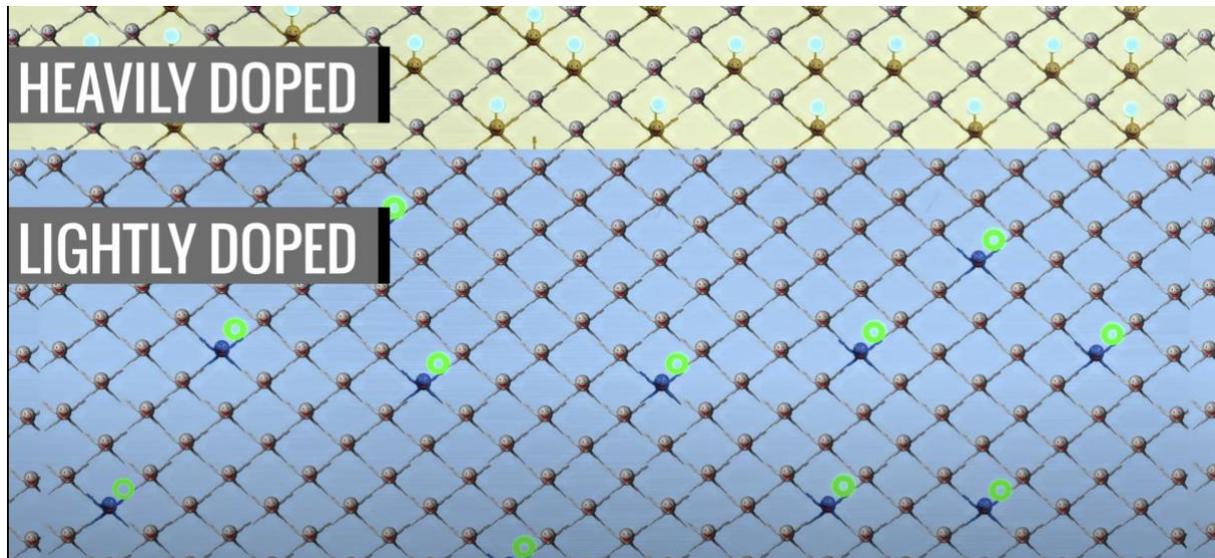


Figure 5 shows structure of a p-n junction is a real solar panel.

The current obtained from solar panels is direct current, or DC, therefore inverters need to change it to alternating current, AC, since households use that.

## 2.2 Structure

Solar panels also use the photovoltaic effect to generate electricity.

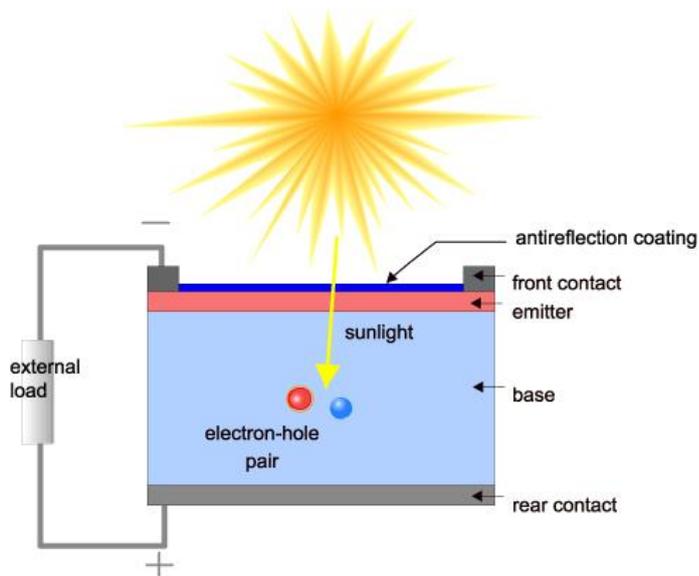


Figure 6 shows the basic structure of a photovoltaic cell.

As seen in figure 4<sup>12</sup>, the first layer is an antireflection coating. To reduce loss by reflection of light this layer is used; it also increases absorption of light and the power conversion efficiency, which is the ratio of incident energy from sunlight converted to usable electricity.

Usually, solar panels are covered with

highly transparent tempered glass, not only to protect it from environmental factors like storms and rain, but also to allow the maximum amount of solar light to reach the photovoltaic cells.

Monocrystalline<sup>13</sup> (mono) panels, which are photovoltaic cells made from a single piece of silicon, are the most efficient. Even though they cost more than the other types of solar panels, monocrystalline ones have the highest efficiency and power output. Since they have a relatively compact design, they can easily be installed on houses with limited roof space.

<sup>12</sup> “Light Generated Current.” *PVEducation*, <https://www.pveducation.org/pvcdrom/solar-cell-operation/light-generated-current>. Accessed 10 October 2023.

<sup>13</sup> “Solar Photovoltaic Cell Basics.” *Department of Energy*, <https://www.energy.gov/eere/solar/solar-photovoltaic-cell-basics>. Accessed 16 September 2023.

## 2.3 Effect of temperature on solar panel efficiency

A solar panel's efficiency depends on its temperature coefficient. This dictates how much its efficiency changes per °C, increase or decrease of the solar panel.

For example, if the temperature coefficient of a solar panel is -0.258% per 1°C, that means that per 1°C, increase in temperature, the efficiency of the solar panel will reduce by 0.258 percent, **and vice versa**. I.e., per 1°C decrease, there will be an increase in efficiency by 0.258%.<sup>14</sup>

Optimal solar panel temperature is 25°C, therefore solar panels are maintained between 15°C and 35°C.

## 3.0 Aim and Hypothesis

### 3.1 Aim

The primary aim of this investigation is to find how varying the angle, of the solar panel with respect to the source of light keeping wavelength constant, affects the power output of a solar panel.

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<sup>14</sup> Fox, Stuart. "How Does Heat Affect Solar Panel Efficiencies?" *Greentech Renewables*,

<https://www.greentechrenewables.com/article/how-does-heat-affect-solar-panel-efficiencies> .

Accessed 17 November 2023.

The secondary aim was finding how varying the wavelength of light affects the power output of a photovoltaic cell keeping angle constant.

### 3.2 Hypothesis

Irradiance is defined as “*the amount of light energy from one thing hitting a square meter of another each second*”<sup>15</sup>.”

The irradiance absorbed by a surface is equal to<sup>16</sup>

$$I_i = I_t \cos (\theta)$$

Where  $I_i$  = Irradiance absorbed by surface

$I_t$  = Total irradiance

$\theta$  = incident angle

Irradiance depends on the material’s orientation, while intensity does not. Due to this, there needs to be a  $\cos (\theta)$  term. Irradiance is related to power with the below equation:

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<sup>15</sup> “The importance of solar irradiance and meteorological data for PV design — RatedPower.”

RatedPower, 26 September 2022, <https://ratedpower.com/blog/solar-irradiance-meteorological-data/> . Accessed 3 October 2023.

<sup>16</sup> “Incident Angle of Sunlight | CE.” Clean Energy. Bright Futures.,

<https://cebrightfutures.org/learn/incident-angle-sunlight> . Accessed 8 January 2024.

$$E = \frac{P}{A}$$

E = Irradiance

P = Power

A = Surface area

According to the above equation, irradiance and power are directly related, and thus, as irradiance increases on a solar panel, the power should increase.

Thus, it is hypothesized that the observations of power output obtained from the angles 0° till 70° should follow the cosine curve, following the  $\cos(\theta)$  term, when keeping the wavelength of light constant. This means that the power output should decrease as the angle of the solar panel approaches 70°.

Since lower wavelengths of light mean higher frequency, it is hypothesized that higher frequencies of light should have the highest energy, and thus the highest power output.

## 4.0 Variables

### 4.1 Independent variables

1. Angle of solar panel relative to the horizontal wooden block (0° to 70° with 10° increments)

2. Wavelength of light incident on the solar panel (five colours used: white, red (620 nm to 750 nm), yellow (570 nm to 590 nm), green (495 nm to 570 nm), and blue (450 nm to 495 nm))

#### 4.2 Dependent variables

Power generated by the solar panel in watts.

#### 4.3 Controlled variables

Control variables	Method of controlling	Reason for controlling
Torch used	The same torch was used throughout the experiment. The torch was left to charge for several hours before usage to maintain a constant brightness.	If different intensities of light are incident on the solar panel the observations of voltage and current would be altered, thus changing the power calculated.
Gelatin paper of same thickness was used – of different colours	--	Different Gelatin paper could have varied thickness, affecting the intensity and wavelength of light incident on the solar panel.
Distance between solar panel and torch –	The ruler was mounted using a clamp and stand.	If the distance changes, then the incident intensity of light on the

measured with a ruler: 25 $\pm 0.05$ cm	The reading for the distance was visually measured.	solar panel would change, as intensity varies inversely as the square of distance, causing a change in the reading.
Wires used to connect solar panel to multimeter	The wires were soldered onto the solar panel right at the start of the experiment.	If a thinner wire was used, it could have a higher resistance, causing a change in the reading of power.
Temperature of the room was at 24 °C	The air conditioner was constant at 24 °C.	If there was a change in temperature, the reading from the multimeter would change because temperature inversely affects the solar panel efficiency.
Ambient light	All lights in the room were switched off. To remove any effects of ambient light, initial and final observations for voltage and current were taken.	Ambient light could interfere with the reading, causing voltage and current to be higher than the actual.

#### 4.4 Apparatus needed.

1. Solar panel – Max voltage: 6 V, Max power: 100 W, 10g - weight
2. Wires
3. Crocodile clips

4. 2 multimeters; one for measuring potential difference (with least count of 0.001 V) and one for measuring current (with least count of 0.001A).
5. 3 clamp stands.
6. Torch
7. Rotatable wooden inclined plane pivoted at one end.
8. Large protractor –  $0^\circ$  to  $180^\circ$ ,  $\pm 0.5^\circ$
9. Wooden blocks to adjust angle.
10. Load resistance.

## 5.0 Experimental Setup

### 5.1 Setting up the apparatus.

Firstly, the wires were soldered onto the solar panel to be connected to the multimeter. After soldering, the solar panel was stuck to the inclined plane using double-sided tape. A clamp stand was used to keep the torch 25cm above the solar panel. Six wooden blocks were stacked on top of one another and moved back and forth to change the angle of the inclined plane, as shown in figure 7. This made the change in angles very easy and accurate.

The voltage and current will be measured with two multimeters connected using crocodile clips and a wire soldered onto the solar panel.

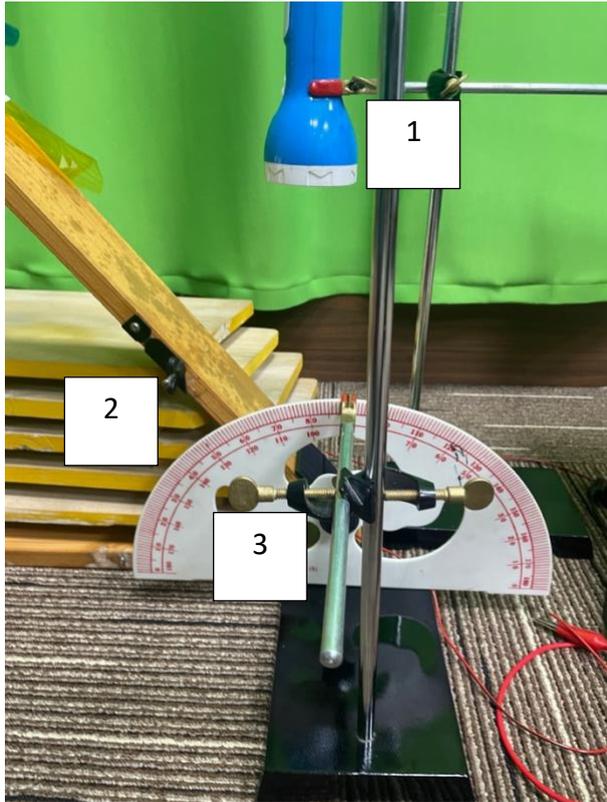


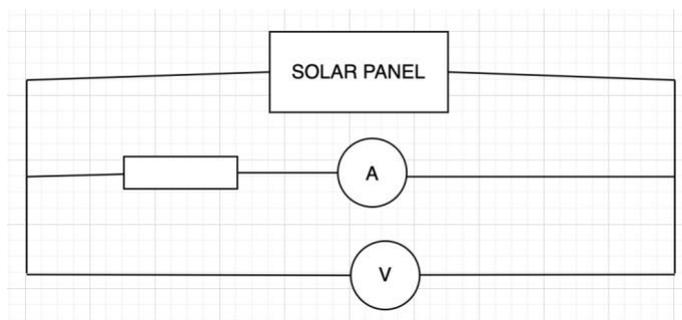
Figure 7 shows the experimental setup when the angle of the solar panel was changed relative to the torch.

The angle of the solar panel was varied in 10° increments using an inclined plane, where the angle of the incline was changed using larger wooden blocks. This was done by moving the stack of wooden planks back and forth. A piece of colored gelatin paper was put over the solar panel, secured with tape, to see variation of output with respect to wavelength of light. As seen in the diagram, the large protractor was held in place by a clamp and stand, and so was the torch vertically above the solar panel. To keep the protractor perfectly horizontal, it was kept in

line with top of the base of the inclined plane.

The power was calculated using the formula:

$$\text{power} = \text{voltage} \times \text{current}$$



This picture shows a self-made circuit diagram.

The diagram on the left shows a self-made sample circuit diagram of the solar panel with the 2 multimeters. The voltmeter was connected in parallel while the ammeter was connected in series.

## 5.2 Safety, environmental and ethical concerns

This experiment did not present any major safety, environmental, nor ethical concerns.

## 6.0 Methodology

1. All lights in the room were switched off to minimize the effect of ambient light on the reading. The torch was charged prior to taking the observations.
2. Before the torch is switched on, the initial observations are taken for voltage and current, and for the ambient light as a control reading.
3. Next, the torch is switched on and immediately the observations for voltage and current are taken.
4. For each angle the potential difference and current was recorded for  $\theta = 0^\circ$  by taking no gelatin paper, i.e. white light is incident on the solar panel.
5. Different colors of gelatin paper were stuck on the incline plane to cover the entire solar panel. Red, blue, green, and yellow colors were used to vary the wavelength of light. Five trials for each wavelength were taken.
6. Steps 1-5 were repeated  $0^\circ - 70^\circ$  with  $10^\circ$  increments for each successive observation.

## 7.0 Data Collection and Processing

### 7.1 Raw data

#### Observations for current and voltage at $\theta = 0^\circ$

Trial no.	Color ( $\lambda$ )	Angle ( $^\circ$ ) $\pm 1^\circ$	Initial potential difference due to ambient light (V) $\pm 0.001$	Final potential difference (V) $\pm 0.001$	$\Delta$ potential difference (V) $\pm 0.001$	Initial Current due to ambient light (A) $\pm 0.001$	Final Current (A) $\pm 0.001$	$\Delta$ Current (A) $\pm 0.001$
1	White	0	0.068	4.480	4.412	0.001	1.360	1.359
2		0	0.069	4.480	4.411	0.001	1.310	1.309
3		0	0.068	4.480	4.412	0.001	1.340	1.339
4		0	0.07	4.400	4.33	0.001	1.250	1.249
5		0	0.068	4.400	4.332	0.001	1.370	1.369
1	Red (620 – 750 nm)	0	0.044	3.660	3.616	0.001	0.570	0.569
2		0	0.044	3.640	3.596	0.001	0.540	0.539
3		0	0.044	3.620	3.576	0.001	0.550	0.549
4		0	0.044	3.60	3.556	0.001	0.530	0.529

5		0	0.044	3.550	3.506	0.001	0.530	0.529
1	Yellow (570 – 590 nm)	0	0.048	3.900	3.852	0.001	0.800	0.799
2		0	0.048	3.860	3.812	0.001	0.780	0.779
3		0	0.048	3.870	3.822	0.001	0.750	0.749
4		0	0.048	3.870	3.822	0.001	0.740	0.739
5		0	0.048	3.860	3.812	0.001	0.900	0.899
1	Green (495 – 570 nm)	0	0.044	3.500	3.456	0.001	0.630	0.629
2		0	0.044	3.480	3.436	0.001	0.640	0.639
3		0	0.044	3.480	3.436	0.001	0.600	0.599
4		0	0.044	3.480	3.436	0.001	0.580	0.579
5		0	0.044	3.480	3.436	0.001	0.640	0.639
1	Blue (450 – 495 nm)	0	0.044	3.470	3.426	0.001	0.630	0.629
2		0	0.044	3.500	3.456	0.001	0.640	0.639
3		0	0.044	3.510	3.466	0.001	0.620	0.619
4		0	0.044	3.480	3.436	0.001	0.630	0.629
5		0	0.044	3.480	3.436	0.001	0.630	0.629

**Observations for current and voltage at  $\theta = 20^\circ$**

<b>Trial no.</b>	<b>Color (<math>\lambda</math>)</b>	<b>Angle (<math>^{\circ}</math>) <math>\pm 1^{\circ}</math></b>	<b>Initial potential difference due to ambient light (V) <math>\pm 0.001</math></b>	<b>Final potential difference (V) <math>\pm 0.001</math></b>	<b><math>\Delta</math> potential difference (V) <math>\pm 0.001</math></b>	<b>Initial Current due to ambient light (A) <math>\pm 0.001</math></b>	<b>Final Current (A) <math>\pm 0.001</math></b>	<b><math>\Delta</math> Current (A) <math>\pm 0.001</math></b>
1	White	20	0.092	4.550	4.458	0.001	1.200	1.199
2		20	0.092	4.550	4.458	0.001	1.130	1.129
3		20	0.091	4.540	4.449	0.001	1.180	1.179
4		20	0.092	4.540	4.448	0.001	1.130	1.129
5		20	0.093	4.530	4.437	0.001	1.150	1.149
1	Red (620 – 750 nm)	20	0.084	3.730	3.646	0.001	0.500	0.499
2		20	0.083	3.730	3.647	0.001	0.446	0.445
3		20	0.096	3.750	3.654	0.001	0.515	0.514
4		20	0.095	3.740	3.645	0.001	0.504	0.503
5		20	0.095	3.730	3.635	0.001	0.508	0.507
1	Yellow (570 – 590 nm)	20	0.098	4.270	4.172	0.001	0.914	0.913
2		20	0.096	4.250	4.154	0.001	0.938	0.937
3		20	0.096	4.260	4.164	0.001	0.906	0.905
4		20	0.096	4.260	4.164	0.001	0.904	0.903
5		20	0.096	4.240	4.144	0.001	0.949	0.948

1	Green (495 – 570 nm)	20	0.08	4.000	3.92	0.001	0.660	0.659
2		20	0.088	3.960	3.872	0.001	0.640	0.639
3		20	0.09	3.950	3.86	0.001	0.644	0.643
4		20	0.091	3.920	3.829	0.001	0.690	0.689
5		20	0.091	3.940	3.849	0.001	0.640	0.639
1	Blue (450 – 495 nm)	20	0.094	3.960	3.866	0.001	0.724	0.723
2		20	0.093	3.970	3.877	0.001	0.660	0.659
3		20	0.093	3.970	3.877	0.001	0.650	0.649
4		20	0.094	3.970	3.876	0.001	0.660	0.659
5		20	0.093	3.960	3.867	0.001	0.647	0.646

**Observations for current and voltage at  $\theta = 50^\circ$**

Trial no.	Color ( $\lambda$ )	Angle ( $^\circ$ ) $\pm 1^\circ$	Initial potential difference due to ambient light (V) $\pm 0.001$	Final potential difference (V) $\pm 0.001$	$\Delta$ potential difference (V) $\pm 0.001$	Initial Current due to ambient light (A) $\pm 0.001$	Final Current (A) $\pm 0.001$	$\Delta$ Current (A) $\pm 0.001$
1	White	50	0.115	4.500	4.385	0.001	0.720	0.719

2		50	0.115	4.550	4.435	0.001	0.680	0.679
3		50	0.115	4.530	4.415	0.001	0.600	0.599
4		50	0.115	4.560	4.445	0.001	0.660	0.659
5		50	0.115	4.620	4.505	0.001	0.720	0.719
1	Red (620 – 750 nm)	50	0.102	3.300	3.198	0.001	0.200	0.199
2		50	0.102	3.400	3.298	0.001	0.200	0.199
3		50	0.102	3.340	3.238	0.001	0.210	0.209
4		50	0.102	3.400	3.298	0.001	0.220	0.219
5		50	0.102	3.500	3.398	0.001	0.210	0.209
1	Yellow (570 – 590 nm)	50	0.103	4.160	4.057	0.001	0.410	0.409
2		50	0.103	4.100	3.997	0.001	0.430	0.429
3		50	0.103	4.050	3.947	0.001	0.400	0.399
4		50	0.103	4.070	3.967	0.001	0.350	0.349
5		50	0.103	3.980	3.877	0.001	0.330	0.329
1	Green (495 – 570 nm)	50	0.1	3.760	3.66	0.001	0.270	0.269
2		50	0.1	3.730	3.63	0.001	0.230	0.229
3		50	0.1	3.690	3.59	0.001	0.250	0.249
4		50	0.1	3.650	3.55	0.001	0.260	0.259
5		50	0.1	3.630	3.53	0.001	0.280	0.279
1	Blue	50	0.1	3.700	3.6	0.001	0.19	0.189

2	(450 – 495 nm)	50	0.1	3.600	3.5	0.001	0.190	0.189
3		50	0.1	3.600	3.5	0.001	0.230	0.229
4		50	0.1	3.580	3.48	0.001	0.240	0.239
5		50	0.1	3.550	3.45	0.001	0.270	0.269

**Observations for current and voltage at  $\theta = 70^\circ$**

Trial no.	Color ( $\lambda$ )	Angle ( $^\circ$ ) $\pm 1^\circ$	Initial potential difference due to ambient light (V) $\pm 0.001$	Final potential difference (V) $\pm 0.001$	$\Delta$ potential difference (V) $\pm 0.001$	Initial Current due to ambient light (A) $\pm 0.001$	Final Current (A) $\pm 0.001$	$\Delta$ Current (A) $\pm 0.001$
1	White	70	0.085	3.590	3.505	0.001	0.260	0.259
2		70	0.085	3.500	3.415	0.001	0.260	0.259
3		70	0.085	3.450	3.365	0.001	0.250	0.249
4		70	0.085	3.470	3.385	0.001	0.240	0.239
5		70	0.085	3.500	3.415	0.001	0.240	0.239
1	Red (620 – 750 nm)	70	0.087	2.400	2.313	0.001	0.070	0.069
2		70	0.087	2.350	2.263	0.001	0.067	0.066
3		70	0.087	2.360	2.273	0.001	0.071	0.07
4		70	0.087	2.380	2.293	0.001	0.070	0.069
5		70	0.087	2.300	2.213	0.001	0.068	0.067

1	Yellow (570 – 590 nm)	70	0.092	3.200	3.108	0.001	0.130	0.129
2		70	0.092	3.150	3.058	0.001	0.140	0.139
3		70	0.092	3.200	3.108	0.001	0.150	0.149
4		70	0.092	3.200	3.108	0.001	0.160	0.159
5		70	0.092	3.100	3.008	0.001	0.170	0.169
1	Green (495 – 570 nm)	70	0.089	2.700	2.611	0.001	0.120	0.119
2		70	0.089	2.650	2.561	0.001	0.116	0.115
3		70	0.089	2.550	2.461	0.001	0.106	0.105
4		70	0.089	2.440	2.351	0.001	0.099	0.098
5		70	0.089	2.500	2.411	0.001	0.107	0.106
1	Blue (450 – 495 nm)	70	0.091	2.600	2.509	0.001	0.120	0.119
2		70	0.091	2.700	2.609	0.001	0.116	0.115
3		70	0.091	2.560	2.469	0.001	0.117	0.116
4		70	0.091	2.500	2.409	0.001	0.106	0.105
5		70	0.091	2.500	2.409	0.001	0.103	0.102

## 7.2 Processed Data

The raw data obtained for  $\theta = 70^\circ$  is:

Trial no.	Color ( $\lambda$ )	Angle ( $^{\circ}$ ) $\pm 1^{\circ}$	Initial potential difference due to ambient light (V) $\pm 0.001$	Final potential difference (V) $\pm 0.001$	$\Delta$ potential difference (V) $\pm 0.001$	Initial Current due to ambient light (A) $\pm 0.001$	Final Current (A) $\pm 0.001$	$\Delta$ Current (A) $\pm 0.001$
1	Blue (450 – 495 nm)	70	0.091	2.6	2.509	0.001	0.12	0.119
2		70	0.091	2.7	2.609	0.001	0.116	0.115
3		70	0.091	2.56	2.469	0.001	0.117	0.116
4		70	0.091	2.5	2.409	0.001	0.106	0.105
5		70	0.091	2.5	2.409	0.001	0.103	0.102

Example calculations for average potential difference and current are:

The average voltage is found by taking the average of the  $\Delta$  potential difference observations:

$$\frac{2.509 + 2.609 + 2.469 + 2.409 + 2.409}{5} = 2.481 \text{ V}$$

Similarly, the average current can be taken the same way:

$$\frac{0.119 + 0.115 + 0.116 + 0.105 + 0.102}{5} = 0.111 \text{ A}$$

### 7.2.1 Uncertainties

### Uncertainty for average power:

Power = voltage x current

$$\frac{\Delta P}{P} = \frac{\Delta V}{V} + \frac{\Delta I}{I}$$

The absolute uncertainty is the sum of fractional uncertainties of voltage and currents, multiplied by the value of power for that reading.

For example, at  $0^\circ$ :

Average V (V) $\pm 0.001$	Average I (A) $\pm 0.001$	Average Power (W)
4.3794	1.325	5.803

$$\frac{\Delta P}{P} = \frac{\Delta V}{V} + \frac{\Delta I}{I} = \frac{0.001}{4.3794} + \frac{0.001}{1.325} = 9.83 \times 10^{-4}$$

$$\Delta P = P \times 9.83 \times 10^{-4} = 5.803 \times 9.83 \times 10^{-4}$$

$$\Delta P = 5.7 \times 10^{-3} = 0.0057\text{W}$$

### 7.2.2 Tables of data.

**Average voltage, current, power with uncertainties at  $\theta = 0^\circ$**

Color of paper (wavelength)	$\theta$ in $^{\circ}$ $\pm 1^{\circ}$	Average V (V) $\pm 0.001$	Average I (A) $\pm 0.001$	Average Power (W)	Uncertainty in average power (W) $\Delta P = P \left( \frac{\Delta V}{V} + \frac{\Delta I}{I} \right)$
White	0	4.380	1.330	5.80	$5.70 \times 10^{-3}$
Red (620 - 750 nm)	0	3.570	0.540	1.94	$4.10 \times 10^{-3}$
Yellow (570 - 590 nm)	0	3.820	0.790	3.03	$4.60 \times 10^{-3}$
Green (495 - 570nm)	0	3.440	0.620	2.12	$4.04 \times 10^{-3}$
Blue (450 – 495 nm)	0	3.440	0.630	2.17	$4.10 \times 10^{-3}$

**Average voltage, current, power with uncertainties at  $\theta = 20^{\circ}$**

Color of paper (wavelength)	$\theta$ in $^{\circ}$ $\pm 1^{\circ}$	Average V (V) $\pm 0.001$	Average I (A) $\pm 0.001$	Average Power (W)	Uncertainty in average power (W) $\Delta P = P \left( \frac{\Delta V}{V} + \frac{\Delta I}{I} \right)$
White	20	4.450	1.160	5.15	$5.60 \times 10^{-3}$

Red (620 - 750 nm)	20	3.650	0.490	1.80	$4.20 \times 10^{-3}$
Yellow (570 - 590 nm)	20	4.160	0.920	3.83	$5.10 \times 10^{-3}$
Green (495 - 570nm)	20	3.870	0.650	2.53	$4.50 \times 10^{-3}$
Blue (450 – 495 nm)	20	3.870	0.670	2.58	$4.50 \times 10^{-3}$

**Average voltage, current, power with uncertainties at  $\theta = 50^\circ$**

<b>Color of paper (wavelength)</b>	<b><math>\theta</math> in <math>^\circ</math> <math>\pm 1^\circ</math></b>	<b>Average V (V) <math>\pm 0.001</math></b>	<b>Average I (A) <math>\pm 0.001</math></b>	<b>Average Power (W)</b>	<b>Uncertainty in average power (W) <math>\Delta P = P \left( \frac{\Delta V}{V} + \frac{\Delta I}{I} \right)</math></b>
White	50	4.440	0.680	2.99	$5.10 \times 10^{-3}$
Red (620 - 750 nm)	50	3.290	0.210	0.68	$3.44 \times 10^{-3}$
Yellow (570 - 590 nm)	50	3.970	0.380	1.52	$4.38 \times 10^{-3}$
Green (495 - 570nm)	50	3.590	0.260	0.92	$3.79 \times 10^{-3}$

Blue (450 – 495 nm)	50	3.510	0.220	0.78	$3.77 \times 10^{-3}$
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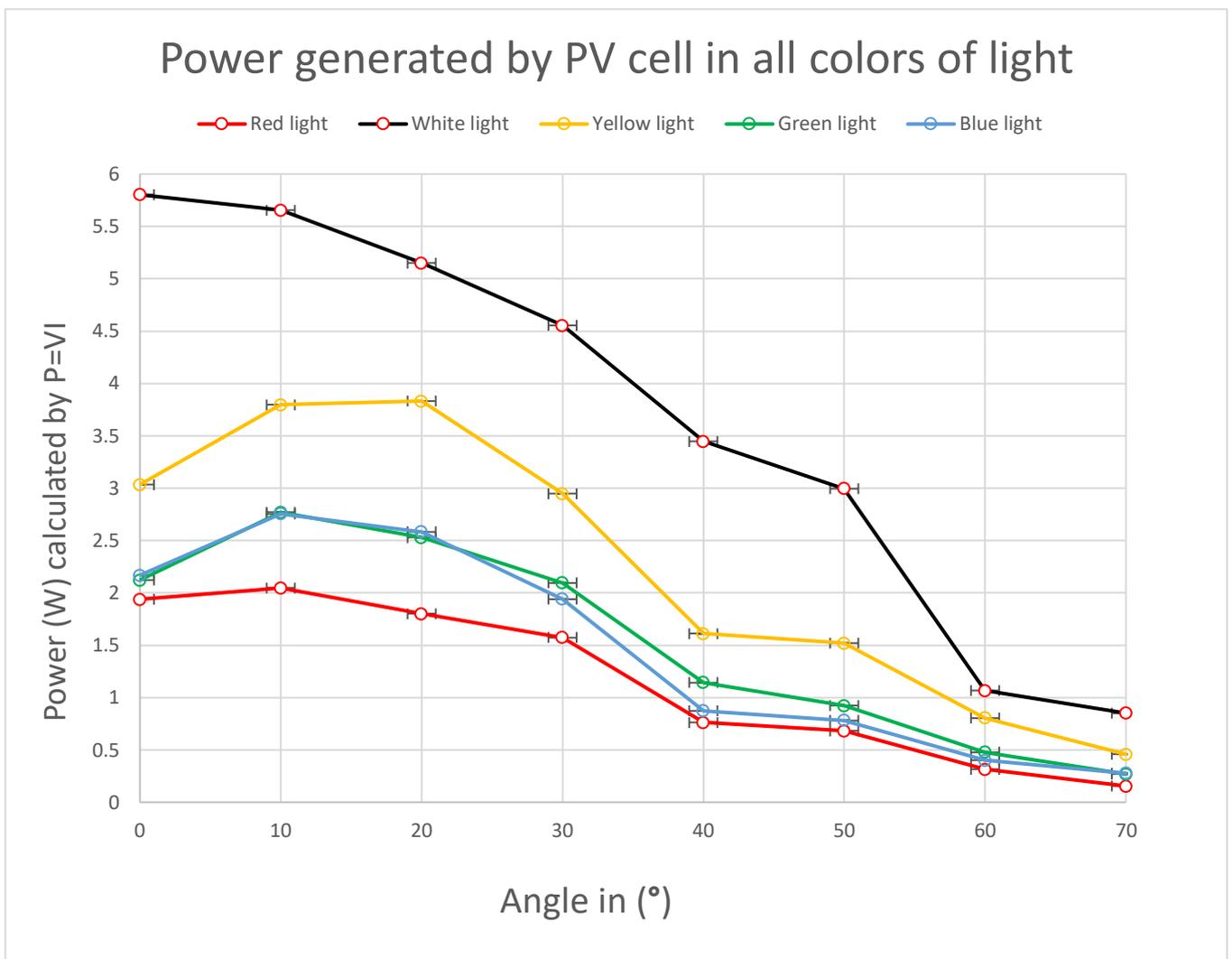
**Average voltage, current, power with uncertainties at  $\theta = 70^\circ$**

<b>Color of paper (wavelength)</b>	<b><math>\theta</math> in <math>^\circ</math> <math>\pm 1^\circ</math></b>	<b>Average V (V) <math>\pm 0.001</math></b>	<b>Average I (A) <math>\pm 0.001</math></b>	<b>Average Power (W)</b>	<b>Uncertainty in average power (W) <math>\Delta P = P \left( \frac{\Delta V}{V} + \frac{\Delta I}{I} \right)</math></b>
White	70	3.420	0.250	0.85	$3.64 \times 10^{-3}$
Red (620 - 750 nm)	70	0.230	0.068	0.15	$2.86 \times 10^{-3}$
Yellow (570 - 590 nm)	70	3.080	0.150	0.46	$3.22 \times 10^{-3}$
Green (495 - 570nm)	70	2.480	0.110	0.27	$2.56 \times 10^{-3}$
Blue (450 – 495 nm)	70	2.480	0.110	0.28	$2.66 \times 10^{-3}$

The rest of the data tables are included in the appendix.

## 7.2.2 Final Graph

Below shows the graph of the average power generated by the solar panel for different angles with varying wavelengths of light incident on the solar panel.



The vertical error bars are not visible as the uncertainty is too small.

## 8.0 Analysis

All the wavelengths of light present major decreases in power output from 30°- 40° and 50°- 60° on the x-axis, possibly due to random error, but it is unlikely since the readings were repeated. We can see that power is approaching zero as the angle measure increases.

In the rest of the wavelengths – red (620 nm to 750 nm), yellow (570 nm to 590 nm), green (495 nm to 570 nm), and blue (450 nm to 495 nm)- the power is not the highest at 0°, as they have observations of 2.04W, 3.79W, 2.77W, and 2.75W respectively at 10°. At 0°, however, they have observations of 1.94W, 3.03W, 2.12W, and 2.17W respectively. The observations are clearly lower at 0°.

This could be due to the gelatin paper used, since the paper might not provide the actual wavelength for the exact color. White light consistently has the highest power output over all the angle measures, since it has the whole spectrum of visible light and thus could have wavelengths of light which are not considered, and red has the lowest. Red having the lowest power output can be explained; due to the higher wavelength frequency would be lower, thus the light would have a low energy and therefore would not be able to excite the electrons in the solar cell as much as yellow light to generate an electric current. However, using this logic, it is interesting to note that blue light is consistently the second lowest in terms of power generation with change in angles, despite its high frequency.

For example, at 30° the observations were the following:

Wavelength of light (nm)	Power output (W)
White	4.55
Red: 620 -750 nm	1.57
Yellow: 570 - 590 nm	2.95
Green: 495 - 570nm	2.10
Blue: 450 – 495 nm	1.94

Since blue light has the lowest wavelength, the frequency would be the highest as seen in  $f=c/\lambda$  (with c being a constant). The highest frequency should mean the highest energy; however, research shows that the highest frequency spectrum of visible light, such as violet light with  $\lambda=380nm$ , simply passes through the solar cell<sup>17</sup>. Electrons are very selective in their choice of photons; they only absorb those which have the right amount of energy. Consequently, photons with too much energy are also not absorbed, thus the blue light photons are too energy dense and so are not absorbed as much as yellow light photons (with wavelength between 570 – 590 nm).

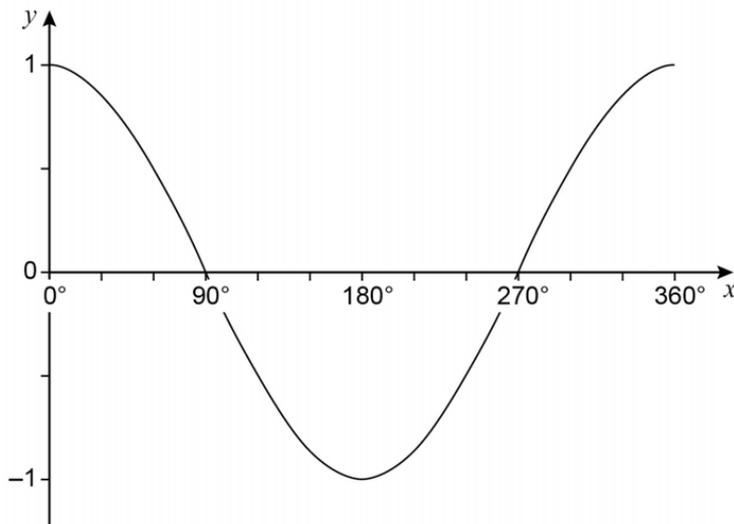
The average voltages for white light across the four angles do not vary much at 70°. Thus, it can be reasonably concluded that the changes in power were caused majorly due to the changing values of current.

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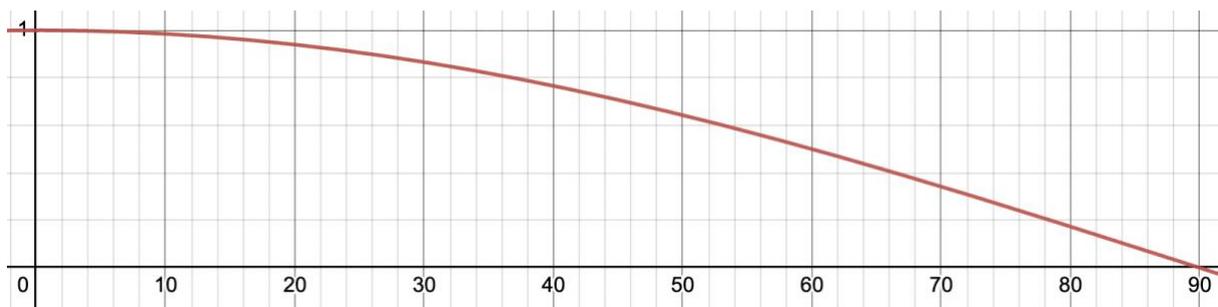
<sup>17</sup> “Effect of Colour of Light on Solar Cells - Easy Solar Guide.” *Easy Solar Guide - Easy Solar Guide*, 22 November 2019, <https://easysolar.guide/effect-of-color-of-light-on-solar-cells/> . Accessed 10 November 2023.

The highest power output was seen at the lower angles ( $0^\circ$  &  $10^\circ$ ), but ideally should have been the highest at zero.

Due to the concept of irradiance mentioned in the hypothesis, the amount of light hitting the solar panel reduces as the angle increases, thus resulting is a graph roughly the shape of  $y = \cos(x)$ , where 'y' is the power output and 'x' is the angle of the solar panel.



The figure on the left shows the full cosine curve but since this experiment deals with angles from  $0 - 70$ , it is important only to see  $0^\circ - 90^\circ$ .



The figure above shows the cosine curve from  $0^\circ - 90^\circ$ . As the angle approaches  $90^\circ$ , the value of  $\cos(\theta)$  approaches zero. This same concept can be seen in irradiance since as the angle of the solar panel approaches  $70^\circ$ , the irradiance approaches zero, since the intensity of light keeps reducing.

The readings therefore follow the shape of the curve of  $y=\cos(\theta)$ .

## 9.0 Evaluation

The wires in the solar panel could have heated up, causing resistance to increase thus reducing current output. To nullify this, every 20 minutes the circuit was left to cool in the air-conditioned room so that the wire's temperature would come back to normal.

The optimal solar panel temperature is 25°C. For this same reason, the temperature of the air-conditioned room where the experiment was conducted was kept at 24°C, to account for some losses in cool air from opening and closing the door.

Furthermore, while measuring the angle of the incline plane parallax error could have occurred. There wasn't a proper horizontal plane that could be referred to while adjusting the distance. This could have caused minute error in the distance between the solar panel and thus affected the reading. An app could have been used to measure the angle, thus minimizing the effect of parallax error.

Additionally, since the ruler and torch were kept stable via clamp and stands, it could be possible that the ruler and torch were not perfectly vertical. This again could have caused an error in the distance between the solar panel and the torch, changing the reading. Since the torch was repeatedly removed and put for charge, the exact distance of the torch might have changed. A torch with a stable power supply could be used to reduce error.

While fixing the solar panel onto the pivoted inclined plane, fingerprints and scratches could appear on the surface of the solar panel, thus reducing the power output since less light is absorbed.

Random errors were reduced by repeating the observations five times. If just the final observations were taken, it would've been impossible to see the actual output of the solar panel with only the light from the torch.

## 10.0 Conclusion

The research question is: **'How does varying the angle of a solar panel affect its power output, keeping wavelength of light constant?'**

As seen in the graph of the cosine curve, the gradient of the curve becomes steeper as it approaches  $90^\circ$ , thus it can be concluded that the resulting graph the primary aim is fulfilled, and the hypothesis is proven to be partially true. The secondary aim was to find the relationship between wavelength of light and power output, keeping angle constant, and it was hypothesized that as frequency of light increases, so should the power output. However, the hypothesis is proved wrong. Even though yellow light had a lower frequency than blue light, it consistently had a higher power output; since electrons only absorb photons with only the right amount of energy, blue light has too much energy for the electrons. Since not many electrons absorb the blue light, less electron-hole pairs are released from the depletion region, and a lower current is generated.

## 11.0 Future scope

The experiment could be performed by taking a larger solar panel which can absorb more light from a light source. The light source should also be concentrated so that the reading is accurate. Lastly, colored light could be used instead of color filters to get light at a particular frequency, and more angles could be taken for a larger range of observations. By using color filters, a range of wavelengths were considered, rather than one wavelength, for each wavelength of light. Light of all wavelengths in the visible region could be used. The colors which were missed out were violet, indigo, and orange. This experiment could also be repeated using different types of solar panels.

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## 13.0 Appendix

The following tables show the raw and processed data tables which were not added in the above sections.

$\theta = \underline{10 \text{ degrees}}$  (raw data)

Trial no.	Color (wavelength)	Angle (degrees) $\pm 1$	Initial Voltage (V) $\pm 0.001$	Final Voltage (V) $\pm 0.001$	Delta Voltage (V) $\pm 0.001$	Initial Current (A) $\pm 0.001$	Final Current (A) $\pm 0.001$	Delta Current (A) $\pm 0.001$
1	White	10	0.115	4.5	4.385	0.001	1.301	1.3
2		10	0.115	4.55	4.435	0.001	1.23	1.229
3		10	0.115	4.53	4.415	0.001	1.237	1.236
4		10	0.115	4.56	4.445	0.001	1.267	1.266
5		10	0.115	4.62	4.505	0.001	1.253	1.252
1	Red (620 – 750 nm)	10	0.053	3.76	3.707	0.001	0.55	0.549
2		10	0.053	3.75	3.697	0.001	0.57	0.569
3		10	0.053	3.74	3.687	0.001	0.573	0.572
4		10	0.053	3.75	3.697	0.001	0.554	0.553

5		10	0.053	3.77	3.717	0.001	0.522	0.521
1	Yellow (570 – 590 nm)	10	0.056	4.3	4.244	0.001	0.889	0.888
2		10	0.055	4.29	4.235	0.001	0.881	0.88
3		10	0.055	4.29	4.235	0.001	0.903	0.902
4		10	0.055	4.24	4.185	0.001	0.941	0.94
5		10	0.056	4.29	4.234	0.001	0.88	0.879
1	Green (495 – 570 nm)	10	0.054	4.02	3.966	0.001	0.67	0.669
2		10	0.054	3.99	3.936	0.001	0.69	0.689
3		10	0.054	3.98	3.926	0.001	0.714	0.713
4		10	0.053	3.98	3.927	0.001	0.729	0.728
5		10	0.054	3.96	3.906	0.001	0.723	0.722
1	Blue (450 – 495 nm)	10	0.055	4	3.945	0.001	0.69	0.689
2		10	0.055	4.02	3.965	0.001	0.7	0.699
3		10	0.055	4.02	3.965	0.001	0.7	0.699
4		10	0.055	4.02	3.965	0.001	0.69	0.689
5		10	0.055	4.02	3.965	0.001	0.701	0.7

$\theta = 30$  degrees (raw data)

<b>Trial no.</b>	<b>Color (wavelength)</b>	<b>Angle (degrees) ± 1</b>	<b>Initial Voltage (V) ± 0.001</b>	<b>Final Voltage (V) ± 0.001</b>	<b>Delta Voltage (V) ± 0.001</b>	<b>Initial Current (A) ± 0.001</b>	<b>Final Current (A) ± 0.001</b>	<b>Delta Current (A) ± 0.001</b>
1	White	30	0.1	4.41	4.31	0.001	1.06	1.059
2		30	0.098	4.39	4.292	0.001	1.06	1.059
3		30	0.098	4.38	4.282	0.001	1.08	1.079
4		30	0.098	4.33	4.232	0.001	1.05	1.049
5		30	0.094	4.36	4.266	0.001	1.08	1.079
1	Red (620 – 750 nm)	30	0.085	3.56	3.475	0.001	0.44	0.439
2		30	0.086	3.55	3.464	0.001	0.47	0.469
3		30	0.086	3.54	3.454	0.001	0.47	0.469
4		30	0.087	3.52	3.433	0.001	0.47	0.469
5		30	0.086	3.56	3.474	0.001	0.43	0.429
1	Yellow (570 – 590 nm)	30	0.088	4.07	3.982	0.001	0.71	0.709
2		30	0.086	4.07	3.984	0.001	0.714	0.713
3		30	0.086	4.06	3.974	0.001	0.74	0.739
4		30	0.088	4.04	3.952	0.001	0.77	0.769
5		30	0.086	4.05	3.964	0.001	0.78	0.779
1	Green (495 – 570 nm)	30	0.084	3.77	3.686	0.001	0.56	0.559
2		30	0.086	3.73	3.644	0.001	0.59	0.589
3		30	0.088	3.73	3.642	0.001	0.59	0.589

4		30	0.088	3.74	3.652	0.001	0.59	0.589
5		30	0.088	3.76	3.672	0.001	0.54	0.539
1	Blue (450 – 495 nm)	50	0.9	3.77	2.87	0.001	0.55	0.549
2		50	0.089	3.74	3.651	0.001	0.59	0.589
3		50	0.089	3.77	3.681	0.001	0.55	0.549
4		50	0.09	3.77	3.68	0.001	0.54	0.539
5		50	0.09	3.76	3.67	0.001	0.54	0.539

$\theta = \underline{40 \text{ degrees}}$  (raw data)

Trial no.	Color (wavelength)	Angle (degrees) $\pm 1$	Initial	Final	Delta	Initial	Final	Delta
			Voltage (V) $\pm 0.001$	Voltage (V) $\pm 0.001$	Voltage (V) $\pm 0.001$	Current (A) $\pm 0.001$	Current (A) $\pm 0.001$	Current (A) $\pm 0.001$
1	White	40	0.079	4.61	4.531	0.001	0.75	0.749
2		40	0.078	4.58	4.502	0.001	0.8	0.749
3		40	0.078	4.57	4.492	0.001	0.85	0.849
4		40	0.078	4.54	4.462	0.001	0.79	0.789
5		40	0.078	4.55	4.472	0.001	0.7	0.699
1	Red (620 – 750 nm)	40	0.067	3.55	3.483	0.001	0.2	0.199
2		40	0.067	3.49	3.423	0.001	0.2	0.199
3		40	0.066	3.5	3.434	0.001	0.24	0.239

4		40	0.068	3.5	3.432	0.001	0.19	0.189
5		40	0.067	3.5	3.433	0.001	0.28	0.279
1	Yellow (570 – 590 nm)	40	0.072	4.1	4.028	0.001	0.4	0.399
2		40	0.072	4.15	4.078	0.001	0.4	0.399
3		40	0.072	4.05	3.978	0.001	0.37	0.369
4		40	0.072	4.07	3.998	0.001	0.35	0.349
5		40	0.072	4.06	3.988	0.001	0.49	0.489
1	Green (495 – 570 nm)	40	0.07	3.75	3.68	0.001	0.31	0.309
2		40	0.07	3.74	3.67	0.001	0.33	0.329
3		40	0.07	3.75	3.68	0.001	0.33	0.329
4		40	0.07	3.7	3.63	0.001	0.3	0.299
5		40	0.07	3.69	3.62	0.001	0.3	0.299
1	Blue (450 – 495 nm)	40	0.07	3.8	3.73	0.001	0.26	0.259
2		40	0.07	3.7	3.63	0.001	0.22	0.219
3		40	0.07	3.67	3.6	0.001	0.24	0.239
4		40	0.07	3.78	3.71	0.001	0.25	0.249
5		40	0.07	3.68	3.61	0.001	0.23	0.229

$\theta = \underline{60 \text{ degrees}}$  (raw data)

<b>Trial no.</b>	<b>Color (wavelength)</b>	<b>Angle (degrees) ± 1</b>	<b>Initial Voltage (V) ± 0.001</b>	<b>Final Voltage (V) ± 0.001</b>	<b>Delta Voltage (V) ± 0.001</b>	<b>Initial Current (A) ± 0.001</b>	<b>Final Current (A) ± 0.001</b>	<b>Delta Current (A) ± 0.001</b>
1	White	60	0.102	4.2	4.098	0.001	0.3	0.299
2		60	0.102	4.17	4.068	0.001	0.32	0.319
3		60	0.102	4.05	3.948	0.001	0.28	0.279
4		60	0.102	3.92	3.818	0.001	0.23	0.229
5		60	0.102	4	3.898	0.001	0.22	0.219
1	Red (620 – 750 nm)	60	0.096	3.1	3.004	0.001	0.11	0.109
2		60	0.096	3.09	2.994	0.001	0.113	0.112
3		60	0.096	3.01	2.914	0.001	0.104	0.103
4		60	0.096	2.9	2.804	0.001	0.104	0.103
5		60	0.096	3	2.904	0.001	0.11	0.109
1	Yellow (570 – 590 nm)	60	0.1	3.78	3.68	0.001	0.24	0.239
2		60	0.1	3.75	3.65	0.001	0.24	0.239
3		60	0.1	3.78	3.68	0.001	0.23	0.229
4		60	0.1	3.65	3.55	0.001	0.207	0.206
5		60	0.1	3.63	3.53	0.001	0.199	0.198
1	Green (495 – 570 nm)	60	0.098	3.25	3.152	0.001	0.15	0.149
2		60	0.098	3.25	3.152	0.001	0.15	0.149
3		60	0.098	3.22	3.122	0.001	0.15	0.149

4		60	0.098	3.2	3.102	0.001	0.156	0.155
5		60	0.098	3.15	3.052	0.001	0.167	0.166
1	Blue (450 – 495 nm)	60	0.1	3.17	3.07	0.001	0.12	0.119
2		60	0.1	3.22	3.12	0.001	0.13	0.129
3		60	0.1	3.19	3.09	0.001	0.13	0.129
4		60	0.1	3.15	3.05	0.001	0.14	0.139
5		60	0.1	3.14	3.04	0.001	0.137	0.136

$\theta = \underline{10 \text{ degrees}}$  (processed data)

Color of paper (wavelength)	Color of paper (wavelength)	$\theta$ in degrees $\pm 1$	Average V (V) $\pm 0.001$	Average I (A) $\pm 0.001$	Average Power (W) $P = V \times I$
White	White	10	4.499	1.2566	5.65
Red (620 - 750 nm)	Red	10	3.701	0.5528	2.05
Yellow (570 - 590 nm)	Yellow	10	4.2266	0.898	3.79
Green (495 - 570nm)	Green	10	3.9322	0.7024	2.77

Blue (450 – 495 nm)	Blue	10	3.961	0.6952	2.75
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$\theta = \underline{30}$  degrees (processed data)

Color of paper (wavelength)	Color of paper (wavelength)	$\theta$ in degrees $\pm 0.5$	Average V (V) $\pm 0.00025$	Average I (A) $\pm 0.00025$	Average Power (W) $P = V \times I$ $\pm \dots$
White	White	30	4.2764	1.065	4.554
Red (620 - 750 nm)	Red	30	3.46	0.455	1.547
Yellow (570 - 590 nm)	Yellow	30	3.97	0.742	2.95
Green (495 - 570nm)	Green	30	3.66	0.573	2.097
Blue (450 – 495 nm)	Blue	30	3.5104	0.553	1.94

$\theta = \underline{40}$  degrees (processed data)

Color of paper (wavelength)	Color of paper (wavelength)	$\theta$ in degrees $\pm 0.5$	Average V (V) $\pm 0.00025$	Average I (A) $\pm 0.00025$	Average Power (W) $P = V \times I$ $\pm \dots$
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White	White	40	4.4918	0.767	3.45
Red (620 - 750 nm)	Red	40	3.441	0.221	0.76
Yellow (570 - 590 nm)	Yellow	40	4.014	0.401	1.61
Green (495 - 570nm)	Green	40	3.656	0.313	1.144
Blue (450 – 495 nm)	Blue	40	3.656	0.239	0.874

$\theta = \underline{60 \text{ degrees}}$  (processed data)

Color of paper (wavelength)	Color of paper (wavelength)	$\theta$ in degrees $\pm 0.5$	Average V (V) $\pm 0.00025$	Average I (A) $\pm 0.00025$	Average Power (W) $P = V \times I$ $\pm \dots$
White	White	60	3.966	0.269	1.067
Red (620 - 750 nm)	Red	60	2.924	0.1072	0.3135
Yellow (570 - 590 nm)	Yellow	60	3.618	0.222	0.804
Green (495 - 570nm)	Green	60	3.116	0.1536	0.479

Blue (450 – 495 nm)	Blue	60	3.074	0.1304	0.4
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